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Argonne National Laboratory

Proceedings of the Conference on

SLOW-NEUTRON-CAPTURE GAMMA-RAY SPECTROSCOPY

Held at Argonne National Laboratory,
2-4 November 1966

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ARGONNE NATIONAL LABORATORY
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Proceedings of the Conference on
SLOW-NEUTRON-CAPTURE GAMMA-RAY SPECTROSCOPY

Held at Argonne National Laboratory,
2-4 November 1966

Edited by
F. E. Throw

H. H. Bolotin
Program Chairman

Published November 1968

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FOREWORD

The Conference on Slow-Neutron-Capture Gamma-Ray Spectroscopy was held 2—4 November 1966 at Argonne National Laboratory. The conference was organized by the Physics Division of the Laboratory and was sponsored by the Laboratory under the auspices of the U.S. Atomic Energy Commission.

During the few years preceding the conference, new technical developments revolutionized the field of slow-neutron-capture gamma-ray spectroscopy, and the need for a conference on this subject became increasingly evident. Invitations were sent to 40 individuals in the United States and Canada who were active in the field. This restriction to a small selected group of participants, virtually all of whom contributed papers, was designed to foster open and detailed critical discussions of the latest developments in the capture-gamma-ray field in an informal atmosphere conducive to a free and stimulating exchange of information and ideas. Although not international in scope, the conference was fortunate to have the participation of a few individuals associated with European laboratories but visiting the United States at the time.

This volume of Proceedings contains all papers presented as well as edited versions of all discussions. Ample time was made available after each contribution to allow for free and wide-ranging discussions; and much of the value and significance of the conference derived from them. In preparing the contributions for publication, edited manuscripts and edited discussions were returned to the participants for their corrections and comments. In many cases, the discussions were quite thoroughly revised in accordance with the announced desire to have the Proceedings reflect what each participant had wished he had said and to provide protection against self-incrimination. The editor has made every effort to accede to the authors'

instructions—but several minor changes were felt necessary to lend continuity to independently revised statements. Since it was not practicable to send final page proofs to the authors, the responsibility for errors in proof must be accepted by the editor. To those authors and discussers who were misquoted in such a way as to detract from the reader's understanding and appreciation of the value of their statements, the editor offers his sincere apologies. For those errors, if any, that have enhanced the significance of particular contributions, the editor desires no formal note of thanks.

The program chairman and (especially) the editor are most appreciative of the efforts of the authors in submitting manuscripts of their formal presentations and of their sanction or correction of edited remarks made by them in the discussions. Special thanks are extended to those members of the formal panel discussion (Session J) who gave so freely of their time, effort, and considered reflections. The good-natured patience and silent long-suffering of all participants in their somewhat lengthy wait for the publication of these Proceedings is gratefully acknowledged. Various impediments have delayed the publication beyond the date hopefully anticipated earlier. (The list of these impediments somewhat overlaps the list of attendees, the program chairman included.) However, the real worth of the conference was derived more from the coming together of virtually all active workers in the field, both as participants and as members of the total audience, than from the printed Proceedings. It is hoped that these Proceedings will interest, stimulate, and inform readers not participating in the conference. Herein, except for archival purposes, lies the value of their publication. A thorough reading makes clear that the contributions have stood the test of time elapsed from their presentation to publication. This is testimony to the quality and value of the papers presented as well as of the associated discussion.

This conference was marked by a high degree of rapport among the participants, many of whom appeared somewhat surprised by the pleasant personalities of some of their colleagues. This congeniality was most evident on the second evening of the conference. Any possible connection between this display of camaraderie and the cocktail party that immediately preceded it has not been established with certainty. This cocktail party and a dinner for the participants were graciously hosted by the University of Chicago. To afford the maximum enjoyment and conviviality, no after-dinner speech was either scheduled or perpetrated.

The participants and the organizing committee are grateful to Mrs. Dorothy Carlson and her staff, who directed the housing and travel accommodations and coordinated most of the physical arrangements of the conference.

They also wish to gratefully acknowledge the efforts of Dr. F. E. Throw of the Argonne Physics Division who edited these Proceedings. His forbearance, skill, and painstaking work are sincerely appreciated.

Those of us who have been directly concerned in the preparation of the Proceedings extend their sincere appreciation to Mrs. Kay Pemble who typed virtually the entire volume and saw to the details of format and layout. It has also been a pleasure to work with Mr. Frank M. Gentile and his staff in the Argonne Graphic Arts Department. In particular, the quality of the figures—especially the half-tones—is attributable to the skill of Mr. Joseph G. Fierce.

The names and affiliations of all registrants are listed at the end of this volume. In addition, an index of authors and participants in the discussions lists the pages on which their contributions and comments are recorded.

H. H. Bolotin
Program Chairman

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SESSION A

2 NOVEMBER 1966

**EXTERNAL-NEUTRON-BEAM AND
COINCIDENCE EXPERIMENTS**

H. H. BOLOTIN, CHAIRMAN

✓ A-1. EXTERNAL BEAMS AND COINCIDENCE FACILITIES

E. B. Shera

Los Alamos Scientific Laboratory, Los Alamos, New Mexico

External Beams

For many types of measurements it is convenient, and often essential, to have a neutron beam external to the reactor. The major problem which one encounters in trying to extract a beam of neutrons for the type of experiment I am considering is that of separating the neutrons from the reactor gamma rays. There is also frequently a problem in separating the fast and slow neutrons. There are several methods in use for performing the separations I have mentioned. I will try to illustrate some of these that are in current use.

The external beam facility at Livermore on their 2-MW reactor, which has been in use for several years, is shown in Fig. 1. This collimator, which looks directly at the reactor core, consists essentially of a number of quartz filters. These filters utilize the fact that the total neutron cross section of quartz is dominated by thermal diffuse scattering. Such scattering decreases with decreasing neutron energy with the result that the more energetic neutrons are selectively removed from the beam.

The transmission of the thermal flux can be improved by cooling the quartz with liquid nitrogen, and I understand that Dr. White plans to modify the Livermore collimator to permit this. At present, this arrangement provides a flux of about 10^6 n/cm²-sec with a Cd ratio in excess of 10^4 .

The gamma-ray attenuation of this type of collimator is, of course, not extremely high and it is necessary to add some additional shielding in the beam path for this purpose. In the Livermore design, this shielding is placed near the reactor core.

Fig. 1. Thermal neutron filter and collimator.

Figure 2 shows a thermal beam arrangement devised by Harvey and Slaughter at Oak Ridge. As you can see, this is basically a fast chopper—but it also makes a very fine thermal facility. Here a neutron beam entering on the left is reflected by the two Inconel collimators. The rotor is fixed at the "open" position. Besides removing the fast neutrons, the reflection process displaces the beam sufficiently that shielding can be interposed to remove the gamma-ray background.

After being twice reflected, the flux obtained is about 5×10^6 n/cm²-sec. The fast-neutron and gamma-ray backgrounds are presumably nearly those due to room background.

Another type of external beam facility I will mention is represented by the arrangement at Los Alamos. Figure 3 shows a horizontal section of the reactor. The core of the reactor is shown at the top and adjacent to it is a large graphite thermal column. The external beam is extracted near the head of the thermal column. A

Fig. 2. Plan view of the arrangement for a doubly reflected thermal neutron beam.

Fig. 3. Horizontal cross section of the reactor.

bismuth-shielded graphite scatterer can be located at any desired position along a line perpendicular to the thermal column. This permits some adjustment of the flux. After leaving the thermal column, the neutrons are collimated by a series of iron, masonite, lead, and LiF apertures. The beam is about $\frac{3}{4}$ in. in diameter at the target. The gamma-ray flux from the reactor core is reduced by several considerations. For example, there is about 7 in. of lead and bismuth between the core and the thermal column. In addition, any core gamma rays which reach the exit of the collimator must first be Compton scattered by $\sim 90^\circ$ in the thermal column. This Compton scattering removes the majority of the gamma energy. In order to reach the detector, a second Compton scattering in the target would be required. The neutron flux at the target position is about 2×10^6 n/cm²-sec; the gamma-ray beam is about 5 mr/hr.

Coincidence Facilities

External beams are useful for a number of types of experiments—for internal-conversion measurements, for angular-correlation measurements, for polarization measurements. A measurement of this latter type has been performed by Bartholomew and co-workers at Chalk River, who have recently published results of a polarization-correlation experiment on the $^{199}\text{Hg}(n, \gamma)^{200}\text{Hg}$ reaction. At present, however, I am concerned with somewhat less sophisticated measurements which are aimed primarily at developing the low-lying level scheme of the daughter nucleus. Most of the present coincidence work is being done with a combination of Ge and NaI detectors. That is, one uses a Ge(Li) detector to view the high-energy primary transitions that populate the low-lying levels and then one watches these levels decay with a NaI detector. In many cases the resolution afforded by NaI is sufficient since much of the complexity of the low-energy capture gamma-ray spectrum is removed by the coincidence requirement. In effect a single

excited level is selected by the Ge detector. If this level does not lie at too high an excitation energy, a NaI detector is normally adequate to interpret its decay. There are, of course, always weak branches for which two Ge detectors would be very useful.

There are some general considerations that apply more or less independently of the particular kind of experimental apparatus. In any coincidence measurement, the ratio of random events to real events is independent of the type of detector and the geometric arrangement and serves to define the maximum usable source strength. This ratio is given by

$$\frac{N_{\text{random}}}{N_{\text{real}}} \approx 2\tau N\beta,$$

where N is the number of captures per second, 2τ is the resolving time of the coincidence circuit, and the factor β is the average number of gammas per capture (say 3—4). If one is willing to accept a chance rate of say 20% and if the resolving time is $2\tau = 20$ nsec, the maximum useful number of captures in the target is about 2×10^6 /sec. We note that this number is of the same order as the fluxes available with present external-beam facilities.

If one uses a NaI detector in one branch of the coincidence circuit, he will usually find that the counting rate in this detector (rather than the chance rate) is the limiting factor. For example, a total detection efficiency in NaI (including the solid-angle factor) of about 3% is not unreasonable. The maximum counting rate that can be tolerated in the NaI (say 50 000 counts/sec) then limits the "source strength" to the order of 5×10^5 captures/sec. Thus with the presently available external beams one can obtain a "maximum usable source" even for rather modest quantities of low-cross-section materials. For example, for the Los Alamos coincidence facility we normally use about 150 mb-mole of target material.

Fig. 4. Schematic diagram of the detector arrangement used at Los Alamos.

Fig. 5. Actual physical arrangement of the detectors.

The detector geometry used at Los Alamos is shown in Fig. 4. The neutron beam is incident from the right and the two detectors are located 90° apart in a plane perpendicular to the beam. Figure 5 shows the actual physical arrangement. The detector assembly consists essentially of a Pb-filled chamber with passages milled out for the beam and the detectors. Considerable shielding is required between the two detectors to eliminate the strong coincidence with 511-keV gammas which arise from the pair-production process in the Ge detector. The arrangement is also designed so that the target region can be evacuated and a cooled silicon electron detector inserted and used to study internal conversion. We have not tried this feature yet.

The incoming beam is defined by a LiF aperture and LiF neutron absorbers are placed in front of each of the detectors. For targets with a small capture cross section, we also use a cylindrical LiF wrapper around the target to absorb neutrons which would otherwise be scattered into the lead shielding. The Ge(Li) detector is about $1\frac{1}{4}$ in. from the center of the target and the 3×3 NaI crystal is about 2 in. away.

Because of the low efficiency of the Ge detector, the coincidence counting rate is very low in spite of the high rate in the NaI

Fig. 6. Coincidence data from the $S^{32}(n,\gamma)S^{33}$ reaction. Each horizontal axis corresponds to the energy deposited in one of the two detectors.

detector. We typically get the order of a few coincidences per second. This low rate means that perhaps a week or more of counting time is required to accumulate useful data. This sort of run is quite practical when you are using a reactor—I think it would be a bit more difficult at most Van de Graaffs. The low counting rate makes multiparameter data storage almost essential—at Los Alamos we write the coincidence data event-by-event onto magnetic tape. The analysis is then carried out later with a computer.

The sort of multiparameter data one gets is shown by Fig. 6, which illustrates some coincidence data from the $S^{32}(n,\gamma)S^{33}$ reaction, taken by Kennett, Archer, and Hughes at McMaster University. If one imagines the array of coincidence data as a surface with the two axes corresponding to the energy deposited in the two detectors, then slices through this surface taken at a particular transition energy correspond to the spectra coincident with that transition.

Fig. 7. Use of the coincidence data to develop a level scheme.

Figure 7 shows in more detail how the coincidence data can be used to develop the level scheme in a particular case. These data from the $^{65}\text{Cu}(n, \gamma)$ reaction were obtained by Dr. Bolotin and myself this past summer at Los Alamos. On the top left side we see the two singles spectra. The one on the left is a low-energy singles spectrum (up about 1 MeV) seen in a NaI counter. Next to it is a part of the high-energy spectrum (5 to 7 MeV) seen in a Ge detector. The prominent lines in this region are lines 4 and 5, which are indicated on the level scheme as occurring between the capture state (7061 keV) and levels at 384 and 463 keV.

The plots below the singles spectrum at the left show some coincidence data. These slices of the coincidence surface correspond to lines 4 and 5; they are generated by taking regions on either side of the desired peak and subtracting the spectra in coincidence with

those regions from the spectra in coincidence with the peak. This procedure helps to correct for the Compton continuum which lies under the peak. It does not improve the statistics. The spectrum in coincidence with line 4 shows a strong ground-state transition at 384 keV, as shown on the level scheme. Similarly, line 5 is in coincidence with a prominent 463-keV transition. Note that these peaks are barely identifiable in the singles spectrum, which is dominated by an intense peak at 511 keV due to annihilation in the Pb shielding.

The right-hand side of Fig. 7 shows the data from a separate coincidence measurement in which both detectors viewed the low-energy spectrum. The NaI spectrum is in the top right corner and the Ge spectrum is next to it. Both spectra cover the approximate range from zero to 1 MeV. Below the NaI singles plot is shown the spectrum in coincidence with the 314-keV peak in the Ge. This spectrum is generated by the same subtraction procedure mentioned above. In coincidence with the 314-keV transition, we see transitions at 88 and 185 keV. These three transitions are interpreted as a triple cascade starting at a state at 587 keV and leading to the ground state.

In this example I have tried to demonstrate how a relatively small amount of coincidence data can provide considerable confidence in constructing the major features of the low-lying level scheme.

In closing I might comment briefly on prospects for replacing the NaI detector with a second Ge(Li) detector. The data of Fig. 7 were taken with a Ge detector of about 1.5-cm^3 volume. If the $3 \times 3\text{-cm}$ NaI detector were replaced by a large-volume Ge detector, the efficiency would drop by roughly two orders of magnitude. However, if also the 1.5-cm^3 detector were replaced by large Ge detector of a size which is currently available, the efficiency would rise by almost 2 orders of magnitude. The over-all change in efficiency would therefore be quite small—and, of course, the data would be considerably improved because of the better resolution at low energies.

* * *

L. M. BOLLINGER, Argonne National Laboratory: Do you consider your flux, which you gave as 2×10^6 neutrons $\text{cm}^{-2} \text{sec}^{-1}$, sufficiently high for the kind of measurements you are talking about?

SHERA: There are a few cases in which it is difficult to obtain enough sample material; in these cases, a somewhat higher flux would be useful. The value of 150 mb-mole of target material, which I quoted, corresponds to a total interacting area of approximately 0.1 cm^2 . The source strength obtained by multiplying this area by the flux is of the order of 2×10^5 captures/sec. This is in the range that I quoted as the strongest usable source for this type of experiment. We might use 2 or 3 times our present flux, but I think anything more than ten times this flux would be wasted on most experiments.

BOLLINGER: Some alternative arithmetic seems to show that one would like about 100 times your flux. I would feel that in these measurements you would like to have available something like 10^4 counts/sec in the Ge diode with 1 g of typical material—since 1 g is about all you could afford of most separated isotopes. With reasonable numbers, this seems to imply that one would like a flux of $\sim 10^8$ neutrons $\text{cm}^{-2} \text{sec}^{-1}$.

SHERA: The limitations I have just suggested are based upon the use of a NaI detector in one branch of the coincidence circuit. If we remove this restriction and consider experiments that use two (small) Ge detectors, then the true-to-chance ratio will permit a tenfold increase in the source strength. Use of the same amount of target material then implies an order of magnitude greater flux. When larger Ge detectors become available, counting-rate limitations will probably reduce the maximum usable source strength to near the present level with NaI.

O. W. B. SCHULT, Technical University, Munich and Brookhaven National Laboratory: I would like to mention that a very nice facility to

extract neutrons from a reactor has been built at Risø. The people there used a big through-hole and a thin light-water scatterer approximately 3 mm thick. The neutrons from this scatterer penetrate a bismuth filter and the result is a neutron flux of about 10^9 neutrons $\text{cm}^{-2}\text{sec}^{-1}$. The gamma-ray background in the beam is ~ 2 mR/h. Comparing this neutron flux with your figure of 2×10^6 neutrons $\text{cm}^{-2}\text{sec}^{-1}$ suggests that the neutron flux at Risø is probably high for many experiments. However, I am convinced that this neutron flux would be needed if one wanted to do coincidence experiments between gamma rays and conversion electrons—since in such experiments one is forced to use a thin target. Thus I would think that at a reactor of intermediate power, such as the DR-3, a setup such as the one used in Risø would be a very nice facility.

SHERA: When the experiment involves coincidences with conversion electrons, the situation is quite different. Dr. Bollinger's two-orders-of-magnitude increase in beam intensity would be very useful in that situation. However, the true-to-chance-ratio limitation still applies.

J. A. HARVEY, Oak Ridge National Laboratory: With regard to the mirror technique mentioned in your talk, we simply used the chopper that has parallel slits. However, by focusing the beam to a point, its flux density can be increased by an order of magnitude—as has been done at Risø.

R. E. CHRIEN, Brookhaven National Laboratory: What is the prospect for reducing the time resolution width from 20 nsec to something lower?

SHERA: Although I am not the one best qualified to answer that question, I think the resolution might be improved by a factor of two. I think that variations in the rise time (which are more or less inherent in the present method of construction of germanium detectors) set a lower limit of that order. I do not think that one is likely to improve

the resolution by an order of magnitude unless he has an improved method of making the detector. As a matter of fact, we have been using twice this width (about 40 nsec) at Los Alamos. When one does multiparameter work covering a large energy range in each detector, he wants to be fairly sure that the coincidence circuit is fully efficient for all of the energies included.

SCHULT: Could you say a little more about the effect of the gamma background on these coincidence experiments? What would you consider a reasonable gamma flux in the beam for a normal kind of experiment?

SHERA: Since the gammas in the beam must always be scattered in the target if they are to reach the detector, one can stand a reasonable gamma flux. I have not made a study of this at our facility. Our major problem is not the gamma background in our beam, but is the difficulty of removing fast neutrons from the beam. LiF is relatively ineffective for this purpose. The mirror, or some type of multipole reflection technique, may be superior because it eliminates practically all of the fast neutrons.

SCHULT: Then I think it would be a good idea to use some kind of a neutron guide tube, which is supposed to give very few fast neutrons. Such guide tubes and their characteristics have been studied extensively at Munich and also at Jülich in Germany. I would think that a neutron guide tube would be a very helpful facility in your experiments too.

SHERA: I agree.

H. H. BOLOTIN, Argonne National Laboratory: Going back to the problem of the counting rate and the flux, we have to remember that if one wants to get as high an energy resolution as possible in both legs of the coincidence circuit, one has to use germanium detectors. Until we have very large germanium detectors, the detection efficiency will remain quite small. This means that a higher source strength is

needed in order to get a reasonably large number of coincidence counts in a finite time. This has the unfortunate by-product of lowering the true-to-chance ratio. In other words, if you raise your flux of 2×10^6 neutrons $\text{cm}^{-2} \text{sec}^{-1}$ by a factor of 100, the true-to-chance ratio will become extremely poor. For germanium detectors (and to a smaller extent in sodium iodide), we will have to do something quite striking if we are to reduce the resolving time enough to allow approximately 100 times the singles counting rate indicated here in each leg of the coincidence system.

M. G. STRAUSS, Argonne National Laboratory: There is a conflict between two requirements. If you make the detector larger (to increase the detection efficiency) you run into poor time resolution. An experimenter will probably have to use some kind of compromise.

~~A-2~~. GAMMA-RAY SPECTRA FROM RESONANCE NEUTRON CAPTURE
USING A REACTOR BEAM*

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The ORNL fast-chopper time-of-flight spectrometer and a NaI crystal 9 in. in diameter by 12 in. long have been used in the past for the measurement of gamma-ray spectra following the capture of neutrons in individual resonances. When the advent of lithium-drifted Ge crystals made the NaI crystal obsolete as a primary instrument for measuring neutron-capture gamma rays, intensity and efficiency considerations made it impossible to use the Ge(Li) crystal in exactly the same manner. There were three obvious choices in the manner of proceeding: (1) continuing to operate in the time-of-flight mode by building a new rotor with higher intensity and poorer neutron resolution, and acquiring much more elaborate and expensive data-acquisition equipment, (2) continuing to operate in the time-of-flight mode with the present rotor and attendant low counting rates, with new data-acquisition equipment, and (3) performing open-beam measurements with high counting rates and adequate data-acquisition equipment. In any case, measurements would be restricted to the largest, lowest energy, well-separated resonances. The decision to eliminate the first two choices and perform experiments with an open dc beam were largely based on the imminent (two years) availability of an electron linear accelerator at ORNL dedicated to neutron physics. The accelerator facility will require large-scale multiparameter data-acquisition equipment, which makes the purchase of interim equipment for chopper time-of-flight experiments uneconomical.

* Research sponsored by the U.S. Atomic Energy Commission under contract with the Union Carbide Corporation.

Crude neutron energy resolution is available through the use of ^{10}B filters with $1/E$ transmissions ranging up to 1500 eV and, in fortuitous cases, resonant filters. Above a few keV of neutron energy, advantage can be taken of the gamma-ray resolution of the Ge(Li) crystal to resolve primary gamma rays which are shifted toward higher energy by the incident neutron energy. If the resonances are separated by many keV, capture in individual resonances can be measured; otherwise, only the average over resonances can be measured.

The ^{10}B and resonance filter technique was used to advantage in some measurements on the isotopes of Sn. Relative gamma-ray angular distributions from neutron capture in the 45.8-eV resonance in ^{118}Sn were measured by using a Mn filter, according to a suggestion by Lowell Bollinger, to take out the 359-eV resonance capture and ^{10}B filters to determine the background from the capture of high-energy neutrons and room background. Angular distributions from the 359-eV resonance were determined by subtraction of the "Mn in" run from the "Mn out" run. The 62-eV resonance in ^{124}Sn (target) dominates the capture, with a resonance integral of 6.8 b, as compared with a resonance integral of less than 0.04 b computed for all other known resonances. Angular-distribution measurements for the 62-eV resonance were made by the use of this difference technique with the ^{10}B filter.

Primary transitions from neutron capture in the 1148-eV resonance of ^{56}Fe were measured using the ^{10}B filter difference technique. Spectra taken at 90° and 135° to the incident neutron beam indicated that the relative angular distribution between the ground-state transition and the transition to the first excited state was probably isotropic. A $d_{5/2}$ capturing state was rendered unlikely by the appearance of transitions to both the $\frac{3}{2}^-$ first excited state and the $\frac{1}{2}^-$ ground state; the transition to the $\frac{1}{2}^-$ state would be M2 or of higher multipolarity for a $d_{5/2}$ capturing state. The data were not of sufficient quality to determine a 1-keV energy shift relative to the position for thermal capture.

Fig. 8. Spectra of gamma rays following capture of neutrons in Al. Above: thermal neutrons. Below: all neutrons captured above 1 keV neutron energy.

Figure 8 shows the gamma-ray spectrum from all neutrons captured in Al above 1 keV, compared to the thermal capture spectrum. A line appearing about 35 keV higher in energy than the prominent 7729-keV ground-state transition in the thermal spectrum is interpreted as the ground-state transition from capture in the 35-keV resonance. No indication is seen of the ground-state transition from capture in the 6-keV resonance. These data are in agreement with the findings of Bergqvist, Biggerstaff, Gibbons, and Good,¹ who observed strong

¹ Bergqvist, Biggerstaff, Gibbons, and Good, Nuclear Structure Study with Neutrons (Proceedings of the International Conference, Antwerp, 19-23 July 1965), edited by M. Nève de Mévergnies, P. Van Assche, and J. Vervier (North-Holland Publishing Co., Amsterdam, 1966), paper 129.

gamma-ray transitions to or near the ground state following neutron capture in the 35-keV resonance of ^{27}Al . M1 transitions in the odd-odd compound nuclei (for example, the ground-state transition from capture in the s-wave 35-keV resonance) were found to be enhanced¹ relative to the E1 transitions (for example, the ground-state transition from capture in the p-wave 6-keV resonance).

Other measurements were made upon Na, F, Pb, Ti, V, Ni, and Pt, but these yielded very little in the way of resonance capture above 1 keV. Since the resonance neutron current available with the open dc beam from the ORR is comparable to that which will be obtainable from the electron linac operating in the pulsed mode, it is apparent that measurement of capture spectra from individual high-energy neutron resonances will be beset with some difficulty.

* * *

L. M. BOLLINGER, Argonne National Laboratory: I am interested in your results on aluminum because we have tried unsuccessfully to make a similar measurement. One thing that makes me slightly skeptical about your results is that you see a fairly big effect in terms of the total number of counts. I wonder if you have, in fact, quantitatively checked to see if the number of counts that you get is roughly what would be expected.

SLAUGHTER: This run took 8000 min. We did another check run, which I looked at just before I left the laboratory to come here; but we have not had time to definitely establish that this is the ground-state transition from the 35-keV resonance. I have not made the calculation that you refer to.

J. A. HARVEY, Oak Ridge National Laboratory: I did calculate the expected capture rate and it is in fair agreement with the experimental

result. Also we have looked to see if this line might be assigned to some other element. However, we cannot find any known gamma-ray line (which presumably would have to be very intense) which would occur at this energy (35 keV above the Al ground-state transition).

R. E. CHRIEN, Brookhaven National Laboratory: In your angular-distribution work on iron, was your detector able to resolve the 14-keV doublet?

SLAUGHTER: Yes, very well. I would say that the valley between the peaks comes down to within 20% of the baseline. The resolution width of our crystal was about 8 keV FWHM in that region.

~~A-3~~. GAMMA RAYS FROM THE $\text{Os}^{189}(n, \gamma)\text{Os}^{190}$ REACTION

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and

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The transition with increasing neutron number from a deformed to a spherical level pattern takes place rather gradually for the isotopes of osmium. Accordingly, it has been recognized for some time that the determination of the properties of collective levels in this region would be valuable.¹ Of the even-A osmium isotopes, the last to exhibit strongly the properties of a deformed nucleus is Os^{190} . An energy level scheme of Os^{190} is given in Fig. 9, showing levels

Fig. 9. Energy levels of Os^{190} populated in the decay of the 3-h and 12-day isomers of Ir^{190} (from Ref. 3).

¹ G. Scharff-Goldhaber, Proceedings of the University of Pittsburgh Conference on Nuclear Structure, June 6-8, 1957, edited by S. Meshkov (University of Pittsburgh and Office of Ordnance Research, U.S. Army, 1957).

populated in the decay^{2,3} of the 3-h and 12-day isomers of Ir^{190} . The ground-state rotational band (with five levels established) and the one-phonon gamma-vibrational band (with three levels established⁴) are shown. The 4^+ state at 1161 keV is believed to represent the two-phonon gamma vibrational excitation.⁵ The 10^- isomeric state at 1700 keV is believed to be a particle excitation arising from the coupling of two neutrons in the $\frac{9}{2}^- [505]$ and $\frac{11}{2}^+ [615]$ Nilsson states. The nature of the odd-parity levels above 1300 keV has not been established.

Os^{190} would be expected to possess still other types of collective and particle excitations. A 0^+ beta-vibrational state and its associated rotational band, and the 0^+ state from the two-phonon gamma-vibrational excitation would be expected to appear. For Os^{188} , two 0^+ states have been identified—at 1078 and 1764 keV. The lower of these is believed to represent the two-phonon gamma-vibrational excitation. The coupling of nucleons in various Nilsson states should form levels with various spins and parities. In particular, the coupling of neutrons in the $\frac{1}{2}^- [510]$ and $\frac{3}{2}^- [512]$ orbitals should give rise to bands based on 1^+ and 2^+ states. Of these, the 2^+ state would be expected to contribute most of its strength to the 2^+ state of the one-phonon gamma band. The 1^+ state, on the other hand, might be expected to exhibit particle character.

Because the isomers of Ir^{190} all have a spin of 4 or greater, these low-spin levels of Os^{190} are not populated directly in the decay of Ir^{190} . For neutron capture by Os^{189} , on the other hand,

²G. Scharff-Goldhaber, D. E. Alburger, G. Harbottle, and M. McKeown, Phys. Rev. 111, 913 (1958).

³W. R. Kane, G. T. Emery, G. Scharff-Goldhaber, and M. McKeown, Phys. Rev. 119, 1953 (1960).

⁴An additional level at 1203 keV, believed to be the 5^+ member of the one-phonon gamma band, and several other new levels at higher energies, have been established by B. Harmatz and T. H. Handley, Nucl. Phys. 56, 1 (1964).

⁵R. K. Sheline, Rev. Mod. Phys. 32, 1 (1960).

Fig. 10. Spectra of the high-energy gamma rays from the Os^{189} and $\text{Cr}^{53}(n, \gamma)$, reactions obtained with a Ge(Li) detector. Curve (a) is the spectrum obtained from a composite target of Os^{189} and Cr^{53} ; curve (b) the spectrum obtained from a target of Os^{189} alone.

the capture state will have a spin and parity of 1 or 2^- , and hence states with spins from 0 to 3 can be populated directly by dipole transitions.

We have studied the thermal-neutron capture gamma rays of Os^{190} . A target of 1.4 g of Os^{189} was situated in an external neutron beam with an intensity of $8 \times 10^6/\text{cm}^2\text{-sec}$, collimated to 3 mm diameter. Two Ge(Li) detectors were used, a 2 cm^3 planar device fabricated by the authors and a 10 cm^3 coaxial device fabricated by H. Kraner of the Brookhaven National Laboratory Instrumentation Division. Both Ge(Li) singles spectra and Ge(Li)-NaI coincidence results were obtained. In the coincidence runs, high-energy gamma rays were registered by the Ge(Li) detector and low-energy gamma rays by a 3×3 -in. NaI detector. The data were accumulated by a two-dimensional pulse-height analyzer in a 256×64 -channel format. Runs made on normal osmium and background runs made with a graphite target were used to confirm the assignment of individual gamma rays to Os^{190} .

Some typical high-energy singles spectra are shown in Fig. 10. Curve (a) is the spectrum from a composite target of Os^{189} and Cr^{53} , and curve (b) that from Os^{189} alone. The runs with the composite target were made in order to determine the energies of the Os^{190} gamma rays by comparison with those of Cr^{54} , whose energies are believed to be known to ± 2 keV.

TABLE I. High-energy transitions in the $^{189}\text{Os}(n, \gamma)^{190}\text{Os}$ reaction.

E_{γ} (keV)	Final state (keV)	K	I	π	I_{γ} (%)	Coincidences
7795 ± 5	0	0	0	+	60	
7609 ± 5	187	0	2	+	24	187
7237 ± 5	557	2	2	+	80	557, 370, 187
7035 ± 5	756	2	3	+	7	569, 198, 187
6870 ± 15	925				3	725, ~ 560 , ~ 370 , 187
6682 ± 5	1113				5	925, ~ 560 , ~ 370 , 187
6410 ± 5	1385				18	~ 1200 , ~ 560 , 187
6356 ± 5	1439				13	
6247 ± 5	1548				34	
5932 ± 3	1863				100	
5878 ± 5	1917				30	

The results of the singles and coincidence measurements are summarized in Table I. Eleven primary transitions were found to states with energies below 2 MeV. The lowest four of these states are the first two members, respectively, of the ground-state rotational band and one-phonon gamma band. The coincidence results bear out the known de-excitation patterns of these levels. The highest four levels have not previously been observed. They do not coincide in energy with any of the levels shown in Fig. 9, nor with any of the additional levels established by Harmatz and Handley.⁴ This is expected, because all of the already established levels in this energy region have high spins.

The two new states at 925 and 1113 keV are of particular interest. The 188-keV spacing of the levels is about what would be expected for spins of 0 and 2 or spins of 2 and 3, respectively, if the two levels are members of the same rotational band. If the two levels had spins of 2 and 3, respectively, and were members of a rotational band built on the 1^+ particle state discussed above, then the 1^+ state would lie at ~ 800 keV. Since this state was not observed, although it could have been populated by E1 transitions from either the 1^- or 2^- capture states, this interpretation appears less likely. Alternatively,

spins of 0 and 2 for the 925- and 1113-keV levels would be consistent with the identification of the two states as members of a rotational band built on either the beta-vibrational excitation or on the two-phonon gamma-vibrational excitation. From the de-excitation of the two levels, it should be possible to distinguish between these two possibilities; the two-phonon gamma-vibrational states should decay strongly to the one-phonon states, while the beta-vibrational states should decay strongly to members of the ground-state rotational band. The coincidence results show that there are strong transitions from both the 925- and 1113-keV levels to the 2^+ first rotational state, and weaker transitions to members of the one-phonon gamma band, suggesting that the 925- and 1113-keV levels are identified with the beta vibration. More complete results on the de-excitation of these two levels will be sought in order to clarify this question.

A level at 1385 keV, populated by a primary transition, has virtually the same energy as a level populated in the decay of Ir^{190} (1384 keV). In the decay of Ir^{190} , on the basis of the existence of two E1 transitions³ from this level to 2^+ and 4^+ levels, respectively, and from angular-correlation results,⁶ a 3^- spin and parity assignment was made. Harmatz and Handley observed four additional weak transitions between this state and lower-lying states and assigned it 2^- character. With the 2^- spin and parity assignment, three of the transitions from the level would be of E1 multipole order, and three would be M2. For the 3^- assignment, five transitions would be E1 and one E3.

If the 1385-keV state populated following neutron capture had odd parity, the primary transition from the capture state would be M1. With the known fluctuations in M1 and E1 transition strengths, this is quite possible but not probable. More important, the coincidence results show that the level populated following neutron capture decays

⁶T. Yamazaki, Nucl. Phys. 44, 353 (1963).

strongly to the 187-keV first excited state, while the state populated by the decay of Ir^{190} decays strongly to the 954- and 1161-keV levels, and only weakly to the 187-keV state. We thus conclude that there are two levels with energy ~ 1385 keV, one with a spin of 3 (or 2) and odd parity (which is strongly populated in the decay of Ir^{190}) and one with a low spin and even parity—which may be weakly populated in the decay of Ir^{190} and is populated with moderate intensity in the $\text{Os}^{189}(n, \gamma)\text{Os}^{190}$ reaction.

* * *

S. B. BURSON, Argonne National Laboratory: This comment is not specifically on the activity you were studying, but rather extends one of your opening remarks about the study of capture-gamma-ray spectra. In the case of Er^{166} , states are populated by the decay from three nuclides—the 0^- and 7^- states of Ho^{166} and the 2^+ state of Tm^{166} . It is interesting to note that the decays from these three levels populate entirely different levels above 1 MeV in Er^{166} . Thus it is not necessary to justify your (n, γ) study on the basis that the radioactive transitions populating these levels feed only from high-spin states; it would still be justified even though the final spin states were similar. (That is, in the capture-gamma-ray spectra, one would expect only low-spin levels to be populated. But since one actually expects different orbitals to be occupied in the different cases, I think the capture-gamma-ray studies are easily justified.)

KANE: I agree.

O. W. B. SCHULT, Technical University, Munich, and Brookhaven National Laboratory: I have a few questions concerning osmium. I believe you said that the 1161-keV 4^+ level in Os^{190} is a two-phonon gamma vibrational level. Evidently an argument for this is that it has

twice the energy of the head of the one-phonon gamma band. Can one definitely conclude that this state is not a two-quasiparticle state?

KANE: I think the argument is based primarily on the fact that it decays very strongly to the one-phonon gamma band.

SCHULT: But if it is a K=4 band, it should not decay to the ground-state band so strongly because of normal K forbiddenness.

KANE: Right.

SCHULT: It would be nice to have some charged-particle data to see how strongly this band is populated. This would definitely help to establish (or at least get an idea about) its wave function.

Also, I wonder if the first 0^+ state in Os¹⁸⁸ is not the band head of the β band rather than a two-phonon gamma vibrational band. What does one know here?

KANE: I think the conclusion again is based on the de-excitation of this state. It seems to decay strongly to the one-phonon gamma vibrational band and not to the ground-state rotational band.

G. T. EMERY, Indiana University: Maybe I can add something to the discussion of the decay of the 4^+ state of Os¹⁹⁰. The branching ratios in its decay to the gamma band are just what one would predict from the pattern of the decay of the first gamma band to the ground-state band. In the case of Os¹⁸⁸, one does not see any E0 transition to the ground state—although such a transition usually is seen in the case of a 0^+ beta band.

V. J. ORPHAN, Massachusetts Institute of Technology: Would you explain briefly how you measured the intensities of the capture gamma rays?

KANE: Yes. That was going to be discussed tomorrow in a talk on chromium (Paper F-2). Briefly, for our own purposes we have tried to set up Cr⁵³ as an internal standard. Its gamma-ray energies have been determined fairly reliably and one can "bootstrap" one's

way up to the binding energy in a couple of steps. As to intensity measurements, it just happens that the levels of Cr^{53} are well enough known and all transitions of any strength have been placed in the decay scheme. What we did was to determine the efficiency of our germanium detector up to 2.75 MeV by the usual procedure of using radioisotopes for which the intensity ratios of the gamma rays are known. These were Na^{24} , Na^{22} , $\text{Ag}^{108\text{m}}$, $\text{Hf}^{180\text{m}}$, and Th^{228} . Then, having determined the efficiency of the detector at 2.75 MeV, we made use of the known relationships between high- and low-energy gamma rays in Cr^{54} . For example, the 7.1-MeV gamma ray is followed by a 1.78-MeV gamma ray, with almost nothing else into or out of the intermediate level. Thus we think we know the intensity ratio of those two gamma rays, and by this means we are able to construct an efficiency curve for the detector in the high-energy region. Thus we get the relative intensities of the higher energy gamma rays of osmium.

H. H. BOLOTIN, Argonne National Laboratory: If you know the energies of the chromium gamma rays to an accuracy of 2 keV, why do you quote an error of 5 keV here when you mix these two targets? Couldn't you do a little better?

KANE: The trouble is that this requires a second comparison. That is, having determined the chromium energies, we still have to get a spectrum, fit all the lines of chromium and of osmium, and then compare the two. If we felt we could determine lines to better than 5 keV, we would quote smaller errors. We know the low-lying levels in the decay scheme, and really the only problem is to identify the transitions and the final states to which they go.

BOLOTIN: My question was mainly to ascertain whether the 5-keV error was just a conservative estimate on your part or had to do with the statistics and/or the method of finding the centroids of the peaks.

KANE: The centroid of a peak of any intensity is usually known to about 0.1—0.2 channel (although, of course, the weaker peaks are less accurately determined), with a typical dispersion of a couple of keV per channel. We suspect that unknown effects—such as small deviations from Gaussian line shapes or the like—may be present, so we quote a larger error.

O. W. B. SCHULT: Three years ago at a conference here at Argonne, it was shown that you can obtain the center of the line with very good accuracy even if you have only a few counts. As a rough example, if the background can be neglected and if the integral over the line is 100 counts, then the position of the peak could be determined to within $\frac{1}{20}$ of the FWHM. One can easily estimate what this means in the case of a normal germanium diode.

V. J. ORPHAN: Isn't it true that insufficient knowledge of the nonlinearities of the electronics is probably what limits the energy determination?

KANE: Certainly. The systems are known to be nonlinear; and in addition there are other effects such as the differential linearity of the pulse-height analyzer. If the bin width for one channel is narrower than that of one a few channels away, the apparent position of the line may be shifted. This is the reason for using chromium in this way; its decay scheme gives a number of energy loops up to the binding energy and we believe the level energies are known to within 2 keV. In the superimposed spectra of the two isotopes, obtained with a composite target, there is a chromium line not far from any osmium line whose energy one wants to measure.

ORPHAN: Have you compared the sums of different cascades between the same two energy levels?

KANE: Yes indeed! In the combined chromium and osmium spectra, we feel that the energy differences we measured for the osmium lines are certainly better than 5 keV.

~~A-44~~. STUDY OF THE $\text{Co}^{59}(n, \gamma)\text{Co}^{60}$ REACTION E. B. Shera

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The odd-odd Co^{60} nucleus is not populated by beta decay, and largely for this reason little has been known about its level structure—particularly in regard to the spin and configuration assignments of the low-lying levels.

The $\text{Co}^{59}(\text{d}, \text{p})$ reaction was studied several years ago at MIT. Also the thermal neutron capture spectrum has been reported by Wasson, Wetzel, and Bockelman.¹ The present investigation included measurement of the high- and low-energy (n, γ) spectra and also some coincidence measurements.

Figure 11 shows the high-energy capture spectrum over the energy range from 4.5 to about 7.5 MeV. The ground-state spin of Co^{59} is $\frac{7}{2}^-$ and the capture state in Co^{60} can have spins 3^- or 4^- . The Co^{60} ground state is known to have spin 5^+ . The E1 transition from the capture state to the ground state is shown as line No. 1 and gives a binding energy of 7489.7 ± 3.0 keV. This is in good agreement

Fig. 11. High-energy portion of the gamma-ray spectrum from the $\text{Co}^{59}(n, \gamma)\text{Co}^{60}$ reaction.

¹O. A. Wasson, K. J. Wetzel, and C. K. Bockelman, Phys. Rev. 136, B1640 (1964).

Fig. 12. Low-energy portion of the gamma-ray spectrum from the $\text{Co}^{59}(n, \gamma)\text{Co}^{60}$ reaction.

with the value 7486 ± 11 keV derived from the (d,p) work. The energy calibration here is based on the $\text{N}^{14}(n, \gamma)$ energies. I understand that there is now evidence that these nitrogen energies are a bit low (paper F-1), so this value of the Co^{60} binding energy should perhaps be raised 1 or 2 keV. This spectrum was taken using a Ge(Li) detector (volume = $1\frac{1}{2}$ cm³) surrounded by a large NaI annulus. This annulus is operated in coincidence with the Ge detector to select only the double-escape peaks. Dr. Journey will discuss this spectrometer system in paper B-3. The observed intensities range from lines No. 8 and 9 which are present in about 10% of the captures to about $1\frac{1}{2}$ gammas per 1000 neutrons for line No. 2.

Figure 12 shows the low-energy spectrum up to about 1800 keV. It was obtained with the same detector and annulus, but the annulus was operated in anticoincidence with the detector to suppress Compton events. The intensity range presented is approximately the same as in Fig. 11. The strongest peak (at 230 keV) is present in 20% of the captures and the small peak at 350 keV is found in 1 or 2 captures out of 1000. Notice the two strong lines at 230 and 277 keV, the pair of triplets around 460 keV, and the strong line at 556 keV.

At the bottom of Fig. 13 we see the same spectrum taken with NaI. The point of the figure, though, is not to show you how bad NaI is but to show how the coincidence data (shown in the upper spectra)

Fig. 13. NaI spectra from the $\text{Co}^{59}(n, \gamma)\text{Co}^{60}$ reaction.

have straightened things out again. The 230- and 277-keV transitions are now separated, as are various components of the two triplets. These data also establish the positions of these transitions in the level scheme with some certainty since they must occur between states that are lower in excitation energy than the level that is directly fed by the particular primary transition.

Figure 14 shows the level structure of Co^{60} . This is based largely on the coincidence measurements. To separate them, the primary transitions are shown in white and the low-energy transitions are shown in black. The widths of the lines are proportional to the intensities. With the exception of a few weaker lines, which are shown dashed, the placement of all the transitions was verified by the coincidence measurements.

We have made tentative spin assignments for these levels as shown on the left. This job was made easier by the fact that the ground state and the 58-keV isomer differ so widely in spin.

In general a fairly good idea of the spin of a given state can be obtained simply by noting to which of these two levels it decays. The range of spins (2—5) that can be populated directly from the capture state also helps to narrow the choice. These considerations are illustrated in Fig. 15. Here the levels

Fig. 14. Level structure of Co^{60} . Primary transitions are shown in white; low-energy transitions are black. The widths of the lines are proportional to the intensities.

have been displaced horizontally according to our spin assignment. If one assumes that the more intense transitions from a particular state will be those with the lowest multipolarity, then the spin sequence shown here can be constructed.

For example, consider the level at 276 keV. This level decays strongly to the 5^+ ground state. It is also populated by a state (namely the 613-keV state) which decays strongly to the 2^+ isomer. According to the rule, then, the 276-keV state is likely to be $I = 4$ and the 613-keV state $I = 3$.

It is true that this rule is not infallible and we occasionally expect to see it violated. However, each level that is added to the scheme tends to confirm the lower assignments; and given enough

Fig. 15. Energy levels of Co^{60} , separated according to the spin assignments. The dashed transitions are weak and have not been verified by coincidence measurements.

Fig. 16. Comparison between the experimental energy levels of Co^{60} and the results of a zero-range calculation for three configurations.

there are transitions that appear to connect it with the isomer and with the 540-keV level, we have assigned it spin 1 or 2—with a slight preference for spin 1.

With these tentative spin assignments in hand, we did some calculations aimed at trying to understand the configurations of these states. Figure 16 shows the results. In calculating the theoretical spectrum of an odd-odd nucleus like Co^{60} , one usually starts by looking at the neighboring odd-A nuclei to see what excited nucleon configurations occur in the region. Considering only the two odd particles, the 27 protons presumably leave one hole in the $f_{7/2}$ shell and the 33rd neutron leaves a hole in the $p_{3/2}$ shell, and at higher excitation a $f_{5/2}$ particle, and still higher a $p_{1/2}$ particle. Coupling these two odd-particle configurations using some form of residual proton-neutron interaction produces a spectrum of states which can be compared with experiment.

In this case we used a zero-range interaction of the form

$$V_{pn} \propto V_o [(1 - a) + a (\vec{\sigma}_p \cdot \vec{\sigma}_n)] \delta(\vec{r}_p - \vec{r}_n).$$

transitions to work with, the vast majority of the assignments should be correct. In this case we were able to make what seem to be quite reasonable assignments for all the levels up to 1 MeV. The major exception, as I recall, is the 738-keV state which is not populated directly by a primary transition from the capture state and no coincidence data were available for it. Because it is not populated directly and because

This leads to the levels shown here for the three configurations. These seem to agree reasonably well with the experimental spectrum.

I will not dwell on this part of the work since Dr. Vervier has recently done a much more sophisticated calculation for Co^{60} which he is going to discuss later (paper H-2).

* * *

O. A. WASSON, Brookhaven National Laboratory: Will you comment on your determination of the absolute intensities you quote?

SHERA: They are based on the known total thermal-capture cross section of cobalt and the known partial cross sections for individual nitrogen gamma rays. By counting the gamma rays from a mixed sample with a known quantity of each nuclide, one can then determine the intensities of the cobalt lines in gammas per neutron capture. I think that the errors we put on intensities are never less than $\sim 20\%$.

H. H. BOLOTIN, Argonne National Laboratory: Since very little charged-particle-gamma coincidence work has been done, although much more will probably be done, the (n, γ) process turns out to be quite useful in studying odd-odd nuclei—whose levels normally are not populated in beta decay. This coincidence work by Shera illustrates this. I think these $(n, \gamma\gamma)$ coincidence measurements will receive increasing recognition since they are one of the few techniques of studying some of these odd-odd nuclei. Of course, it would also be extremely valuable for more people to do such things as $(d, p\gamma)$ experiments, although these may be more difficult.

A-5. GAMMA SPECTRA FROM DECAY OF RESIDUAL STATES FOLLOWING PHOTODISINTEGRATION OF O^{16}

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The work reported in this paper concerns the 20—30-MeV photodisintegration of O^{16} . As such, its nuclear physics has very little bearing on the (n, γ) experiments which are the basis for this conference. However, the techniques involved raise some technical questions which I believe are worth discussing here; and the nature of our final conclusions is perhaps of general interest too.

Let me first describe the experiment (Fig. 17). This figure shows the O^{16} giant resonance cross section, having dominant peaks at 22 and 24 MeV and subsidiary peaks at several nearby energies. Efforts to account for the structure in terms of a single-particle single-hole model of an E1 resonance are successful insofar as they indicate that the dominant dipole strength occurs at about the right

Fig. 17. Giant resonance in O^{16} .

[†] Work supported by the U.S. Atomic Energy Commission. This paper was presented for the authors by O. A. Wasson of Brookhaven National Laboratory.

Fig. 18. Schematic diagram showing the excitation of the giant-resonance state in O^{16} and the subsequent decay of this state.

energy. However, the origin of the multiplicity of cross-section peaks is so far not established. Primarily, there is a clear need for experimental determination of the extent of 2-particle, 2-hole or $M1/E2$ contribution present, preferably with reference to individual resonance peaks.

The nature of the O^{16} resonance state excited may be examined by studying the branching of its neutron or proton decay to the ground state or first few excited states of the residual nucleus (O^{15} or N^{15}). The process is illustrated in Fig. 18. After the O^{16} giant-resonance state is excited, a neutron or proton will probably be emitted, leaving O^{15} or N^{15} , possibly in an excited state. The excited residual state will then de-excite with emission of a gamma ray.

The question of interest is whether the O^{16} giant resonance states decay appreciably to the $(\frac{5}{2}^+, \frac{1}{2}^+)$ states at 5 MeV. In the pure single-particle single-hole model, the residual state would need to have a $p_{3/2}$ or $p_{1/2}$ hole configuration, and only the ground residual state and the $\frac{3}{2}^-$ state at 6 MeV would be populated. Evidence of branching to the positive-parity states would imply a departure from the simple dipole resonance picture—which would call for further examination.

We have set out to look at these decay modes by studying the spectra of de-excitation γ rays at 5 and 6 MeV, using a 6-cc lithium-drifted germanium detector. Since the 6-MeV states are known

Fig. 19. Experimental layout.

to decay 100% to the ground state, the 5-MeV gamma rays which we record cannot be simply part of a cascade from the $\frac{3}{2}^-$ states, and we do not observe any γ rays which would accompany them in cascading from higher levels. Their presence therefore defines the population of the 5-MeV states unambiguously.

The experimental layout is shown in Fig. 19. A thin-target bremsstrahlung beam produced by the Yale Electron Linac was directed on to a 2-in. water target. The germanium detector, placed to receive gammas at 135° to the incident beam, was shielded with 8 in. of lead, and the whole experimental area was isolated from the electron beam dump by a 6-ft-thick concrete wall.

Some further precautions were necessary to eliminate serious electron-pulse pile-up in the detector during the 4- μ sec duration of each beam burst. They included the use of a 12-in. graphite and beryllium beam hardener at the front end of the bremsstrahlung collimator, and the use of a graded filter to harden the spectrum admitted to the detector through its collimating aperture. Of great importance also was the short (200 nsec) delay-line clipping applied to the detector pulses before presenting them to a biased amplifier which would remove the small unwanted pulses before analysis.

The resolution obtainable in the resulting gamma spectrum remained seriously impaired by the residual background and by the necessary fast-pulse clipping. In the 6-MeV gamma lines, however, a natural Doppler broadening of 50 keV occurs in any case. The resulting peak width of 70 keV is therefore not surprising. A typical spectrum is shown in Fig. 20, where we see the double-escape peaks

Fig. 20. Typical gamma spectrum from the $O^{16}(\gamma, p\gamma')$ reaction at $E_\gamma = 28.5$ MeV.

corresponding to the 6.33-MeV (N^{15}) line, the 6.16-MeV (O^{15}) line, and a broad hump in which four available positive-parity states clustered at 5.2 MeV are not resolved. This spectrum, which was taken with 28.5-MeV bremsstrahlung, clearly indicates a considerable branching to the 5-MeV states. This tells us that somewhere in the O^{16} giant resonance below 28.5 MeV, some 2-particle 2-hole or M1/E2 excitation is occurring.

Of great importance to our effort now is to localize the energy region in which this happens. More completely, we wish to find the energy dependence of the cross section leading to each group of residual states.

To do this, one must record spectra at several bremsstrahlung tip energies and unfold the "yield curves" produced for each gamma line. The sort of change which occurs as we step the energy up from 23 to 31 MeV is illustrated in Fig. 21. Here we observe for example, that the step from 23 to 25 MeV is largely responsible for exciting the 5-MeV group. And the 6.16-MeV state appears strongly only above 27 MeV.

We have, in fact, stepped bremsstrahlung energies in 0.5-MeV intervals. The "yield" per unit incident x-ray flux was estimated for each gamma line from the content of its double-escape peak. After extraction of the energy dependence of the counter

Fig. 21. Gamma spectra from the $O^{16}(\gamma, n p \gamma')$ reaction at $E_\gamma = 23.0, 25.0, 27.3$, and 31 MeV.

Fig. 22. Yield curves after extraction of the energy dependence of the counter efficiency. The width of the shaded area represents the limits within which statistics define the cross section.

efficiency, the three resulting yield curves were unfolded, giving the cross sections shown in Fig. 22. Here, the shaded area represents the limit within which statistics dictate the real cross section (its resolution smoothed to 2 MeV width) should lie. The swathes are broad, and the resolution poor. This is due to the necessarily low rate of accumulation of counts into the spectral peaks, resulting in undesirably poor statistics for each yield point.

The cross-section curves lead to some interesting conclusions. One notes the large contribution to the cross section of the 5-MeV state in the middle of the giant-resonance region, which certainly implies a significant deviation from the E1

single-particle process in O^{16} . The percentage distribution of non-ground-state cross section up to 28.5 MeV is $(60 \pm 5)\%$ for the 6.33-MeV state (N^{15}); $(16 \pm 5)\%$ for the 6.16-MeV state (O^{15}); and $(24 \pm 5)\%$ for the 5-MeV states. The 6.16-MeV line is unexpectedly weak, especially in the first few MeV above its production threshold of 21.8 MeV. The significant difference between the shape of its cross section and that of its counterpart 6.33-MeV line in N^{15} implies the existence of an appreciable difference between the characteristics of (γ, n) and (γ, p) processes in O^{16} .

I should like to conclude by referring again to a somewhat technical aspect of this work—the extraction of γ -line strengths from each composite spectrum. As can be seen from the foregoing material, the accurate assessment of "yields" of these lines is of great importance to this experiment. Yet it proved to be one of the more difficult things to achieve.

In obtaining the curves shown in Fig. 21, the peak content had to be assessed by subtracting a smooth "background" based on a polynomial fit of the flanking regions of the spectrum. This method had to be adopted at the time because we had no standard monochromatic line profiles for the germanium detector which could be used to make a 3-component least-squares fit to the composite spectrum.

In principle, the main loss thereby incurred was the loss of valuable counts properly belonging to each γ ray but thrown away as "background." This consideration alone was sufficient to prompt us to determine line profiles for our detector, using known (n, γ) lines from titanium, iron, and sulphur.

The processing of this information, leading to a full fitting procedure for these O^{16} data, is presently under way. An important preliminary correction has in fact already been made. The line profiles have shown the presence of a broad subsidiary hump in a spectral region just below the double-escape peak. For a 6.33-MeV line, this unhappily

coincides closely with our 6.16-MeV peak! It is clear that in our first analysis we inadvertently attributed this peak content to the 6.16-MeV gamma ray, and some 25% of the 6.33-MeV line strength was "fed through." This error has now been corrected. However, it does serve to illustrate one danger inherent in assessing line strengths from the double-escape peak content alone, especially in the case of poor peak resolution or naturally broad peaks.

Our studies of line profiles also emphasize the need for a clearer understanding of the nature of the very complex structure of the profiles of high-energy gamma lines in a small germanium detector.

* * *

H. T. MOTZ, Los Alamos Scientific Laboratory: Am I correct in believing that the resolution width obtainable at 5 or 6 MeV with the sodium iodide total-energy spectrometer at Yale is somewhere between 100 and 150 keV?

O. A. WASSON, Brookhaven National Laboratory (presenting the paper for the authors): I believe the resolution width was more like 200—250 keV. Preliminary experiments for that detector were made several years ago. At that time we simply observed the spectra. Individual lines were not resolved and no conclusions were drawn.

E. HADDAD, U.S. Atomic Energy Commission, Washington, D.C.: Does anyone know what resolution width is attainable with these machines? Is it 1% out of 20 MeV, or what?

WASSON: I should think they would get widths of about 100 keV, but I am just guessing. I cannot quote the exact figures.

C. F. CLEMENT, Florida State University: It would be interesting to compare those results with the calculations of Buck and Hill at Oxford.

These are still unpublished, but they have done some very detailed calculations on the giant resonance in O^{16} solely on the basis of particle-hole states. They achieve a spectrum with a large number of isolated resonances. It would be of interest to see if any deviations in their spectrum coincide with the ones you have just reported in the region in which more excited states might be expected.

WASSON: This is an interesting comment.

SESSION B

2 NOVEMBER 1966

INTERNAL-TARGET EXPERIMENTS

W. R. KANE, CHAIRMAN

✓ B-4. INSTALLATION AND USE OF AN INTERNAL-TARGET FACILITY

G. E. Thomas

Argonne National Laboratory, Argonne, Illinois

Soon after the discovery of the Li-drifted Ge gamma-ray detector, it became apparent that a precise capture-gamma-ray facility would be a natural application. We were fortunate that at this time they were phasing out the use of a Compton spectrometer at a tangential beam tube (through hole) at the Argonne CP-5 reactor. The tangential beam hole has inherent advantages over a radial one in that it gives virtually the same neutron flux at the sample position (near the reactor core) but a much lower background intensity in the emerging neutron and gamma beam than can be obtained with a radial beam. In addition, the through hole allows insertion of samples at one side of the reactor while the experimental apparatus is at the other end of the tube. The design and installation of an internal-target facility for use at this through hole of CP-5 was therefore undertaken immediately. Those taking part in the work at one time or another were L. M. Bollinger, H. E. Jackson, D. E. Blatchley, W. V. Prestwich, J. R. Specht, and myself.

Figure 23 shows the basic idea of an internal-target system. The target is placed in the high-flux region near the core of the reactor. An internal collimator, placed to take advantage of the

Fig. 23. Schematic horizontal cross section of the internal-target facility at the CP-5 reactor. It shows the through tube with the Ge(Li) detector at one end and mechanism for inserting or removing samples at the other.

Fig. 24. Schematic diagrams comparing the internal-target and external-target systems.

reactor shielding, is followed by an external collimator and a fast-neutron absorber; and behind the external shielding is placed the germanium detector.

In Fig. 24 we see something of the motivation behind an internal-target system. The expected counting rate for an internal-target system is

$$\text{Internal rate} = (\text{Capture rate}) T_{\gamma} \Omega_{\epsilon} = k \Phi W \sigma T_{\gamma} \Omega_{\epsilon},$$

where T_{γ} is the transmission of gamma rays through the fast-neutron absorber, Ω is the solid angle of the emerging gamma-ray beam, W is the weight of the sample, σ is the cross section of the sample nuclide in barns, ϵ is the efficiency of the detector, and Φ is the thermal-neutron flux. The corresponding expected counting rate for an external-target system is

$$\text{External rate} = (\text{Capture rate}) \Omega_{\gamma} \epsilon = k \Phi \Omega_n T_n \sigma W \Omega_{\gamma} \epsilon,$$

where Ω_n and Ω_{γ} are the respective solid angles for the emerging neutron beam and for the resulting gamma-ray beam, T_n is the transmission of fast neutrons through any possible neutron absorber one might use with this system, and the other symbols are as defined above. Then if the same small sample of weight W is used in both systems, the ratio of the internal rate to the external rate is

$$\frac{\text{Internal rate}}{\text{External rate}} = \frac{\Omega T_{\gamma}}{\Omega_n \Omega_{\gamma} T_n}.$$

From this we can readily see that the ratio is rather large because the rate for the internal system depends upon only one solid angle,

Fig. 25. Three-dimensional drawing of the experimental arrangement for the study of capture gamma rays at the CP-5 reactor. At the left is the mechanism for inserting or removing samples. On the right are the collimators and the gamma-ray detector.

whereas the rate for the external system depends on both the solid angle from the neutron source and that of the gamma rays from the target. The internal system offers the further advantage that the neutrons are completely contained within the reactor, while the scattering of the emerging beam in the external system requires a much more elaborate shield around the detector.

The Argonne internal-target facility is shown schematically in Fig. 25. To put a sample in place while the reactor is in operation, it is first inserted through a port in the 6-in.-thick lead biological shield and placed on one of the four positions of a storage wheel. The

three lead beam plugs are then removed from the through hole and placed on an elevator. The sample is then transferred from the storage wheel to a titanium tape—the titanium being used because of its relatively short half-life, hardness, and high melting point. This tape is about $\frac{7}{8}$ in. wide and 0.020 in. thick. The tape, which is driven along an aluminum track, then transports the sample to the center of the reactor. The sample position is reproducible within about 0.1 in. Notice that the through hole does not pass through the core but just grazes it. The time for a complete sample change is approximately 10 min. When samples are removed, their activities range from a few Roentgens to more than 2000 Roentgens. The very radioactive samples are then stored on the wheel inside the lead biological shield until their activity has dropped enough to permit removal.

At the center of the through hole, the thermal-neutron flux is about 3×10^{13} neutrons $\text{cm}^{-2} \text{sec}^{-1}$, the cadmium ratio is about 7, and the gamma-ray flux is about 3×10^8 Roentgens/hr. But of course the background contributions from these are only the small fractions scattered by the sample itself. The neutron flux drops by a factor of 2 for each foot from the center of the through hole. This offers a convenient method of adjusting the counting rate at the detector so that it does not exceed the capabilities of the electronic circuitry. The through tube is normally filled with helium at atmospheric pressure.

To re-emphasize what was said above, placing the sample in the center of the through hole exposes it to a neutron flux density comparable to that for a radial beam; but since the detector outside the reactor does not see either the walls of the beam tube or the reactor core, the emerging gamma-ray beam does not include the high fast-neutron and gamma-ray backgrounds which are unavoidable with a radial beam.

At the opposite side of the reactor is located the experimental facility. The internal collimator is 30 in. long and collimates

Fig. 26. The well-known iron doublet as it appears in a spectrum obtained with the 4096-channel analyzer. It is shown primarily as a measure of the resolution obtainable, but the prominence of these lines from an impurity in the system also illustrates the sensitivity of the facility.

the beam to an effective diameter of about $\frac{1}{2}$ in. The final collimator used in the external shielding is a piece of lead 8 in. long; the diameter of the hole can be varied from $\frac{1}{8}$ in. to about 1 in. Looking through this collimating system at a sample placed near the center of the reactor, the detector sees an area that can be varied from 0.8 in. to a little over 1 in. in diameter—depending on the size of the final collimator used. This reduced field of view offers the important advantage that the detector does not see the walls of the through-hole, which otherwise would contribute additional background lines to confuse the already complex spectra.

Also located in the external shielding is a fast-neutron absorber of polyethylene to protect the detector. Since we actually have excess flux, the thickness of this absorber can be varied to attenuate the gamma-ray beam so that the counting rate in the Ge detector is reduced to a suitable level.

One of the more interesting characteristics of this system is the sample size that one can use. Our present samples vary from a few milligrams to many grams. The actual size required for a given material can be determined from the fact that this system gives a counting rate of about 200 counts per second per millibarn-mole of sample material.

A segment of a spectrum obtained with our Ge detector system is shown in Fig. 26. The prominent peaks actually are

background lines—the well-known iron doublet. This figure is included to illustrate the resolution obtainable with this detector. With our 4-cc detector (with an active counting volume of 3.6 cc), the doublet is very nearly completely resolved. The resolution width of this detector is approximately 6.7 keV at 7 MeV.

The question of the optimum detector size cannot be decided without an elaborate Monte Carlo calculation. However, experience gives us a feeling for this. Since the dominant process in such a detector is double escape, the primary requirement is that the detector should be large enough to intercept the entire emerging beam. Perhaps a somewhat larger one of different shape would be desirable if one were doing pair-spectrometer measurements.

The electronic system used with this detector is a conventional one. It uses an uncooled FET preamplifier, a Tennelec-200 amplifier, and a Nuclear Data 4096-channel analyzer and stabilizer (which stabilizes on one of the peaks in the spectrum). By stabilizing on the peak from a precision pulser, we expect to improve the resolution of the system somewhat and to gain greater convenience in coincidence and anticoincidence measurements.

As an illustration of the data taken with this detector, Fig. 27 shows a segment of the spectrum from one run with the 4096-channel analyzer. This gives an idea of the statistical accuracy attained in a typical overnight run. The target was a 1-g sample of C^{13} . Notice that both the double-escape and single-escape lines from the 8174-keV ground-state transition stand out clearly. Some of the other lines are from a Cl impurity in the sample. Because of the high sensitivity of this system, this impurity (of the order of 2 parts per million) produced all of these Cl lines and made it difficult to see the spectrum from the sample under study. Further, notice that the background level is relatively low when this sample is used.

Fig. 27. Portion of a spectrum from a 1-g sample of C^{13} as obtained in an overnight run.

Figure 28 shows a typical set of background lines observed when using this system. With the beam hole closed, practically no background lines are seen. In other words, most of the background must be coming from the beam itself. Also, if one does not carefully flush out all of the nitrogen in the through hole and make certain it contains only helium, lines from the nitrogen impurity will be troublesome. In fact, although the through-tube was thoroughly flushed out before the spectrum in Fig. 28 was taken, one still sees a very small peak from the ground-state line of nitrogen. (Incidentally, if the tube is filled with nitrogen, one can easily use the nitrogen lines for energy calibration and for determining the detector efficiency.)

Our sample holders are usually made of graphite because of its very low cross section and because the comparatively small number of gamma-ray lines in its spectrum leads to a correspondingly small contribution to the general background. However, other sources of background introduce lines from chromium, nickel, and iron. We believe these come in either because the detector can see the beam plug at the far end of the through hole or because neutrons scattered out of the beam fall on materials that in turn produce these background lines. One also sees titanium background lines which we suspect may

Fig. 28. Spectrum from another run with the same 1-g sample of C^{13} as in Fig. 27. It shows lines from the sample, impurities in the sample, and background.

originate in the titanium tape and reach the detector after being elastically scattered in the sample. Compton scattering of the many characteristic gamma rays also adds to the general background continuum. Although we hope in the future to eliminate most of these background lines, this total background sets an upper limit on the sensitivity of the system. The present limiting sensitivity is believed to be of the order of 10^{-6} mole-barns at an energy greater than 7 MeV.

One of the problems attendant on the relatively high flux of the reactor is sample insertion. At the time of the conference, it is still necessary to change samples when the reactor is at zero power because otherwise the biological shielding simply is inadequate.

Subsequent improvements in the design may enable us to change samples even when the reactor is operating at full power.

Another problem encountered with this system is nuclear heating—both directly in the sample and indirectly from the walls of the through hole. Our first indication of excessive temperature was from experiences with melted samples. We then placed a thermocouple on a piece of aluminum and placed it in the sample position in the through hole. The ambient temperature at this position was found to be about 500°C . We expect that the through tube will have to be cooled in some way to hold the temperature in the neighborhood of 100°C .

The heating caused by neutrons and gamma rays reacting with the sample itself is unavoidable. However, most of the nuclear heating can be attributed to the design of the through tube. In addition to the fairly thick aluminum walls of the tube itself, there are several liners. Also the particular tube we are now using has very poor heat-transfer characteristics because of a dead air space about $\frac{3}{16}$ in. thick between the tube and the reactor liner. Under these circumstances, the observed temperature is about what would be expected.

Another problem from the high unmoderated neutron flux is the background discussed earlier. We believe that this difficulty can be corrected by improved collimation and shielding.

The data shown above were all taken with a single detector. However, the internal-target system is ideally suited for use with a pair spectrometer (although this instrument would be very difficult to use with an external-target system). Figure 29 is a schematic diagram of the circuitry used with a pair spectrometer. It is similar to the design described by Arnell *et al.*¹ At present we are using two 4×4-in.

¹S. E. Arnell, R. Hardell, A. Hasselgren, L. Jonssen, and O. Skeppstedt, in *Proceedings of a Panel on the Use of Lithium-Drifted Germanium Gamma-Ray Detectors for Research in Nuclear Physics*, Vienna, 6–10 June 1966 (International Atomic Energy Agency, Vienna, 1966), p. 185; V. J. Orphan and N. C. Rasmussen, *Nucl. Instr. Methods* 48, 282 (1967).

Fig. 29. Block diagram of the circuitry used in the pair-spectrometer mode.

NaI(Tl) detectors in coincidence with the Ge detector. This gives a relatively low efficiency for detection of the 511-keV gamma ray; but we expect to improve this by surrounding the Ge detector with a split annulus and by using a cooled FET preamplifier. The counting rate expected from the pair spectrometer would then be about 30% of that obtained with a singles system. One advantage of this system is that it gives a simpler spectrum; it eliminates all of the single-escape and full-energy peaks that often mask out small peaks in a singles spectrum. Furthermore, the coincidence system can eliminate the background caused by Compton scattering and in general obtain a much cleaner spectrum. Another advantage is that it simplifies the problem of accurately determining the area of a given line.

Several problems are associated with the pair spectrometer. Its lower sensitivity makes it somewhat more difficult to obtain good statistics. Also, it is more unstable because (with the present system) it is difficult to stabilize on one of the lines in the spectrum. However, the use of a precision pulser is expected to alleviate this problem.

Probably the most important advantage of the Argonne facility is its versatility. The most significant class of experiments it makes possible is studies using resonance neutrons, as will be described by L. M. Bollinger in paper I-11.

The internal-target facility at Los Alamos will be described in detail by E. Journey in the next paper. However, it may be interesting to mention a few of the strong features and weaknesses of each. (1) The thermal-neutron flux in the Argonne system is about 100 times that at Los Alamos. This allows us to use very small samples of separated isotopes and to obtain data having very good statistical accuracy in a relatively short time. (2) On the other hand, the lower flux at Los Alamos allows greater ease and flexibility in inserting and removing samples. (3) The samples removed from the Los Alamos reactor may have a low level of radioactivity so that they are relatively easy to handle. (4) The detector in the Argonne system must have more shielding because of the higher room background.

Probably the optimum system would have a flux in between those of the Los Alamos and Argonne facilities; the Los Alamos system could use a little more flux and we have more than we need. A very good experiment can be performed in either type of system if one takes what he has and designs his experiment around it. At any rate, the discovery of the small Ge(Li) detector with its superior resolution has certainly made possible many interesting and exciting experiments with an internal-target system at a reactor.

* * *

O. W. B. SCHULT, Technical University, Munich and Brookhaven National Laboratory: The pair-production cross section is the predominant cross section and is larger than the Compton cross section, etc. at the higher energies. In your spectra, however, the integrated area

under the single- and double-escape peaks is only a small fraction of the integrated background. What is the reason for this?

R. K. SMITHER, Argonne National Laboratory: Two comments.
(1) The Compton cross section is not small. It often is larger than that for pair formation at 5 MeV, and I believe this is true in germanium.
(2) As the Ge diode gets larger, some appreciable fraction of the escaping annihilation radiation interacts with the diode. It is true that the full-energy and single-escape peaks are smaller than the double-escape peak; but these ratios are a function of the size and shape of the detector and will change appreciably as the detectors are made larger. Most of the energy loss of the escaping annihilation radiation is by Compton scattering and thus only a part of its energy is left in the detector. These events, therefore, do not contribute appreciably to any of the sharp peaks (the full-energy or single-escape peaks) in the spectrum; they simply appear as more counts in the background. In fact, going from a 1-cc crystal to one with a volume of 4 cc does not quadruple the strength of the double-escape peak. With the 4-cc detector, some 40% of these events are lost from the double-escape peak and contributed to the background; and the effect is even worse with a 10-cc detector. As germanium diodes get bigger and bigger, they reach a point at which the double-escape peak decreases faster than the volume increases. The numerous Compton events, the escaping electrons, and the interaction of the annihilation radiation all contribute to the background.

SCHULT: If I understand this correctly, it means that it does not pay to use a really large Ge diode.

SMITHER: It pays at the low-energy end of the spectrum where you are looking at the full-energy peak, because here the peak counting rate increases even faster than the volume. For the detection of (n, γ) transitions above a certain energy, however, it would be better to go to a multiple array—e.g., two, three, or four 10-cc detectors rather than one 150-cc detector.

SCHULT: This leads to another conclusion with respect to what Shera said earlier in this meeting. To compensate for the efficiency loss in doing coincidence experiments, one needs a larger detector for the high-energy gamma-ray transitions. From your explanation, it appears that one should use several smaller detectors instead of a single larger one for the detection of high-energy (n, γ) lines.

W. R. KANE, Brookhaven National Laboratory: For a larger detector, the full-energy peak is increased by a large factor. Thus if you have a large detector, coincidence experiments are most advantageously done in the energy region in which you have the full-energy peaks of the high-energy gamma rays. Conversely, in the energy region of the double-escape peaks of the same gammas, the full-energy peaks of the gamma rays 1 MeV lower in energy are superimposed on these double-escape peaks.

M. G. STRAUSS, Argonne National Laboratory: There is another way of increasing the double-escape peaks and decreasing the background. We have studied the problem of electron escape and will report on it in a later session (Paper C-4). In some cases we have found that in both the singles and the pair spectra we can reduce the background by up to 50% by rejecting events characterized by electron escape.

S. B. BURSON, Argonne National Laboratory: Attenuating a gamma-ray beam by an absorption method has the undesirable effect that small-angle scattering in the absorber broadens the peak on the low-energy side. With the poorer resolution of sodium iodide, the gamma-ray beam intensity at a few hundred keV can be reduced perhaps an order of magnitude in spite of this; but with germanium, any substantial attenuation by this method might be expected to impair the resolution perceptibly. Of course, the high collimation of the beam in your system would minimize the effect of small-angle scattering. When you use a lot of absorber, have you observed a broadening on the low-energy side?

THOMAS: To my knowledge, we have not observed it.

2. THE LOS ALAMOS THERMAL NEUTRON-CAPTURE FACILITY*

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The internal-target capture-gamma-ray facility at Los Alamos has been in operation since early in 1962. Originally the system was used with a NaI detector. In July 1964 a cryostat was installed, and since that time all work has been done with Ge(Li) detectors.

The target-irradiation position of the Los Alamos facility is located inside the graphite thermal column of the Omega West reactor. The reactor has a water-cooled, water-moderated, solid-fuel-element core. At the present operating power level of 6.5 MW, the thermal neutron flux at the target position is $\sim 2 \times 10^{11}$ n/sec-cm² with a Cd ratio of $\sim 5 \times 10^3$. As shown in Fig. 30, the thermal column is shielded from core gamma rays by a 7.6-cm thickness of Pb and a 12.7-cm

Fig. 30. Experimental arrangement of the Los Alamos thermal-neutron capture-gamma-ray facility.

*Work supported by the U.S. Atomic Energy Commission.

thickness of Bi. With this amount of shielding, the predominant gamma-ray intensity in the part of the thermal column at the target position results from neutron capture in carbon.

Targets are placed inside a bismuth channel which traverses the thermal column of the reactor. The channel is 9 cm square and has a 3.8-cm-diameter bore along its axis. One end of the channel is embedded in the reactor shielding; the gamma-ray beam from the target is extracted from the other end through collimators. The materials at the closed end of the channel have been selected to minimize neutron capture; a boron-aluminum lining of the entire thermal column greatly reduces the number of neutrons undergoing capture in the reactor shielding.

The gamma-ray beam is extracted through a removable Pb collimator having a 1-cm final diameter. Thermal neutrons are excluded from the gamma-ray beam by a 2.5-mm-thick Li^6F ceramic disk. A 0.13-mm Be window over the end of the collimator together with an O-ring seal permits evacuation of the channel. This is an important feature of the system: it permits removal of the background spectrum resulting from neutron capture by nitrogen, and it permits the introduction of gas targets into the channel.

After an additional collimation, again through a 1-cm-diameter aperture, the gamma-ray beam reaches a lithium-drifted germanium detector operated inside a large NaI anticoincidence shield. At high energies ($E > 2$ MeV) the shield is used as a double-escape detector by requiring a pulse from it equivalent to 1022 ± 100 keV. At present a rather small Ge(Li) planar detector, 3 mm depletion depth by 2.8 cm^2 , is in operation. An important lack of sensitivity results from these small detector dimensions, especially in the energy region between 1 and 2.5 MeV and above ~ 7 MeV.

Target materials are usually contained in small cylindrical machined graphite holders. These containers are provided with a lip

Fig. 31. Background spectrum between 1690 and 6175 keV, taken with the reactor operating but with no target in position. Running time = 1000 min.

which allows them to be inserted or retrieved easily with a simple spring-loaded handling tool. Target changing is facilitated by a boron-aluminum curtain which can be lowered across the thermal column at a position where the Cd ratio is about 500. Targets are changed in about 1–2 min; sample sizes are small enough that radiation exposure to personnel is negligible.

No electronic stabilization is currently being used, although the complete amplifier system is temperature controlled. The resolution width is typically 6–8 keV at 5 MeV and 3 keV at 500 keV.

Figure 31 is the background spectrum between 1690 and 6175 keV taken with the Bi channel evacuated and containing no target (reactor on). Note the weak line at 2 MeV from $\text{Li}^7(n, \gamma)$ originating from the LiF disk outside the far end of the channel.

Because the annulus gate can accept Compton-scattered gamma rays corresponding to varying amounts of electron energy deposited in the diode, each high-energy peak has under it a smooth, rounded background component. This is shown clearly in Fig. 32, the 2223-keV line from $\text{H}^1(n, \gamma)$. Here the effect is pronounced because the Compton cross section is competing strongly with the pair-production cross section.

Fig. 32. The 2223-keV transition from $H^1(n, \gamma)H^2$, showing the increased background caused by Compton-scattered gamma rays falling within the coincidence gating limits.

Fig. 33. The high-energy capture-gamma-ray spectrum from a natural argon target at 580 mm pressure.

Figure 33 shows the capture-gamma-ray spectrum from natural argon, obtained by filling the channel to 580 mm pressure. The amount of target was equivalent to ~ 1.2 mb-mol placed at the normal target position.

The doublet from $Nb^{93}(n, \gamma)$ shown in Fig. 34 has an energy separation of 2.8 keV at 254 keV. It was obtained with a 2-g target and represents combined about 85 mb of capture.

Fig. 34. Doublet from $\text{Nb}^{93}(n, \gamma)\text{Nb}^{94}$ having an energy separation of 2.8 keV at 254 keV. It was obtained with a 2-g target in 1180 min.

* * *

MOTZ: I would like to make a comment relative to two earlier papers, both A-1 on the Los Alamos facility and B-1 on the Argonne facility. When the reactor at Los Alamos was started up in 1956, we compared two through-ports. One through-port was an aluminum tube that grazed the core very much like the CP-5 port described earlier. The other was a channel through the graphite thermal column. To make this comparison, we put a boron target on a thick graphite stringer. A sodium iodide detector was lined up with the beam from which neutrons had been absorbed. We could see the $\text{B}^{10}(n, \alpha)$ line at 480 keV and the carbon cutoff at 5 MeV. As expected, the flux in the through port next to the core was ten times as great as in the through port that Shera described (paper A-1). But the signal-to-noise ratio in the graphite thermal column was ten times that in the high-flux aluminum one. The

higher background in the aluminum port was ascribed in part to the many kilocuries of aluminum radioactivity surrounding the target. The background was still high even when the carbon and boron targets were placed beyond the reactor core so that core gamma rays scattered in the target and graphite had to be backscattered to get back in the beam. Of course, the aluminum radioactivity always surrounds the radiator or the target. The scattering can be at 90° or even perhaps at 45° because this radioactivity goes beyond the target. This is a comparison I want to point out.

I would like to mention also that this setup that Journey just described was reported at the Argonne meeting held here three years ago this week (International Conference on Nuclear Physics with Reactor Neutrons, Argonne, 15—17 October 1963, Argonne National Laboratory Report ANL-6797, p. 236). This report describes the use of sodium iodide to observe capture in D_2O and even in C^{13} in natural carbon (which has a very small cross section). In other words, one gets a good signal-to-noise ratio for cross sections of 0.1 mb or less.

JURNEY: I would like to add a comment. In the earlier work with sodium iodide, we were attempting to find transitions following capture in O^{16} —which has an extremely low cross section. When we admitted oxygen gas into the channel, the background rose very dramatically. We ascribed this to scattered gamma rays not originating in the target or to the degradation of gamma rays emitted by the target.

~~B-9.~~ LOW-LYING EXCITED STATES IN Ag^{108} AND Ag^{110} POPULATED BY PRIMARY THERMAL-CAPTURE GAMMA RAYS

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As we shall hear later in this conference, striking systematic regularities have been observed in the neutron-capture gamma-ray spectra of some of the rare-earth rotational nuclei. The present study was undertaken to investigate any possible similar systematic regularities which might be present in the region of spherical nuclei.

The silver isotopes were selected for study for several reasons. Silver has only two stable isotopes, and both are available in approximately 100% enrichments. Therefore, no ambiguities should exist in the isotopic identification of the observed transitions.

The two silver isotopes are very similar. Both target nuclides have ground-state spins and parities of $\frac{1}{2}^-$ and hence the s-wave capture states can have spins 0^- and 1^- only. Primary dipole capture gamma rays therefore populate excited states having spins of 0, 1, or 2 in both product nuclides.

Fig. 35. Typical singles γ -ray spectrum observed for the reaction $\text{Ag}^{107}(n, \gamma)\text{Ag}^{108}$. The abscissa denotes the γ -ray energy to be associated with the double-escape peaks in the spectrum.

Figure 35 shows a singles spectrum taken with the target Ag^{107} . The abscissa is labeled in gamma-ray energy corresponding to the double-escape peaks appearing in the spectrum. These data were accumulated in a period of

approximately 20 hours. Figure 36 is a similar singles spectrum obtained with a target of enriched Ag^{109} . In some regions of these spectra the complex proximity of

Fig. 36. Typical singles γ -ray spectrum observed for the reaction $\text{Ag}^{109}(n, \gamma)\text{Ag}^{110}$. The abscissa denotes the γ -ray energy to be associated with the double-escape peaks in the spectrum.

the various types of lines associated with the different gamma rays required some clarification. This was provided by operating in a pair-spectrometer mode. Two 4X4-in. sodium iodide detectors, mounted at 180° to one another and straddling the germanium detector, were used in this mode of operation. As a result of the small solid angle accepted by this particular pair spectrometer, the counting rate in the double-escape peaks was reduced to about a twentieth of that in the singles mode of operation. Hence the statistics were relatively poor, so the pair mode was used primarily for clarification purposes only. The analysis was performed on the singles spectrum.

Figure 37 shows the spectrum for the reaction $\text{Ag}^{109}(n, \gamma)\text{Ag}^{110}$ obtained with the pair-spectrometer mode of operation. In the region around 6800 keV, which was quite complex in the singles spectrum, one observes that the pair spectrum shows this region to be quite simple—only one transition is present.

Fig. 37. Pair-spectrometer γ -ray spectrum observed for the reaction $\text{Ag}^{109}(n, \gamma)\text{Ag}^{110}$. Only double-escape peaks are present in this spectrum.

for the reaction $\text{Ag}^{109}(n, \gamma)\text{Ag}^{110}$. In this, 46 transitions were observed to populate states up to an excitation energy of approximately 1300 keV. Again, the gamma-ray intensities have been normalized to the strength of the strongest transition observed, that of the 5703-keV transition. The intensities of the transitions listed in Tables II and III were corrected for the efficiency of the detector system.

There do not appear to be any systematic regularities in the decay of the capture states of these nuclides. Both Ag ground states have spins of 1^+ . In the case of Ag^{108} , the ground-state transition is one of the strongest in the entire spectrum. In Ag^{110} , the ground-state transition is among the weakest observed. In addition, strong transitions appear to populate several of the lower excited states in Ag^{108} , while the strong lines in Ag^{110} do not appear until an excitation energy of 700 keV is reached. There seem to be no particularly striking characteristics which might indicate some strange or peculiar decay of the capture state. In fact, there does not seem to be much similarity in the decay of the capture states of these two Ag isotopes.

The results for the case of Ag^{108} are summarized in Table II. From the 33 transitions observed, low-lying excited states up to an energy of approximately 1300 keV were established. The gamma-ray intensities listed are relative and have been normalized to the strength of the strongest transition observed, that of the 7076-keV transition.

Table III is a summary of the results obtained

TABLE II. Summary of the γ -ray energies and intensities and the excitation energies of states populated in the thermal-neutron reaction $\text{Ag}^{107}(\text{n},\gamma)\text{Ag}^{108}$.

Excitation energy (keV)	γ -ray energy (keV)	Relative intensity ^a	Excitation energy (keV)	γ -ray energy (keV)	Relative intensity ^a
0	7267 $\pm$ 1	98 $\pm$ 15	706	6561 $\pm$ 1	10.0 $\pm$ 1.5
79	7188 $\pm$ 2	1.6 $\pm$ 0.9	879	6388 $\pm$ 2	5.5 $\pm$ 1.0
191	7076 $\pm$ 1	100	897	6370 $\pm$ 3	1.8 $\pm$ 0.4
205	7062 $\pm$ 1	38 $\pm$ 6	975	6292 $\pm$ 3	2.6 $\pm$ 0.5
285	6982 $\pm$ 2	3.0 $\pm$ 0.6	1002	6265 $\pm$ 1	27 $\pm$ 4
293	6974 $\pm$ 1	46 $\pm$ 7	1012	6255 $\pm$ 1	13 $\pm$ 2
333	6934 $\pm$ 2	1.2 $\pm$ 0.2	1047	6220 $\pm$ 1	21 $\pm$ 4
338	6929 $\pm$ 1	2.3 $\pm$ 0.4	1105	6162 $\pm$ 1	19 $\pm$ 3
451	6816 $\pm$ 1	2.9 $\pm$ 0.5	1111	6156 $\pm$ 1	57 $\pm$ 9
460	6807 $\pm$ 2	3.2 $\pm$ 1.0	1136	6131 $\pm$ 2	3.3 $\pm$ 0.7
465	6802 $\pm$ 2	3.7 $\pm$ 0.9	1157	6110 $\pm$ 2	3.0 $\pm$ 0.6
508	6759 $\pm$ 1	4.4 $\pm$ 0.7	1200	6067 $\pm$ 2	2.2 $\pm$ 0.4
547	6720 $\pm$ 3	1.1 $\pm$ 0.4	1214	6053 $\pm$ 1	15 $\pm$ 3
563	6704 $\pm$ 1	32 $\pm$ 5	1231	6036 $\pm$ 2	9.3 $\pm$ 1.6
578	6689 $\pm$ 2	2.9 $\pm$ 0.6	1242	6025 $\pm$ 2	18 $\pm$ 3
606	6661 $\pm$ 2	2.5 $\pm$ 0.6	1271	5996 $\pm$ 2	5.8 $\pm$ 1.0
699	6568 $\pm$ 3	1.8 $\pm$ 0.8			

^aThe errors assigned to the relative intensities listed here also reflect an $\sim 15\%$ uncertainty quoted for the intensities of the transitions in nitrogen (Ref. 14) which were used in the empirical determination of the relative double-escape-peak efficiencies of the Ge(Li) detector. The strengths of all lines listed have been corrected for detector efficiency and have been normalized to that of the strongest transition (7076 keV) observed in the spectrum.

One possible type of correlation that might be of some interest is examined in Fig. 38, which shows the level diagrams of the low-lying states of Ag^{108} and Ag^{110} . The levels on the left in each case were taken solely from the present study. The low-lying excited states reported from previous (d,p) investigations are shown on the right. The widths of the levels on the right, indicated by the diagonal shading, are a measure of the accuracy with which these energies were determined in these charged-particle experiments.

The shell-model configurations expected for these odd-odd Ag isotopes indicate that the (d,p) stripping reaction should populate

TABLE III. Summary of the γ -ray energies and intensities and the excitation energies of states populated in the thermal-neutron reaction $\text{Ag}^{109}(n, \gamma)\text{Ag}^{110}$.

Excita- tion energy (keV)	γ -ray energy (keV)	Relative intensity ^a	Excita- tion energy (keV)	γ -ray energy (keV)	Relative intensity ^a
0	6810 $\pm$ 1	2.6 $\pm$ 0.4	775	6035 $\pm$ 1	11 $\pm$ 2
197	6613 $\pm$ 1	3.3 $\pm$ 0.6	786	6024 $\pm$ 1	36 $\pm$ 6
238	6572 $\pm$ 1	6.3 $\pm$ 0.9	813	5997 $\pm$ 1	20 $\pm$ 4
248	6562 $\pm$ 2	1.1 $\pm$ 0.5	825	5985 $\pm$ 1	12 $\pm$ 2
270	6540 $\pm$ 1	42 $\pm$ 7	857	5953 $\pm$ 1	4.7 $\pm$ 0.8
360	6450 $\pm$ 1	9.8 $\pm$ 1.4	897	5913 $\pm$ 2	4.2 $\pm$ 1.3
381	6429 $\pm$ 1	6.3 $\pm$ 1.1	906	5904 $\pm$ 1	11 $\pm$ 2
416	6394 $\pm$ 2	0.9 $\pm$ 0.3	992	5818 $\pm$ 2	4.6 $\pm$ 1.0
426	6384 $\pm$ 1	5.7 $\pm$ 0.9	1000	5810 $\pm$ 1	41 $\pm$ 6
432	6378 $\pm$ 2	0.8 $\pm$ 0.4	1017	5793 $\pm$ 1	79 $\pm$ 12
498	6312 $\pm$ 2	3.4 $\pm$ 0.7	1037	5773 $\pm$ 1	28 $\pm$ 4
525	6285 $\pm$ 1	7.9 $\pm$ 1.3	1065	5745 $\pm$ 1	17 $\pm$ 3
539	6271 $\pm$ 1	12 $\pm$ 2	1089	5721 $\pm$ 2	2.1 $\pm$ 0.4
548	6262 $\pm$ 1	3.7 $\pm$ 0.7	1098	5712 $\pm$ 1	31 $\pm$ 5
587	6223 $\pm$ 1	4.0 $\pm$ 0.6	1107	5703 $\pm$ 1	100
615	6195 $\pm$ 1	6.5 $\pm$ 1.0	1166	5644 $\pm$ 1	23 $\pm$ 4
633	6177 $\pm$ 1	2.8 $\pm$ 0.6	1176	5634 $\pm$ 1	13 $\pm$ 2
654	6156 $\pm$ 3	0.7 $\pm$ 0.3	1185	5625 $\pm$ 2	4.1 $\pm$ 0.8
698	6112 $\pm$ 1	7.7 $\pm$ 1.4	1194	5616 $\pm$ 1	27 $\pm$ 4
706	6104 $\pm$ 1	12 $\pm$ 1	1229	5581 $\pm$ 1	42 $\pm$ 7
727	6083 $\pm$ 1	7.4 $\pm$ 1.2	1255	5555 $\pm$ 1	17 $\pm$ 3
751	6059 $\pm$ 1	87 $\pm$ 13	1263	5547 $\pm$ 1	10 $\pm$ 2
760	6050 $\pm$ 2	2.0 $\pm$ 0.4	1270	5540 $\pm$ 1	17 $\pm$ 3

^aThe listed errors were assigned as described in footnote a of Table II, except that the strengths of the lines were normalized to the 5703-keV transition—the strongest one in this spectrum.

only the negative-parity low-lying states. The positive-parity states are expected to arise from excited proton configurations which are populated extremely weakly if at all in (d, p) reactions. Unfortunately, the accuracy of the existing (d, p) data¹ is inadequate for establishing

¹A. Sperduto, M.I.T. Lincoln Laboratory Nuclear Science Progress Report, 1959, p. 105 (unpublished); M. Mazari, M.I.T. Lincoln Laboratory Nuclear Science Progress Report, 1957, p. 44 (unpublished).

Fig. 38. Level schemes of Ag^{108} (left) and Ag^{110} (right). For each isotope, the results of the present investigation are shown to the left and the previously reported (d, p), (n, γ), and isomeric-decay studies are shown to the right. The diagonally shaded areas represent the uncertainties in the positions of the states observed in the (d, p) reaction.

a one-to-one correspondence between the levels populated in this reaction and those seen in the capture-gamma-ray experiments. Moreover, these (d, p) studies did not include proton angular distributions which might have firmly established the parity of these states. However, some gross comparisons can be made. If only the expected negative-parity states are seen in the (d, p) studies, primary transitions terminating at these levels would be M1 radiation and would be expected to be much weaker than known E1 transitions. In this context, it is interesting to note that with two exceptions (the 302- and 572-keV states), all (d, p) excited states in both Ag^{108} and Ag^{110} are seen only in the proximity of states that are relatively weakly populated by primary gamma rays. This seeming anticorrelation may be evidence that these (d, p) levels are of negative parity and that consequently the primary

transitions to these states are of M1 character. The unfortunate lack of a one-to-one identification between the states seen in the two reactions does not permit a more explicit statement of this anticorrelation. Improved (d,p) studies with higher resolution would be of considerable interest in checking these negative-parity assignments. Of course, complete angular-distribution measurements of the outgoing proton groups might conclusively establish the parities of these levels. This information, when coupled with the present experimental (n, γ) results, would allow an interesting comparison between E1 and M1 transition probabilities.

* * *

O. W. B. SCHULT, Technical University, Munich, and Brookhaven National Laboratory: Will you explain how you did the calibration and which lines you used?

BOLOTIN: This will be discussed in detail in a later section (paper D-3), but I will not put you off completely. We used the ground-state transition in carbon, the argon line that we always see, and a pulser. Pulses from the latter are inserted at small intervals in the spectrum. We think we get reasonable accuracy.

R. T. CARPENTER, University of Iowa, Iowa City: I assume that many of these levels had not been observed before. Did you assign them exclusively on the basis of high-energy transitions?

BOLOTIN: The tacit assumption in assigning levels was that in populating states within 1—2 MeV of the ground state, the E^3 energy dependence for the high-energy gamma rays is very much more significant than the density of states.

H. T. MOTZ, Los Alamos Scientific Laboratory: I think the only known exceptions to this are in the very light nuclei, in which there is a very low density of levels—e. g., in $C^{12}(n,\gamma)$ and $Be(n,\gamma)$. I don't

think there is any doubt that these high-energy transitions come from the capture state. If they do not—if levels within 1 MeV of the capture state are being populated with any reasonable intensity—you would have a tremendous number of these gamma rays. They are in the background somewhere, but their intensities are down by many orders of magnitude.

R. K. SMITHER, Argonne National Laboratory: The low probability of a high-energy gamma ray coming from a secondary transition does not arise mainly from the unlikelihood of a 1-MeV transition from the primary capture state. The argument is that there are very many ways of depopulating this state 1 MeV down from the capture state. Hence the strength of the 1-MeV transition must be split up among all these alternative branches to the lower levels, and there is very little chance that any one of these will have an intensity comparable to that of the primary 1-MeV transition. In other words, it is not only unlikely that a 1-MeV primary transition will be strong; it is also very unlikely that there would be only one or two strong transitions depopulating the state it feeds.

G. T. EMERY, Indiana University: I think that it is good to be reminded of this point from time to time—though we don't often worry about it.

I wanted to mention that there is a mystery in the decay scheme of the Ag^{110} isomer in that the spins are established as 6 and 1, and yet the isomer decays by an M4 transition. The missing 2^- state in Ag^{110} has never yet been found, so far as I know. Unfortunately you do not find it either.

BOLOTIN: No. The transition to this state would have to be M1. We may have been lucky to see the M1 transition to the 2^- state in Ag^{108} .

EMERY: If you assume that the intensity ratio between the E1 transition to the ground state and the M1 to the 2^- state is the same in Ag^{110} as in Ag^{108} , then you would never see it in Ag^{110} .

BOLOTIN: On the other hand, because of the Porter-Thomas distribution these intensities could be reversed; it could be stronger in Ag^{110} than in Ag^{108} . But we do not see it.

E. D. EARLE, Chalk River Nuclear Laboratories: One way of telling if a high-energy transition is primary is by coincidence experiments. If it feeds an excited state that branches to two lower states, there is no question.

~~B-4.~~ STUDY OF THE $\text{F}^{19}(\text{n}, \gamma)\text{F}^{20}$ REACTION

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The present results were obtained from an investigation of the de-excitation gamma rays following thermal-neutron capture in F^{19} . The target in this case was beryllium fluoride encapsulated in an aluminum can with beryllium end windows. It was irradiated in the through-hole facility at the CP-5 reactor. The levels in F^{20} have been investigated by numerous authors using the (d,p) and the (n, γ) reactions.¹⁻³

Figure 39 illustrates what is known about the low-lying levels of F^{20} , mainly from (d,p) work and also beta decay. Because of its observed⁴ beta decay to the first excited state in Ne^{20} , the ground state of F^{20} is believed to be 2^+ . The level at 1057 keV is believed to be 1^+ because of the observation that O^{20} beta decays to it.⁵ The numbers on the left correspond to the ℓ values of the transferred neutron as measured in the (d,p) reaction and on the right are spins and parities which have been assigned on the basis of these ℓ values. In many cases the measured cross section for the stripping reaction to these levels is very much smaller than the cross section to levels for which it can be stated with confidence that the reaction is going via the stripping

¹ V. M. Rout, W. M. Jones, and D. G. Waters, Nucl. Phys. 45, 369 (1963).

² M. E. O. DeLópez, J. Rickards, and M. Mazari, Nucl. Phys. 51, 321 (1964).

³ E. G. Nadjakov, Nucl. Phys. 48, 492 (1963).

⁴ V. M. Lobashev and V. A. Nazarenko, Soviet Phys. —JETP 42, 370 (1962).

⁵ G. Scharff-Goldhaber, A. Goodman, and M. G. Silbert, Phys. Rev. Letters 4, 25 (1960).

Fig. 39. Low-lying levels of F^{20} .

mechanism. Therefore, one may not be justified in assuming a stripping mechanism in order to assign these ℓ values. As you can see, there is some ambiguity in the ℓ values that have been assigned. Since the spin of F^{19} is $\frac{1}{2}^+$, the thermal-neutron-capture state has the possibilities of 0^+ and 1^+ .

We would like to present some results from the $\text{F}^{19}(\text{n}, \gamma)\text{F}^{20}$ reaction and then draw tentative conclusions about the spins of the low-lying states in F^{20} .

Previous (n, γ) work has shown a very strong transition from the capture state to the ground state. If the ground state of F^{20} is 2^+ , then it would be logical to assume that the capture state is predominantly 1^+ and that the strong gamma ray which has been previously observed is an M1 transition from the capture state to the ground state.

Figure 40 shows the high-energy end of the F^{20} gamma-ray spectrum. The ground-state transition is at 6601 keV. Another dominant feature of the high-energy end of the spectrum is a gamma ray of energy 6018 keV which is not a transition from the capture state to a low-lying state, but is rather a transition from the capture state to a level at 6018 keV which then decays. In addition to the decay from the capture state to the ground state, weak primary transitions have also been observed to the first, third, fourth, and fifth excited states of F^{20} , but not to the second excited state.

Figure 41 shows the intermediate region of the gamma-ray spectrum and displays cascades of intermediate energy between the capture state and ground state, and also between the 6018-keV level and the ground state. Also seen are gamma rays from Be^{10} , which are used as calibration lines. Figure 42 shows the low-energy

Fig. 40. High-energy end of the $F^{19}(n, \gamma)F^{20}$ spectrum.

Fig. 41. Intermediate-energy region of the $F^{19}(n, \gamma)F^{20}$ spectrum.

end of the spectrum, which is dominated of course by the gamma ray in Ne^{20} following the beta decay of F^{20} . The low-energy line at 584 keV is the primary transition to the 6018-keV level. Also we see the 1294-keV line in K^{41} following the beta decay of A^{41} . This is a

Fig. 42. Low-energy end of the $F^{19}(n, \gamma)F^{20}$ spectrum.

TABLE IV. Energies of primary capture gamma rays observed in the $F^{19}(n, \gamma)F^{20}$ reaction.

Gamma-ray energy (keV)	Initial state (keV)	Terminal state (keV)	Relative intensity
6601	6601	0	25
5936	6601	665	2.7
5618	6601	984	4.1
5545	6601	1057	11
5291	6601	1310	6.8
4757	6601	1844	4.2
4557	6601	2045	11
3113	6601	3488	4.4
3015	6601	3588	8.1
584	6601	6018	>60

contaminant line which is always present in our spectra and is used for calibration purposes.

Table IV is a list of primary capture-gamma-ray energies that have been observed, along with their relative intensities which are

TABLE V. Gamma rays from the de-excitation of the 6018-keV level in the $F^{19}(n, \gamma)F^{20}$ reaction.

Gamma-ray energy (keV)	Initial state (keV)	Terminal state (keV)	Relative intensity
6018	6018	0	24
5034	6018	984	14
4961	6018	1057	0.7
4708	6018	1310	0.9
4174	6018	1844	3.6
2530	6018	3488	11
2430	6018	3588	6.3

not normalized. As can be seen, the capture state decays to the ground state and to the first, third, and fourth excited states, but not to the second excited state. There is also a very strong transition from the capture state to the 6018-keV level. Closing the loops on these cascades yields a neutron binding energy, including a recoil correction, of 6602 ± 2 keV for F^{20} .

Table V is a list of gamma rays arising from the de-excitation of the 6018-keV level. It can be seen that the 6018-keV state decays to the ground state and to the third and fourth excited states, but not to the first or second excited states in F^{20} .

In order to draw tentative conclusions on the basis of these results, we shall assume that the ground-state spin of F^{20} is 2^+ , the capture state is predominantly 1^+ , and the primary transition from the capture state to the 6018-keV level is a strong E1 transition to a state of negative parity. We also take into account the fact that the capture state decays to each of the first four excited states with the exception of the second excited state, while the 6018-keV level decays to the third and fourth excited states but not to the first or second. Kurath has calculated the properties of the F^{20} ground state on the

E	J^π	basis of the K=1 and K=2 bands in the Nilsson
1057	(1 ⁺)	model with strong band mixing. Among the
984	(2 ⁺)	low-lying levels in this model would be a
828	(4 ⁺)	pair of spin-2 levels plus one each of spin 1,
665	(3 ⁺)	spin 3, and spin 4. The ordering of these
		levels is quite dependent on the parameters
		used in the calculation.

0 ————— 2⁺
 ${}^9\text{F}_{11}^{20}$

Fig. 43. Low-lying levels of F^{20} with tentative spin assignments.

Figure 43 shows tentative spin assignments for the low-lying levels of F^{20} , based on the assumptions that the capture state is predominantly 1⁺, and the 6018-keV state is 1⁻. Since neither the capture state nor the 6018-keV state decays to the level

at 828 keV, it is tentatively assigned to be 4⁺. Because the capture state decays to the 665-keV level while the 6018-keV state does not, it is tentatively assigned to be 3⁺, which is in agreement with a previous theoretical prediction for this state.⁶ The 1057-keV level has previously been assigned 1⁺ on the basis of beta-decay measurements. That leaves another spin-2 level to be taken into account, and it is tentatively placed at 984 keV. It should be emphasized that these assignments are tentative and more work, both theoretical and experimental, is needed to conclusively establish the spins of these levels.

* * *

J. VERVIER, C.E.N. -S.C.K., Mol, Belgium: Do you have any idea why the 6-MeV level is populated so strongly directly from the capture state?

BLATCHLEY: The F^{20} nucleus has only positive-parity levels up to the region above 5 MeV. One possible explanation is that the level at 6018 keV is the lowest one to which an E1 transition could go.

⁶ T. Dazai, *Progr. Theoret. Phys. (Kyoto)* 27, 433 (1962).

R. T. CARPENTER, University of Iowa, Iowa City: From the spectra that you showed, is it at all possible to obtain branching ratios for any of these lower states in F^{20} ? Can you see enough of the transitions from them to enable you to obtain relative intensities?

BLATCHLEY: It is possible, but I think it would be difficult.

CARPENTER: I presume that the difficulty arises mostly because the efficiency is changing rapidly and is not well enough known in that region.

BLATCHLEY: Right.

CARPENTER: Nevertheless, such measurements would provide a very significant check on your tentative spin assignments.

(H) (H)

~~B.S.~~ GAMMA-RAY SPECTRUM FOLLOWING THERMAL-NEUTRON
CAPTURE IN Er^{166} .

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Introduction

A study of the gamma-ray spectra following thermal-neutron capture in an even-even target is particularly informative. Only one capture state of spin $J = \frac{1}{2}^+$ is involved, and the predominance of dipole radiation in this reaction requires that final states populated by direct transitions be $J = \frac{1}{2}$ and $\frac{3}{2}$ — mainly with odd parity.

The product nucleus is an odd-neutron nucleus. The character of the states to be expected is illustrated in Fig. 44. The highest-energy gamma rays, with energies near the neutron separation energy, populate single-particle Nilsson orbits. At increased excitation energies, we expect vibrational states coupled to particle modes; and at excitation energies exceeding the pairing gap, we expect to find states of complicated (and little understood) quasi-particle configurations. The regions indicated in the figure are only illustrative; in fact, there is considerable overlapping of the regions in practice.

The existence of resonances near the neutron separation energy is rare for most even-even targets because of their much lower

Fig. 44. Excitations in an odd-neutron deformed nucleus.

TABLE VI. Relative contributions from the isotopes in a target of natural erbium.

Isotope	F	σ	% Contribution
Er ¹⁶²	0.136	2.03 ± 0.20	$1 \cdot 10^{-3}$
Er ¹⁶⁴	1.56	1.65 ± 0.17	$1 \cdot 10^{-2}$
Er ¹⁶⁶	33.41	45	~ 10
Er ¹⁶⁷	22.94	620	~ 90
Er ¹⁶⁸	27.07	2.0 ± 0.4	0.3
Er ¹⁷⁰	14.88	9 ± 2	0.8

TABLE VII. Relative contributions from the isotopes in a sample enriched in Er¹⁶⁶.

Isotope	F	σ	% Contribution
162	0.005	2	
164	0.005	1.7	
166	99.97	45	99.5
167	0.03	620	0.4
168	0.01	2	
170	0.005	9	

Sm	< 0.05	5500	< 10
Gd	< 0.02	46000	< 20
Dy	< 0.2	1100	< 8

level density. As a result, these isotopes normally have relatively small cross sections, so that the capture process in natural samples is dominated by the neighboring odd-A isotopes. This is shown in Table VI, which lists the relative isotopic contributions for a natural target.

As Table VII shows, Er¹⁶⁶ is a favorable target in that only one odd-A erbium isotope occurs in nature and the cross sections are in the ratio $\sigma(\text{Er}^{166}) : \sigma(\text{Er}^{167}) \approx 1 : 5$. For the enriched sample

Fig. 45. The singles spectrum for the $\text{Er}^{166}(n, \gamma)\text{Er}^{167}$ reaction observed with a Ge(Li) detector. Each peak indicated by a number is a double-escape peak corresponding to a primary transition in Er^{167} .

used, it can be seen that capture in Er^{166} is dominant. Also no appreciable intensity from transitions corresponding to the spectra of natural Gd, Sm, and Dy—the most likely elemental contaminants—was observed. Both mass spectrometric analysis and activation analysis indicate the presence of Ce and possibly Lu.

Experimental Results

Figure 45 shows the over-all spectrum obtained for the enriched sample encapsulated in a graphite container and inserted in the through-hole facility of the CP-5 reactor. As you can see, the spectrum is dominated by a transition at roughly 6.23 MeV, labeled $[521] \frac{1}{2}^-$. The positions of the double-escape peaks corresponding to transitions to known levels in Er^{167} have also been labeled. These levels have been observed in (d, p) work by the Florida group.¹

Since the identification is made on the basis of energies, the sort of agreement that obtains is shown in Table VIII. For the first four levels, the precise energies of which have been determined from the crystal-spectrometer work of Koch,² the dispersion in the data corresponds to 0.5 keV, while with respect to the charged-particle work there is a dispersion corresponding to 3 keV. There is good

¹R. A. Harlan, Thesis, Florida State University, 1963 (unpublished).

²H. R. Koch, Z. Physik 187, 450 (1965).

TABLE VIII. Neutron binding energies S_n in Er^{166} .

Gamma-ray energies ^a (keV)	Excitation energy (keV)	Binding energy, S_n (keV)
<u>Crystal spectrometer</u>		
6228.4	207.80	6436.2
6171.2	264.87	6436.1
5683.9	752.75	6436.7
5635.6	801.62	6437.2
	average	6436.6 ± 0.5
<u>(d, p)</u>		
5259.9	1173	6433
5210.6	1227	6438
5053.9	1385	6439
4891	1546	6437
4719	1720	6439
4682	1749	6431
4568	1867	6435
4365	2067	6432
4327	2113	6440
	average	6436.0 ± 3
	Mass data	6444.0 ± 5
	Reaction (d, p)	6434.0 ± 10

^aFrom the Ge-diode spectrometer.

reason to believe that the level assignments given are correct. There is also relatively good agreement between the values of the neutron separation energy obtained in the three quite different methods.

Table IX lists the relative reduced partial widths for the four transitions populating states for which there is a model assignment, as regards their dynamical origin. The reduced widths for transitions to final states characterized as collective in nature (the $[521]_\gamma$ and $[512]_\gamma$ states) are smaller by approximately two orders of magnitude. In addition, the ratio $\Gamma_\gamma(K=\frac{1}{2}, J=\frac{3}{2}^-)/\Gamma_\gamma(K=\frac{1}{2}, J=\frac{1}{2}^-)$ is very similar to that observed for similar transitions to the $[510]$ band in W^{183} and the hafnium isotopes.

TABLE IX. Relative reduced partial widths in Er^{167} .

Level	Γ_{γ}/E^3 (arbitrary units)
[521] $\frac{1}{2}^-$	1.000
[521] $\frac{3}{2}^-$	0.238
[521] γ $\frac{3}{2}^-$	0.026
[512] γ $\frac{3}{2}^-$	0.018

The similarity of the relative widths to those of the first two members of $K=\frac{1}{2}^-$ bands in several nuclides prompted us to consider the implications of a direct-capture mechanism. Let me hasten to say, before we become embroiled in the mystique surrounding this concept, that (to this experimentalist) the implications are restricted to one simple model—the initial radiating state may be represented by an s-wave neutron weakly coupled to an inert target. Armed with this restricted viewpoint, the results calculated for the extreme model are shown in Fig. 46. Here the relative reduced widths for transitions to the [521] $K=\frac{1}{2}^-$ and $\frac{3}{2}^-$ levels have been plotted as a function of deformation. In addition, it shows the ratio

$$R_{10} = \frac{B(E1; i \rightarrow \frac{1}{2} \frac{3}{2}^-)}{B(E1; i \rightarrow \frac{1}{2} \frac{1}{2}^-)}.$$

As you can see, the observed ratio for Er^{167} is consistent with $n = 4$, or generally $n > 4$ if we are not dogmatic about the precise structure of the final state. One also expects, in this model, that collective states that involve core excitations will have retarded transition rates as is observed.

* * *

O. W. B. SCHULT, Technical University, Munich and Brookhaven National Laboratory: Your next to the last figure (Fig. 45) showed the [521] $K=\frac{3}{2}^-$ γ -vibrational band. Theoretical calculations published in the literature have predicted that this [521] band contains not only the γ -vibrational structure coupled with the [521] $K=\frac{1}{2}^-$ Nilsson

orbital but also the $[521] K=\frac{3}{2}$ Nilsson orbital which is expected in this region. Then the $[521\uparrow]$ γ band should have $K = \frac{1}{2}$. Have you seen the $I=\frac{1}{2}$ state?

PRESTWICH: I did not identify the states as far as this structure is concerned. I only used the ones assigned by Koch who, as you know, uses the lower energy decay to identify the levels.

Fig. 46. Curves showing the relative reduced widths for transitions to the $[521] K=\frac{1}{2}^-$ and $\frac{3}{2}^-$ levels as a function of the deformation parameter η . Also shown is the ratio

$$R_{10} = \frac{B(E1; i \rightarrow \frac{1}{2} \frac{3}{2}^-)}{B(E1; i \rightarrow \frac{1}{2} \frac{1}{2}^-)}.$$

~~B-6.~~ ⁴¹⁷ GAMMA-RAY SPECTRA FROM CAPTURE OF THERMAL NEUTRONS IN B^{10} , C^{12} , AND C^{13}

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It should be emphasized that the data presented here are strictly of a preliminary nature. They are actually a by-product of work we have been doing on capture gamma rays from resonance neutrons.

The first set of data to be discussed was obtained with C^{12} and C^{13} targets. For the C^{12} measurements, the target was reactor-grade graphite; the C^{13} target was a 1-g sample of supposedly high-purity material. The latter target was placed in a reactor-grade graphite container made with very thin walls to minimize its dilution of the C^{13} .

A chlorine impurity presented a problem in our work with the C^{13} sample. Although the impurity was only a few parts per million, the system was so sensitive that even this produced many background lines. To check the possibility that the Cl lines came from handling the graphite container in preparing the sample, two completely separate runs were made with the C^{13} sample in different containers. Use of the container that had not been handled cut the intensity of the Cl lines about in half. Thus, some of our impurity had come from the salty moisture on hands; but a substantial part of the Cl lines resulted from the sample itself.

In the spectrum from the C^{12} target (Fig. 47), we see the ground-state line at 4946 keV and the lines at 3684 and 1262 keV. We believe that the bump at about 4.4 MeV (channel No. 1395) is due to inelastic scattering from the C^{12} . The spectrum from the C^{13} target (Fig. 28 in paper B-1) shows the 8174-keV ground-state line and lines at 6093 and 6623 keV. In this singles run, the single-escape peak from the 6112-keV chlorine line makes it difficult to determine if there is a

Fig. 47. Capture-gamma-ray singles spectrum obtained in an overnight run with a C^{12} target.

line from C^{14} at 6623 keV. We therefore made a run with the pair spectrometer, which would remove the escape peaks from the 6112-keV line. Although we saw what appeared to be two lines, the interpretation was complicated by the fact that there is a chlorine doublet near 6623 keV. All we can say, therefore, is that if there is a line here from C^{14} it is indeed very small. This illustrates the problems with impurities when one uses a system as sensitive as this. In the present case, even the small amount of chlorine in the sample gives lines that are very nearly strong enough to be used for calibration purposes.

We have also obtained results with a B^{10} target. When we first told the people in charge of reactor operations that we would

Fig. 48. Low-energy portion of the capture-gamma-ray singles spectrum obtained with a B^{10} target. The carbon lines, which come from the sample holder, are useful as energy calibrations.

like to put a B^{10} sample in the through hole, they shuddered because we had already melted down a Cd sample and they expected this one to be quite a problem. We calculated that the heat generated in it would be about 250 W. We therefore attached a thermocouple to the sample when we first placed it in the reactor. The temperature rise was about 200°C , and this coupled with the ambient temperature of 500°C from the reactor itself gave a total temperature rise of about 700°C . However, since it is very localized it presented no problem.

Figure 48 is the spectrum obtained with this B^{10} target. It is interesting to note that we see a small full-energy peak at 2534 keV and also the double-escape peak of this very small B^{11} line. The

Fig. 49. High-energy (6700—11500 keV) portion of the $B^{10}(n, \gamma)B^{11}$ singles spectrum. It is from the same run as Fig. 48.

4444-keV and 4711-keV lines are the only other ones seen in this low-energy portion of the B^{11} spectrum. In this set of measurements, the 4946-keV line of C^{13} was used both for stabilization and for calibration. The method of calibration and energy determination is somewhat different for this sample. We use the double-escape, single-escape, and full-energy peaks; and on the assumption that there is a 511-keV difference between successive peaks we determine the keV per channel. This turns out to be a very reliable method for determining the energies of the gamma-ray lines.

In Fig. 49 we see some of the high-energy lines in B^{11} . In addition to the ground-state line at 11 447 keV, there are lines at 8196, 7006, and 6739 keV.

Fig. 50. Level scheme showing the gamma rays following the $B^{10}(n, \gamma)B^{11}$ reaction. The thickness of a line is a qualitative indication of its intensity. The energies listed on the arrows do not include the recoil energies.

Figure 50 shows the level scheme for B^{11} . Several points deserve notice. (1) There is a low-energy primary transition at 2534 keV. (2) The 7006-keV line has a large relative intensity. (3) In a resonance-gamma-ray experiment performed at the CP-5 reactor in collaboration with Dr. Hans, we saw the 2140-, 4460-, and 5030-keV lines; but in the present through-hole experiment we can see only the 4444-keV line. It is interesting to note that we do not see the other two. The error associated with these lines is about $\pm 2-3$ keV, but we believe that with further

work we can reduce it. We also have tentative plans to determine the relative intensities of the lines more accurately.

SESSION C

2 NOVEMBER 1966

**BENT-CRYSTAL GAMMA-RAY SPECTROMETERS,
Ge(Li) DETECTOR SYSTEMS, AND ELECTRONICS**

R. E. COTÉ[/], CHAIRMAN

BENT-CRYSTAL SPECTROMETERS

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A. Crystal Spectrometers for the Measurement of Gamma Radiation from Neutron Capture

A considerable fraction of the neutron-capture gamma-ray spectrum consists of γ quanta with energies comparable to x-ray energies. Hence crystal spectrometers, which have been successfully used for the determination of x-ray spectra, are as well suited for low-energy (n, γ) measurements. When talking about crystal spectrometers in general or during a discussion of their advantages and disadvantages for (n, γ) measurements, it seems advisable to separate them into two groups of instruments: focusing devices and flat-crystal spectrometers.

➤ The focusing spectrometer utilizes a cylindrically curved crystal lamina. Two variations of apparatus are then possible. The Cauchois spectrometer requires an extended source located on the convex side of the curved crystal. The reflected γ beam is focused in a narrow line. The chance that a quantum originating in the source is being reflected in a Cauchois spectrograph is given through the integrated reflection power of the crystal and not through the crystal breadth (which does, however, limit the useful breadth of the source). This is the decisive difference between the Cauchois spectrometer and the DuMond-type spectrograph, which uses a very thin source on the concave side of the curved crystal and for which the chance that a quantum from the source can be reflected is roughly proportional to the crystal breadth (and therefore is about two orders of magnitude larger than in a Cauchois spectrograph). The source breadth in a DuMond-type spectrometer is, on the other hand, about

two orders of magnitude smaller than in the Cauchois geometry so that the peak counting rates are roughly the same in both spectrometers. The γ spectrum is measured point by point in a DuMond-type spectrometer, in which reflected quanta are detected with high efficiency in large counters. The Cauchois device permits the simultaneous measurement of a small section of the spectrum. For this, nuclear emulsion plates are used, but their low efficiency seems to compensate the advantage of the simultaneous detection. Sumbayev,¹ probably for this reason, has replaced the emulsion by a scintillation counter in connection with a slit. So far, Cauchois spectrographs and DuMond spectrometers should be approximately equal with respect to their capabilities.

Precision spectroscopy with DuMond-type spectrometers is complicated if the source moves. Here, the Cauchois device has a definite advantage over the DuMond geometry. Also, an increase of the source depth (an extension in the direction of the γ beam) gives rise to defocusing effects. It impairs the resolution which can be obtained with DuMond spectrographs. Thus, the Cauchois geometry is clearly better if large sources must be used as, for example, during the measurement of the 2.2-MeV gamma line from the reaction $H(n, \gamma)D$.

The DuMond geometry is much less expensive if the source contains enriched material—as is usually the case. The costs of enriched isotopes from Oak Ridge have steadily and considerably been decreasing during the past years. This fact still does not reduce the superiority of the DuMond-type spectrometer because of the complexity of (n, γ) spectra which can be studied more favorably if very highly enriched mass-separated isotopes are used. These isotopes are only in part available at Oak Ridge. Smaller separators can produce quantities around 50 mg for DuMond-type spectrometers in a reasonable time at costs between \$300 and \$2000 each.

Furthermore, a smaller source yields a cleaner γ spectrum than large samples. In the latter, the quanta originating from nuclei within

¹I. O. Sumbayev and A. I. Smirnov, Nucl. Instr. Methods 22, 125 (1963).

the source have a larger chance to be Compton scattered in the sample so that they reach the spectrometer crystal. It also seems as if the most accurate energies of neutron-capture gamma rays have been measured with DuMond-type spectrometers.

↘ The simplest kind of a flat-crystal spectrometer is a single-flat-crystal spectrograph. The main component of such a device is a narrow Soller-slit collimator which determines the resolution of the spectrometer and which is located between the extended source and the diffracting crystal. A resolution width as good as

$$\Delta E/E \approx 8 \times 10^{-6} \times E(\text{keV})$$

could be obtained with a single-flat-crystal spectrometer equipped with a collimator 5 m long with 0.5-mm-broad slits and a crystal whose atomic planes are spaced $0.5 \text{ \AA}$ apart. The counting rate in the reflexes produced in such a system is estimated to be 2—4 times as large as in a Cauchois spectrometer above about 100 keV because a flat crystal can be much thicker than the curved crystal plates. On the other hand, the resolution which can be achieved with Cauchois spectrometers is at least three times as good as the number given above, and high resolution is much more important than a small gain in counting rate. At the present time, there is hardly any evidence that a single-flat-crystal spectrometer with a collimator having extremely small angular divergence can successfully compete with a Cauchois device.

The highest possible resolution can be achieved with a double-flat-crystal spectrometer, for which

$$\Delta E/E \approx 8 \times 10^{-7} \times E(\text{keV}).$$

The reflex counting rate is, however, 1—3 orders of magnitude smaller

Fig. 51. Detection efficiency E of a curved-crystal spectrometer for detection of γ rays. The full line is obtained if γ -ray attenuation in the source can be neglected. The dashed and dotted curves show how the sensitivity is reduced because of γ -ray absorption within the sources, the depths of which are given together with the chemical symbol of the source material.

than with a single-flat-crystal spectrometer. If sufficiently strong sources are available, double-flat-crystal spectrographs could yield line widths (FWHM) around $\Delta E = 1.8$ keV at $E_\gamma = 1.5$ MeV and $\Delta E = 0.2$ keV around $E_\gamma = 500$ keV.

After these general remarks, let us consider in a little more detail the sensitivity limit of curved-crystal spectrometers and let us briefly say a few words about the quality of data which can be obtained at such instruments. Since the author has experience only with DuMond-type spectrographs, these considerations will be limited to these devices.

Numerous low-energy (n, γ) spectra have been measured at such spectrometers by Smither at Argonne and with the Risø spectrometer. The two systems seem comparable; the Argonne spectrometer appears to be a little more

sensitive and the Risø device permitted a little more precise energy determinations. The minimum partial cross section for a line to be detectable with these spectrometers is around 1 mb for $E_\gamma = 150\text{--}200$ keV. As is shown in Fig. 51, the sensitivity decreases, and correspondingly the minimum partial cross section (which is proportional to E_{rel}^{-1}), strongly increases for higher energies because of the reflection properties

of the crystal and at lower energies because of the γ -ray absorption in the crystal (full-drawn line) and in the source (dashed and dotted curves). It is evident from this figure that curved-crystal spectrometers are reasonably sensitive in the energy region from 30 to 600 keV. At the Risø spectrometer, the values routinely obtained for the energy uncertainty dE/E and the resolution width $\Delta E/E$ of strong transitions were

$$dE/E \approx 0.8-1.2 \times 10^{-7} \times E(\text{keV}),$$

$$\Delta E/E \approx 2-3 \times 10^{-6} \times E(\text{keV}).$$

The amount of material in the source

is normally around 50 mg in the case of powder and 100—300 mg if metal foils can be used.

A real comparison of different types of crystal spectrometers is extremely difficult and it cannot be given here. The main reason for this is the background radiation. An investigation of this problem has been started at Risø. For the first test, the channel of the discriminator has been set so that only those pulses from the scintillation counter were recorded which corresponded to the photopeak produced by quanta of a given energy (corresponding to a strong γ line from neutron capture). The number of counts was then recorded as a function of the angular setting of the crystal. Instead of the expected result (different order reflections on top of an almost constant background), the measurement showed that the background changed considerably as is shown in Fig. 52. Evidently, the background counting rate in the deep valley

Fig. 52. Background at the Risø curved-crystal spectrometers. The schematic figure is explained in the text in detail.

between the first- and second-order reflections is due to radiation that penetrates the shield surrounding the detector; it comes from Compton scattering in the curved crystal and at the plates of the collimator between the crystal and the detector. During a measurement in the first order of reflection, the actual background is about 30 times larger. The background areas below the different order reflections are proportional to the integral reflection power of the crystal, and the heights of these background peaks are proportional to the heights of the γ -ray reflexes in the corresponding order divided by the reflection order. From this we conclude that the background peaks are almost entirely caused by true reflection of a white background spectrum which impinges on the crystal together with the (n, γ) radiation. This situation illustrates that a considerable gain in sensitivity could be achieved if the intensity of this background spectrum could be reduced. The origin of this background spectrum has not yet been studied in detail. Experiments along this line are planned for the near future.

Since the germanium detectors have been developed so that they can be used with great success for γ -ray spectroscopy, the question may arise whether the crystal spectrometers should not be replaced by germanium diodes. In attempting to answer this question, we may compare results which have been obtained from the two types of apparatus. Since both devices can be improved, it is legitimate to perform such a comparison by considering a present-day Ge(Li) detector and an ordinary curved-crystal spectrometer. Yamazaki and Hollander,² who used a 0.5-cm³ detector in connection with a field-effect-transistor preamplifier, have recently reported a line width $\Delta E(\text{FWHM}) = 1.5\text{--}1.7$ keV for γ -ray energies between 60 and 270 keV. Figure 53 shows part of the γ spectrum from neutron capture in holmium. Even at the higher energies at which the resolution of a curved-crystal spectrometer rapidly becomes poorer, the line width $\Delta E = 0.7$ keV at $E \approx 490$ keV is much smaller than for the Ge(Li) detector.

²T. Yamazaki and J. M. Hollander, Nucl. Phys. 84, 505 (1966).

At lower energies (e.g., around 100 keV), the situation is much more in favor of the curved-crystal spectrometer, for which the line width $\Delta E(\text{FWHM})$ of a fifth-order reflection of a 116-keV transition is around 0.04 keV. With a Ge(Li) spectrometer, a considerable background is recorded in the low-energy region because of the higher energy radiation. This reduces the dynamic range of the system; i.e., the observation of weak low-energy lines is rendered

difficult. This problem is absent with curved-crystal spectrometers, as is clearly seen in the second-order reflection of the group of lines around 116 keV in Ho^{166} .

As mentioned previously, high resolution is of major importance for the spectroscopy of γ radiation from neutron capture. If strong sources are available, as is presently the case if the neutron-capture cross section exceeds say 10 barns, the curved-crystal spectrometer is more powerful than the Ge(Li) spectrometer in the energy range from 30 keV to approximately 500 keV. Above about 800 keV, the germanium detector will usually be superior.³ The (n, γ) spectra from sources with very small cross sections should be investigated with Ge detectors.

Fig. 53. Part of the $\text{Ho}^{165}(n, \gamma)$ spectrum recorded with the Risø spectrometer.

³H. T. Motz, E. T. Journey, and R. K. Smither (private communication).

B. On the Automation of the Risø Curved-Crystal Spectrometer

with

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and

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The use of DuMond-type curved-crystal spectrometers for the measurement of low-energy gamma radiation from neutron capture has the great advantage that only small sources are required. Therefore, it is usually possible to work with isotope-separated sources obtained from smaller mass separators (e.g., the instrument of the Austrian Study Group for Nuclear Energy in Seibersdorf⁴). The capture contributions from neighboring isotopes are then mostly negligible. On the other hand, the DuMond geometry has a severe disadvantage: the source is somehow fixed in a tangential through tube which by no means is rigid, i.e., which moves less than say 10^{-4} in. A considerable source movement has been systematically observed while the reactor is started or shut down. But smaller irregular dislocations were also seen during long (20-day) operation periods. Consequently, the limit in energy precision is determined through the source movement and not by the accuracy of a good spectrometer if this instrument is operated as if the source were rigid.

The errors due to source movements can be largely reduced either through a measuring procedure resembling the old-fashioned method of determining accurate weights, namely through consecutive measurements at both sides of the zero point, or through some method of measuring the source movement. The first method is very simple and has been used in Munich and Risø; however, it is not well suited to automatic

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⁴We are very much indebted to Professor Dr. P. Weinzierl for kindly making this source of extremely pure isotopes available to us.

operation of a spectrometer. Manual measurements of neutron-capture gamma-ray spectra have been performed; but the chance that errors occur during the 3000—10000 steps of evaluation is sizeable. For this reason and because of the troublesome manual measurements, it was decided that the second method, the measurement of the source movement, should be applied in automating the Risø spectrometer.

The gamma beam originating from the source penetrates a servo crystal which is located about 50 cm in front of the spectrometer crystal. This latter crystal is used for the diffraction of the neutron-capture gamma spectrum. The servo crystal is oriented so that it reflects the intense K_{α_1} x-ray beam which also comes from the source because of the internal conversion and photoeffect. The source movement is determined through a small, slow, and continuous angular oscillation of the servo crystal and a counter arrangement which adds counts N_L corresponding to the detected K_{α_1} quanta while the servo crystal sweeps through the left-hand side of the x-ray reflex and which subtracts counts N_R while the system moves through the right-hand side of the reflex. A movement of the source shifts the centroid of the x-ray reflex by $\Delta\psi$ and the difference $n = N_L - N_R$ between the numbers of left and right counts is then no longer within the statistical limits of the numbers of counts. A servo motor now changes the angular orientation ψ of the servo crystal by the amount $\Delta\psi$ proportional to n so that the servo crystal always follows the movement of the source.

The spectrometer crystal is rotated by means of a Zeiss screw which pushes a 2-m arm. The angular position α of the screw is roughly proportional to $\sin\phi$, where ϕ is the angle of reflection at the spectrometer crystal. A mechanical lever system has been constructed which rotates the screw by additional amounts $\Delta\alpha \propto \Delta\psi$ so that the spectrometer crystal should also follow the source movement with fair accuracy.

The collimator (1.4 m long) and the radiation shield (8 in. lead and 4 in. boric acid plus paraffin) which surrounds the detector, a total weight of 1.1 tons, is counterbalanced by an equivalent weight of lead bricks. This part of the spectrometer is rotated by use of another Zeiss screw which is provided with a properly machined arm in order to obtain the required ratio of 2:1 for the angular settings of the spectrometer crystal and the detection system. This second screw does not follow the movement of the source since the angular orientation of the collimator may differ from twice the Bragg angle ϕ by as much as ± 15 sec of arc without sacrificing any precision during the intensity measurement.

The angular setting α of the precision screw is mechanically digitalized. The intention is to collect on magnetic tape the position α , the counting time (if the monitor count is preset) or number of monitor counts (if the time is preset), the integral number of counts, and the number of counts in the first, second, third, fourth, fifth, and seventh order of reflection. These data should then be treated in a computer.

The system is being assembled at the present time. There is not yet any information available on the precision and reliability of the mechanically quite complicated device. The angular position of the spectrometer crystal will be measured with an interferometer if the precision screw and the 2-m arm do not give the desired precision.

C. A Few Remarks about the Crystal Size in DuMond-Type Spectrometers for (n, γ) Measurements

Curved-crystal spectrometers have turned out to be rather powerful instruments for the detection and measurement of low-energy (n, γ) spectra, mainly because of the high resolution which can be as good as $\Delta E/E \approx 2 \times 10^{-4}$ for $E \approx 100$ keV. Unfortunately the detection efficiency of

such devices is very small (usually less than 10^{-6}). The availability of strong sources produced in powerful reactors has largely compensated this disadvantage. Even then the experimentalist will make an effort to design the instrument so that its dimensions are close to what might be considered optimal for the detection of very weak transitions. Because of a considerable background at reactors, it is of interest to maximize the sensitivity S (ratio of counting rate C of the (n, γ) spectrum to the square root of the background counting rate U) and not to obtain the highest possible detection efficiency ($\propto C$) of the apparatus.

In the most simple-minded approach, one might consider the reactor a black box and think that C is proportional to the linear dimensions (height H and breadth B) of the reflecting crystal. The same assumption may underlie the background estimate. The conclusion would then be that

$$C \propto H \times B,$$

$$U \propto H \times B,$$

$$S \propto \sqrt{H \times B},$$

and one would conclude that the largest crystal will give the maximum sensitivity.

In reality, however, the effective source strength and the background depend in a more complicated manner on the effectively utilized crystal dimensions because of the final geometry of the beam hole—in particular, its diameter. The background consists of six components as follows.

(1) U_S is due to the scattering of reactor (core, etc.) gamma radiation at the source. Fast electrons will produce bremsstrahlung in the source. The reduction of this background component requires shielding against gamma radiation from the core and is generally very difficult. There exists no possibility of removing this background through the use of shielding between the source and the reflecting crystal. We therefore consider U_S a principal background.

Fig. 54. Schematic section showing the basic geometry of a DuMond type curved-crystal spectrometer for (n, γ) studies at a reactor.

(2) U_D originates from the diaphragm in the beam tube. Neutron capture and γ -ray scattering contribute to U_D . This background can be largely reduced—supposedly so much that it becomes negligible compared to U_S —by installing a collimator between the source and the crystal, a possibility proposed by Smither.⁵

(3) U_C is due to the (assumed) ideal γ beam which comes from the neutron capture in the source and which impinges on the curved crystal where part of it is Compton scattered and penetrates the Soller-slit collimator between crystal and detector with almost no absorption. U_C can be reduced through the use of a long collimator.

(4) U_p is the background contribution from capture and scattering at the front end of the plug which is inserted in the beam hole at the opposite end of the spectrometer. We neglect this part on the assumption that the use of lithium carbonate produces very little (n, γ) radiation. Also, the back-scattered γ quanta do probably contribute a negligible amount to U because of their low energy.

(5) U_T originates from the gas inside the liner. It is neglected in our considerations since we consider an evacuated channel.

(6) U_R is the background contribution which comes from the reactor hall. A sufficiently effective shield is supposed to reduce U_R far below U_S and U_C . Consequently we need not deal with U_R here.

The further considerations rest on the basic assumption that the fringing rays (dashed lines in the schematic diagram, Fig. 54) do

⁵R. K. Smither (private communication).

not come from the very active wall of the beam tube but that any spot of the reflecting crystal "sees" only part of the very weakly radiating (lithium carbonate) area with inner diameter D . These fringing rays determine a relation between the crystal height H and the height h of the aperture in the diaphragm. The value for h is easily found for every assumed H and these quantities permit a straightforward calculation of the maximum effective source strength s . (This source strength is equal to the height of the source $\times p$, where $p \times H$ is the probability that an emitted quantum will reach the crystal and p depends, of course, on the position of the radiating element in the source.) Figure 54 shows a vertical section through the beam. The horizontal section is similar except for the section through the source, which then appears as a point.

Dealing first with the dependence of the sensitivity S on the crystal height, we find

$$\begin{aligned} C &\propto s \times H, \\ U_S &\propto s \times H, \\ U_D &\propto h \times H, \end{aligned}$$

and approximately

$$U_C \propto s \times H \times N,$$

where N is the height of the detector as determined by the fringing rays in Fig. 54. Since it is not known a priori to what extent the three background components contribute, $S(H)$ is determined for the three limiting cases:

$$U_S \gg U_D, \quad U_S \gg U_C \quad \text{in Fig. 55a}$$

$$U_D \gg U_S, \quad U_D \gg U_C \quad \text{in Fig. 55b}$$

$$U_C \gg U_S, \quad U_C \gg U_D \quad \text{in Fig. 55c.}$$

The interesting result is a decreasing sensitivity for a crystal height $H > 1.2 D$. The maximum is quite broad, which means that the use of a crystal height of only $H \approx 0.4 D$ already yields a sensitivity which is not more than around 20% below the maximum value. In cases in which U_C is

Fig. 55. Dependence of the sensitivity of the spectrometer: (a, b, c) on the height H of the curved crystal for three different background conditions described in the text and (d) on the crystal breadth B . The dimensions H and B are given in units of the free diameter D of the beam tube (Fig. 54).

contributing considerably to the background, a crystal height around $H \approx 0.4 D$ is preferable to one with $H \approx D$. Smaller crystals are more easily available and it is supposed that they can be curved with higher precision than large plates.

Considering the dependence of S on the crystal breadth B now, it is evident that the breadth of the diaphragm aperture is always proportional to B . Consequently also C , U_S , U_D , and U_C are proportional to B . We therefore obtain (Fig. 55d)

$$S \propto \sqrt{B} \quad \text{for } B < B_{\max}.$$

Here our result is the same as the one found in the most simple-minded approach except for the limitation $B < B_{\max}$. For $B > B_{\max}$, the fringing rays would come from the strongly radiating parts of the in-pile components and S would thus strongly decrease above the limit for the crystal breadth.

The crystal breadth actually chosen will in general be less than $B_{\max}$, especially if the diameter of the beam tube is large. The reason for this is the defocusing effect which reduces the peak height (and thus C) of γ reflections mainly at lower energies where the crystal spectrometers are most powerful.

THE USE OF CRYSTAL DIFFRACTION WITH A Ge(Li) DETECTOR
FOR HIGH-RESOLUTION GAMMA-RAY SPECTROSCOPY

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The development of the Ge(Li) diode as a gamma-ray detector wrought a dynamic change in the (n, γ) program here at Argonne. One of the programs affected directly was the research program at the large bent-crystal spectrometer. Much of this effort has been concerned with the development of the level schemes of medium to heavy even-Z even-N nuclei. A typical level scheme, that of Hf^{178} , appears in Fig. 56. The key to this level scheme and to much of the interesting physics is tied up in the analysis of the 1—2-MeV transitions from the excited-state rotational bands to the ground-state rotational band. This is a difficult energy region for the bent-crystal spectrometer because the resolution of the spectrometer is decreasing rapidly with increasing gamma-ray energy. The development of the Ge diode γ detectors appeared, at least at first, to solve this problem in that it offered a considerable improvement in energy resolution in the 1—2-MeV range. Problems, however, developed in the use of the Ge-diode detector as is seen in Fig. 57. Here we have plotted the photoelectron cross section and the pair cross section in germanium. As you can see, the worst region to work in is just this 1—2-MeV energy range. Here the 1.5-MeV photopeaks are obscured by the second-escape peaks of the 2.5-MeV gammas, while the second-escape peaks of the 1.5-MeV gammas are buried under the full-energy peaks of the 0.5-MeV gammas.

The first approach tried in an attempt to resolve this problem is shown in Fig. 58. Here the Ge diode is placed inside a NaI ring which is split into four quadrants. The γ beam enters from the left. The system is used both as a three-crystal pair spectrometer for the detection of double-escape pair events and as an anticoincidence ring for

Fig. 56. Level scheme of Hf^{178} as deduced from the gamma-ray measurements made with the Argonne 7.7-m bent-crystal spectrometer. The energies of the levels and gamma rays are given in keV. The K value, spin, and parity of a level are given on the left in that order. The width of a line in the level scheme is meant to reflect the relative intensity of the gamma ray.

the preferential selection of full-energy events. This system resulted in a considerable improvement in both the double-escape and full-energy spectra, but problems still remained in signal-to-noise ratios and in the resolution of close doublets in which one peak was considerably weaker than the other.

At this point a rather interesting idea occurred to me: Why not use the crystal spectrometer to select out that unresolved doublet or complex structure, and then place the Ge diode in the diffracted beam where it would accumu-

late a pulse-height spectrum that includes only the peaks of interest? The experimental arrangement is shown in Fig. 59. At the left is the neutron-capturing sample in a through beam tube in the reactor. The gamma beam leaves the reactor through a collimator and is diffracted by the bent crystal; the diffracted beam is separated from the undiffracted beam by the multislit collimator and is detected in the Ge diode. This was first tried with the Ge diode still inside its NaI ring, but the signal-to-noise ratio was usually so good that the anticoincidence ring was not needed. Note that the Compton events from the peaks under investigation do not contribute to the background under the full-energy peaks, and that Compton edges and double-escape and single-escape peaks do not complicate the spectrum. One's first reaction to such a scheme is that the counting rate would be zero. The efficiency is indeed low as is seen in Fig. 60; but the source in the reactor is very strong,

Fig. 57. Cross sections for the production of photoelectrons and electron-positron pairs in Ge as a function of gamma energy.

Fig. 58. Schematic diagram of the Ge-diode detector assembly used in this paper and the split-NaI-ring detector used for the coincidence and anticoincidence experiments. The Ge detector is mounted horizontally on the end of a thin Al tube which is attached to a hollow Cu cold finger. Liquid nitrogen is fed down into the Cu cold finger from a reservoir located above it. The NaI ring slides over the horizontal part of the cold finger so that the Ge-diode detector is near the center of the split NaI ring. The gamma beam enters from the left, passes through a hole in the copper cold finger and through the Al tube which supports the Ge detector, enters the side of the detector in a direction parallel to the face of the detector and perpendicular to the electric field applied to the detector, and finally leaves the detector and passes out through the hole in the NaI ring. The Pb gamma shield and part of the Li_2CO_3 neutron shield for the sodium iodide ring are not shown. All parts are aluminum unless otherwise noted.

so counting rates of a few per minute in the peak are quite common. Here we have plotted the efficiency for a 1-cc Ge detector placed in the diffracted beam of the bent-crystal spectrometer. The curve for photoelectron events is on the left. Above it is the efficiency for full-energy events—including both photoelectron events and Compton events when both the Compton electron and the Compton gamma are absorbed.

The efficiency for electron-pair events curves down at high energies because more of the electrons and positrons escape from the detector at higher energies and also because the reflectivity of the bent crystal is decreasing with increasing gamma energy. Note, however, that the relative efficiency remains quite high even at 5 MeV. The efficiency is given in units of events in the 1-cc detector per photon in the source. Since capture rates often approach 10^{14} per sec in the sample, 1% line would give approximately 6 counts/min at 1 MeV. The use of a 10-cc detector

will change this rate to a few counts per second in the peak, a quite reasonable rate for most experiments. The total counting rate in the detector will of course be quite low since only a very limited region of the (n, γ) spectrum is diffracted. Figure 61 shows the $\text{Cd}^{113}(n, \gamma)\text{Cd}^{114}$ pulse-height spectrum in the 1-cc Ge diode when the full (n, γ) spectrum is incident on the detector. Note the high background at low energies. The response of the bent-crystal spectrometer to the 1.2–1.5-MeV region of the $\text{Cd}^{113}(n, \gamma)\text{Cd}^{114}$ spectrum is shown in Fig. 62, in which the counting rate in the diffracted gamma beam is plotted as a function of the Bragg angle (which has been converted into gamma energy).

We shall now set the bent-crystal spectrometer at the Bragg angle corresponding to a particular point in Fig. 62 (high-energy side of the 1364-keV line) and place the Ge diode in the diffracted beam

Fig. 59. The combination of the bent-crystal spectrometer and a Ge-diode detector used for high-resolution gamma-ray spectroscopy. The gamma rays are produced by neutron capture in a sample located in a through tube near the core of the CP-5 research reactor at Argonne. The gamma beam emerges from the reactor through a series of circular collimators and is diffracted by the bent crystal. The diffracted beam is separated from the undiffracted beam by a multislit collimator 1 m long and is detected in the Ge-diode detector as well as the NaI detector.

Fig. 60. Plots of efficiency vs gamma-ray energy for the combined bent-crystal and Ge-diode spectrometer. The efficiency is expressed in events in 1 cc of active detector volume per photon from the sample. The number of full-energy events is equal to the number of photoelectron events plus the number of Compton events in which both the electron and the scattered photon are stopped in the active volume of the Ge detector. The ratio of the number of these full-energy Compton events to the number of photoelectron events depends sensitively on the physical dimensions of the Ge detector and increases rapidly with an increase in its size.

Fig. 61. Singles spectrum of $\text{Cd}^{113}(n, \gamma)\text{Cd}^{114}$ as recorded with a Ge-diode gamma detector with an active volume of 1 cc. The spectrum has been corrected for the absorption of the gamma rays by material in the beam. This increases the peak-to-background ratio at the low-energy end of the spectrum.

Fig. 62. Bent-crystal-spectrometer data in the 1.2—1.5-MeV region, taken with the 4-mm-thick quartz crystal set for 1st-order diffraction by the (310) planes. The counting rate in the NaI detector in the diffracted beam of the spectrometer is plotted as a function of Bragg angle.

Fig. 63. The close doublet at 1364 and 1370 keV in the γ spectrum from the $\text{Cd}^{113}(\text{n}, \gamma)\text{Cd}^{114}$ reaction. Upper curve: Response of the bent-crystal spectrometer (counting rate in the NaI detector vs gamma energy). The energy scale is determined from the Bragg angle. Lower curve: Pulse-height spectrum from a Ge diode placed in the diffracted beam of the bent crystal. The data in the lower curve were taken with the bent crystal set at a Bragg angle just above the peak at 1370.3 keV so that the diffraction process would favor the weaker member of the doublet. The dashed lines indicate the background. Note the improvement in the ratio of signal to background in the lower curve.

Fig. 64. Comparison of the line widths (FWHM) obtainable with the bent-crystal spectrometer (using the new 2-mm-thick quartz crystal with the Ge-diode detector) under different conditions. The gently sloping solid line corresponds to the present Ge-diode detector system. The gently-sloping dashed curve corresponds to an estimate of what will be available in the next few years. The steeper straight lines give the FWHM of the diffracted peak in the bent-crystal spectrometer for different crystal planes in the bent crystal.

where it can accumulate a pulse-height spectrum. The improvement obtained by going to the spectrometer employing both the Ge diode and the bent crystal is shown in Fig. 63.

The upper curve is an enlargement of the 1364-keV peak as observed with the bent crystal alone; below is the pulse-height spectrum obtained when the Ge diode is placed in the diffracted beam. The weaker member of the doublet is now well resolved. Setting the crystal spectrometer so that it favored the diffraction of the weaker member of the doublet improved the resolution in the Ge-diode spectrum by about a factor of 2 over what can be obtained if the two gammas are equally diffracted. Note the flat background and good signal-to-background ratio.

Figure 64 compares the line width (FWHM) of the Ge

system with that of the bent-crystal spectrometer. The upper solid curve indicates the resolution of the present Ge-diode system. The upper dashed curve corresponds to the resolution we expect to have in the near future. The steeply sloped lines, in order from left to right, are the respective line widths for first-order diffraction from the (310) planes of the quartz crystal presently installed in the bent-crystal spectrometer (but note that this is not the crystal used in the $\text{Cd}^{113}(\text{n}, \gamma)\text{Cd}^{114}$ work), for second-order

diffraction from the same planes, for the first order from the (550) planes, and for the first order from the (310) planes of a near-perfect crystal (1-sec rocking curve). Note that the energy resolution of the bent-crystal spectrometer could be better than that of the Ge diode at 1 MeV if near-perfect crystals are used. In the region from 600 keV to 2 MeV, the resolutions of the two systems are similar; it is therefore in this region that the combination is most useful for resolving close doublets.

Figure 65 is the curve obtained when the combined system is used to compare a well calibrated Co^{60} line with two gammas in the (n, γ) spectrum. This is done by placing a Co^{60} source near the Ge detector in the diffracted gamma beam. If it were not for the energy selectivity of the diffraction process, other (n, γ) lines would overlap the Co line and such a simple clean comparison could not be made.

Another application of the Ge-diode and bent-crystal spectrometer is just being explored now. As indicated in Fig. 66, the spectrometer is set at a series of positions within a diffraction peak (as shown in the successive insets) and the Ge-diode spectrum is obtained at each setting. By combining runs of this type with the known response function of the bent-crystal spectrometer, considerably more information

Fig. 65. An example of the intercalibration of the 1173-keV Co^{60} gamma ray with the 1199–1209-keV doublet in the $\text{Cd}^{113}(n, \gamma) \text{Cd}^{114}$ spectrum by use of the combined Ge-diode and bent-crystal spectrometer (Fig. 59). The crystal spectrometer is set so as to favor the diffraction of the weaker member of the doublet. The resulting enhancement of the weaker member of the doublet considerably improves the resolution of the weaker peak.

Fig. 66. Pulse-height spectra obtained with the Ge-diode detector in the diffracted gamma-ray beam of the Argonne bent-crystal spectrometer, with the latter set at three different Bragg angles. For each spectrum, the spectrometer setting is indicated by an arrow in the insert that shows the response curve (counting rate in the NaI detectors vs spectrometer setting) of the bent crystal for this region of the (n, γ) spectrum. The structure being analyzed includes the three strong gamma rays at 1282.9, 1300.9, and 1305.5 keV, and one weak gamma at 1292.9 keV. By fitting all three spectra simultaneously, a computer program obtains the energies and intensities of the individual transitions.

can be obtained than is available in a single spectrum. When the new detector system (four Ge detectors in one chamber, with a total active volume of 50–100 cc) is completed, it will be possible to go one step farther and use the Ge diodes as the primary gamma detectors in the bent-crystal spectrometer when recording the counting rate in the diffracted beam as a function of the Bragg angle.

An application of this method to the measurement of a 5.8-MeV gamma is being considered. Figure 67 shows the pulse-height spectrum obtained with the Ge diode in the 5.8-MeV region. The FWHM of the crystal diffraction peak of similar energy for the bent-crystal spectrometer with second-order diffraction of the (310) planes in the new 2-mm-thick crystal is shown below the data points. The new approach to the resolution of this region is to use Ge-diode detectors as the primary detectors in the bent-crystal spectrometer and to record the counting rate

Fig. 67. Ge-diode measurement of a limited region of the pulse-height spectrum of the $\text{Cd}^{113}(\text{n}, \gamma)\text{Cd}^{114}$ reaction. A biased amplifier is used to expand the energy scale. The brackets A, B, and C indicate digital windows set on the individual peaks. The plot of counting rate vs Bragg angle for these peaks will be analyzed separately to obtain the values of their corresponding gamma energies. The lower bracket is the line width (full width at half maximum height) of the second-order diffraction process when the (310) planes of the 2-mm-thick quartz crystal are used in the Argonne instrument.

as a function of Bragg angle in the digital windows (A, B, C) set on the individual peaks of the Ge-diode spectrum. In this manner one obtains a separate diffraction peak for each component, and one can treat the data as if only one well-resolved peak were present in each case. The energy precision of such a measurement on the 5.8-MeV gamma could approach one part in 20 000, i. e., 0.3 keV. The success of this approach depends on the use of large Ge detectors.

* * *

R. E. SEGEL, Argonne National Laboratory: When you go to fine resolution, is there any evidence that you really have any sort of grouping of the transitions? You showed some broad bumps that you later resolved into fine bumps. This looks very much like a yield curve showing intermediate structure. Have you any analysis to show whether there really is a grouping of these lines? That is, did you split these broad bumps into more lines than you would have expected when you got to high resolution?

SMITHER: No, I wouldn't say that. The (n, γ) spectrum has a background of weaker and weaker lines underneath it. The history has always been that an improvement in resolution has always been accompanied by an increase in sensitivity so that more gamma rays can be seen. With this new system we see weaker lines than we could see with the crystal spectrometer alone, but their line width is typical of the germanium detector.

As the crystal spectrometer is moved, the lines appear and then disappear with the dependence typical of the diffraction of the crystal spectrometer; so it looks as if there is one gamma ray in each bump. If there were an unresolved spectrum, a bump in the background would move along with the motion of the spectrometer and its width would correspond to the energy resolution of the diffraction process. In the lower region of the (n, γ) spectra, this is indeed true; the energy spectrum of the diffracted portion of the continuum is seen in the background. We use this spectrum to actually measure the energy dependence of the crystal diffraction.

I may also mention that we have also been using our new system to look at the wings that Schult talked about (paper C-1). It appears that these wings in the crystal diffraction arise—at least in part—from a sharp gamma ray. Thus a part of this wing may actually come from the diffraction process and not from the continuum.

J. VERVIER, C.E.N.-S.C.K., Mol, Belgium: I suppose that one of the reasons why you have such a low efficiency is that your germanium detector is small. In other words, would it not be better to have the reverse geometry—the Cauchois geometry—with a germanium detector?

SMITHER: We are now constructing a chamber that will hold a set of four germanium diodes, and hope to raise the effective volume from the present 1 cc to something like 50 or possibly 100 cc. This, of course, will increase the counting rates. Since our bent crystal is 12 in. on a side, there is plenty of room behind it to put as many Ge diodes as you would like.

Fig. 68. Use of a Ge-diode detector in a spectrometer of the Cauchois type. Gamma rays from the broad source at the left are incident on the bent crystal, which diffracts a small fraction of them into the Ge detector

placed on the focal circle. The diffracted beam deviates from the undiffracted beam by twice the Bragg angle. Diffracted gamma rays of one energy are focused at a point on the focal circle and ideally would pass through a line perpendicular to the paper at this point. The positions of the source and the detector are reversed from the DuMond configuration (Fig. 59). The position, shape, and sizes of the collimator and detector shield are only meant to be suggestive since these will depend on the energy range of the diffracted beam. The radius of curvature of the bent crystal is equal to the diameter of the focal circle.

In fact, the usefulness of the whole process depends on going to larger Ge diodes. When we use the Ge diode as a primary detector, we want to be able to take data in a reasonable amount of time.

VERVIER: But is it not true that the Cauchois geometry is intrinsically better because it does not require a big detector?

SMITHER: Yes, the Cauchois geometry (Fig. 68) has some advantages, but it usually has poorer resolution. The use of a small Ge diode with the broad source of a Cauchois spectrometer requires that the Ge diode be placed on the focal circle. Then why not use this arrangement with the small detector? What happens is that the broad source allows a number of energies to appear at the detector; and consequently the resolution is determined by a set of slits placed directly in front of the detector. This means that to achieve the good resolution required in order that only a few components in the spectrum will reach the detector, the slit has to be very narrow—a few thousandths of an inch wide.

VERVIER: If you rely on the germanium detector to give the necessary resolution, you can resolve these lines in the detector itself. The curved crystal is then used only for a first rough separation of the lines.

SMITHER: This system (Cauchois geometry) can be used very nicely to look at a region of the spectrum. In fact, it has been done by White et al.¹ — but not at Argonne. The method then is to use this system to pick out a few hundred keV, if you like, in the low-energy spectrum; and instead of looking at one or two lines, you can use the germanium detector to look at a region of many lines. This is perfectly feasible, but this arrangement will not give the precise energy determination that can be obtained by rotating the crystal in the other arrangement. It will just give you a better signal-to-noise ratio. Because the source is broad, the relationship between the crystal and the source means very little; the only thing that is left is the relationship between the crystal and the slit system.

D.H. WHITE, Lawrence Radiation Laboratory, Livermore:
We have done just this at Livermore, where we have a Cauchois-geometry system with a germanium detector in the focal plane. We have used this technique to study fission gamma rays, which are so numerous that you really cannot do it any other way. In a region from 300 keV up to about 900 keV, we find that by putting a relatively small detector on the focal circle we can take fairly large bites — say 100 keV/bite. We get the positions from the germanium detector, yet the bent crystal offers the advantage of suppressing everything but the photopeaks in the region in which we are looking. In other words, we get around all these problems of pair-escape peaks and Compton edges because each bite we take is only wide enough to pick up the photopeaks.

SMITHER: To get precision you use the accuracy of the germanium diode as calibrated by a pulser, or something like that?

WHITE: Yes, we use a pulser and gamma-ray standards. But it appears to me that you must do virtually the same thing in order to calibrate the germanium detector at high energies.

¹D. H. White, W. John, B. G. Saunders, and D.J. Groves, Bull. Am. Phys. Soc. 11, 30 (1966).

SMITHER: You resolve an individual peak with a germanium diode and record the counting rate in it as a function of the Bragg angle. This gives the Bragg angle of the diffraction and thus the energy of the gamma ray—just as in the low-energy region. Once the bent crystal has been calibrated, the relationship between energy and angle is as good at 5 MeV as it is at 100 keV—so we don't use the precision pulser. It is still an open question whether this will be any better than building up a cascade and defining the 5—8-MeV energy from the sum of two or three low-energy gamma rays; in the final analysis it may not even be as good. All I am bringing out is that our system is capable of a precision of 0.5 keV.

C-3. PRESENT STATUS OF THE DEVELOPMENT OF Ge(Li) SPECTROMETER SYSTEMS AT ARGONNE*

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I. Introduction

Development of the Ge(Li) diode as a detector and energy spectrometer for γ rays has made possible new experiments in low-energy nuclear physics and refinements in existing ones. The most extensive use of the detector is for studies of nuclear structure and decay schemes by means of (n, γ) reactions, where previously Compton spectrometers, crystal-diffraction spectrometers, or scintillation spectrometers were used. Other experiments with higher energy γ rays produced by charged-particle reactions are fruitfully pursued despite the relatively small size and low efficiency above 10 MeV. The detector has been used over the γ -ray energy range from a few keV up to about 20 MeV. The lower limit is set by electronic noise and absorption in dead layers, the high-energy limit by the dimensions of the detector.

The status of the extensive research and development effort concerned with the use of semiconductor diodes for detection and measurement of nuclear radiation was recently reviewed in two of the periodic symposia on new developments in this field. At the 10th Scintillation and Semiconductor Counter Symposium,¹ methods of fabrication of Ge(Li) detectors, limits on their performance with γ rays and protons, and electronic circuit developments pertinent to their use

*Work performed under the auspices of the U.S. Atomic Energy Commission.

¹Tenth Scintillation and Semiconductor Counter Symposium, Washington, D.C., 2-4 March 1966; IEEE Trans. Nucl. Sci. NS-13 (No. 3), 1-590 (1966).

were presented. At the 13th Nuclear Science Symposium,² additional results of work in these areas were presented. These symposia provide a periodic review of the research and development of semiconductor detectors and applications. The need for refinements in germanium and silicon crystals to meet detector requirements and the desire to make use of other materials led to a special meeting on Semiconductor Materials for γ -Ray Detectors.³ Two groups have been organized to deal with the characterization of germanium and silicon for detector applications.^{4,5} Another informal group⁶ is now concerned with improvement of the field-effect transistors that are required for low-noise preamplifiers.

An informal conference, held recently at Gatlinburg,⁷ sought to identify the areas of greatest interest for future work. This was similar to a conference at Asheville seven years earlier,⁸ after

²Thirteenth Nuclear Science Symposium, Boston, Massachusetts, 19—21 October 1966; IEEE Trans. Nucl. Sci. NS-14 (No. 1), 1-685 (1966).

³Semiconductor Materials for γ -Ray Detectors (report of the meeting at Brookhaven National Laboratory, 24 June 1966), edited by W. L. Brown and S. Wagner. Copies of this report may be obtained from W. L. Brown, Bell Telephone Laboratories, Murray Hill, New Jersey 07971.

⁴J. Coleman, National Bureau of Standards, informal committee of semiconductor materials and detector manufacturers.

⁵R. D. Westbrook, Oak Ridge National Laboratory, Chairman of Germanium Task Force, ASTM Subcommittee VI, Committee F-1 on Materials for Electron Devices and Microelectronics.

⁶V. Radeka, Brookhaven National Laboratory, coordinator of informal committee concerned with further development of field-effect transistors.

⁷Semiconductor Detectors and Circuits, Proceedings of an Informal Conference, Gatlinburg, Tennessee, 15—18 May 1967 (National Academy of Sciences—National Research Council, Washington, D.C. 20418), in preparation.

⁸Semiconductor Nuclear Particle Detectors (Proceedings of an Informal Conference at Asheville, North Carolina, 28—30 September 1960), edited by J. W. T. Dabbs and F. J. Walter (National Academy of Sciences—National Research Council, Washington, D.C. 20418), NAS-NRC Publication 871 (1961).

the initial work on germanium surface-barrier counters⁹ had led to the development of silicon surface-barrier and diffused-junction detectors. At that time the lithium-ion-drift process was suggested¹⁰ as a means for obtaining thick silicon detectors. Shortly thereafter, a 1.5-mm thickness was obtained in silicon.¹¹ Detectors with considerably larger volume are now obtainable in both silicon and germanium.¹² The importance of the Ge(Li) spectrometer in nuclear physics research was recognized by the International Atomic Energy Agency.¹³

In the first half of the period between the two conferences at Gatlinburg and Asheville, the emphasis was mainly on applications of silicon detectors to charged particles and low-energy x rays. In the second half it shifted to germanium. The same spectrometer can also be used for protons or other charged particles over an energy interval determined by the window thickness and total thickness of the detector. In recent work, the resolution that can be achieved for protons has been shown to be comparable to that demonstrated earlier for γ rays.

Information relevant to applications of the semiconductor detector to research in nuclear physics,¹⁴ and perhaps to research in

⁹J. Mayer and B. Gossick, Rev. Sci. Instr. 27, 407 (1956); J. W. Mayer, J. Appl. Phys. 30, 1937 (1959).

¹⁰E. M. Pell, in Ref. 8, pp. 136-142.

¹¹J. W. Mayer, in Ref. 8, p. 143.

¹²G. T. Ewan and A. J. Tavendale, Can. J. Phys. 42, 2286 (1964).

¹³Lithium-Drifted Germanium Detectors, Proceedings of a Panel on the Use of Lithium-Drifted Germanium Gamma-Ray Detectors for Research in Nuclear Physics, Vienna, 6-10 June 1966 (International Atomic Energy Agency, Vienna, 1966).

¹⁴H. M. Mann, F. J. Janarek, and H. W. Helenberg, IEEE Trans. Nucl. Sci. NS-13 (No. 3), 336 (1966). Some of the early results on the use of the detectors at Argonne were reported in this publication. R. E. Holland and F. J. Lynch called attention to the study of the decay $K^{43} \rightarrow Ca^{43} + \beta$, in which the observed line width was less than expected from reported values of F at that time. See also R. E. Holland, F. J. Lynch, and H. M. Mann, Bull. Am. Phys. Soc. 10, 119 (1965).

space¹⁵ and medicine,¹⁶ has been summarized in recent review articles. More extensive descriptions of detector mechanisms, fabrication, electronic circuits, and applications are available in texts devoted to this subject.^{17,18}

The primary advantage of the detector is its energy-resolving capability, which has been given strong emphasis in the development of the detector and associated electronic apparatus at Argonne. Detector development and improvements in electronic design are closely coupled. Early studies and use of the Ge(Li) spectrometer revealed the need for refinements in electronic apparatus used with the detector. Detector studies included determination of the limit of energy

¹⁵H. M. Mann, IEEE Trans. Nucl. Sci. NS-14 (No. 6), 10 (1967). More detailed reviews of performance and applications have become available. See, for example, David C. Camp, Applications and Optimization of the Lithium-Drifted Germanium Detector System (University of California, Lawrence Radiation Laboratory, Livermore, 1967), Report No. UCRL-50156; E. M. Gunnersen, in Rep. Progr. Phys. 30, Part 1, p. 27 (1967).

¹⁶An array of Ge(Li) detectors for use in a medical application has been designed and detectors for it are under construction at Los Alamos Scientific Laboratory [W. H. Briscoe, private communication].

¹⁷G. Dearnaley and D. C. Northrop, Semiconductor Counters for Nuclear Radiations (E. and F. Spon, Ltd., London, 1966), 2nd ed.

¹⁸Among the texts and review articles see, for example, R. Heinrich and C. E. Crouthamel, "Recent Advances in Counting Techniques," in Analytical Chemistry, Vol. 2, pp. 1-79 (1961), Series IX of Progress in Nuclear Energy (Pergamon Press, London); W. Cz Julius, H. D. Engler, and H. Kuckuck, "Halbleiter-Sperrschichtzähler," in Ergeb. Exakt. Naturw. 34, 235 (1962); Neils J. Hansen, "Solid State Charged Particle Detectors," in Analytical Chemistry, Vol. 4, part 1, pp. 1-72 (1964), Series IX of Progress in Nuclear Energy (Pergamon Press, London).

resolution in the detector¹⁹ and of the time spread of detector pulses.²⁰ Specific projects led to development of low-noise preamplifiers,²¹ a biased amplifier,²² and a stable pulser.²³ Further refinements are under way.

Substantial effort has been expended on the preparation of detectors with the largest possible volume. In the work at this Laboratory, only planar detectors have been prepared for use in experiments. These have ranged in volume up to 20 cm^3 . Larger volumes (up to $\sim 50 \text{ cm}^3$) have been achieved elsewhere⁵ in Ge(Li) detectors of nonplanar shape, and volumes up to 30 cm^3 are available commercially. The nonplanar shape, however, remains less attractive because of its larger nonuniformity in collection of charge and the consequent spread in arrival times. Therefore, we have aimed toward achievement of the largest possible thickness of compensation by use of lithium-ion-drift methods, operation at high detector voltage, and conversion of coaxially-drifted (or radially-drifted) diode structures to planar form after they are compensated. The users of these planar detectors have found that improved resolution at a sacrifice in size is generally advantageous.

¹⁹H. M. Mann, H. R. Bilger, and I. S. Sherman, IEEE Trans. Nucl. Sci. NS-13 (No. 3), 252 (1966); H. R. Bilger, Phys. Rev. 163, 238 (1967).

²⁰M. G. Strauss, R. N. Larsen, and L. L. Sifter, IEEE Trans. Nucl. Sci. NS-13 (No. 3), 265 (1966).

²¹I. S. Sherman, "A Versatile Preamplifier for Semiconductor Detectors Providing High Resolution Capability at High and Low Counting Rates," Ref. 7.

²²R. G. Roddick, "A Highly Stable Biased Amplifier and Stretcher System," Ref. 7.

²³M. G. Strauss, L. L. Sifter, F. R. Lenkszus, and R. Brenner, "Ultra Stable Reference Pulser for High Resolution Spectrometers," 11th Scintillation and Semiconductor Counter Symposium, Washington, D.C., 28 February—1 March 1968, to be published in IEEE Trans. Nucl. Sci.

II. The Ge(Li) Detector

The symbolic (and cryptic) designation Ge(Li) is used in reference to the introduction of lithium donor atoms into a selected germanium crystal which contains acceptor atoms introduced during crystal growth. If the concentration N_D of the donor impurity is made precisely equal to the concentration N_A of the acceptor impurity, then $N_D - N_A = 0$ and the crystal is said to be intrinsic. In practice, a sufficiently close approximation to the intrinsic condition is achieved when $|N_D - N_A| \ll 10^{13}/\text{cm}^3$ at or near room temperature. The physical properties of intrinsic semiconductor crystals are not yet well understood, and it is not yet possible to obtain monocrystalline germanium with an impurity content substantially less than $1-3 \times 10^{11}/\text{cm}^3$ in reproducible fashion. Crystals described as "essentially monocrystalline" and having an impurity content of $1-3 \times 10^{11}$ atoms/ cm^3 (believed to be boron) are commercially available. However, these are found not to be monocrystalline throughout. Instead, they are composed of smaller monocrystals and would require further refinement. Because of the limitations of present technology, such refinement leads to introduction of other impurities. For present use in nuclear physics experiments, it has been necessary to start with crystals containing an acceptor concentration $N_A \approx 10^{13} - 10^{14}/\text{cm}^3$ and thereby effectively mask the effects of other undesired impurities which are not removed in present refinement processes. The method of compensation by use of Li has proved to be successful primarily because the difficult-to-remove impurity (principally boron) is a valence impurity whose ionization energy is comparable to that of lithium. In effect, the crystal behaves as if it were intrinsic; at 77°K the intrinsic carrier concentration is estimated to be $\sim 10^{-4}/\text{cm}^3$. A wide range in impurity content remains to be explored, and it is necessary to confirm that the compensated region of existing detectors is intrinsic.

Aside from the practical limitations in preparation and possible departures from complete compensation, we can refer to the sensitive region of the detector as the i region or intrinsic region. Departures of significance are presently represented in terms of departures from expected relations for the voltage dependence of the current I and capacitance C .

Another symbolic designation, namely p-i-n, is used in reference to the electrical structure (i. e. , impurity distribution) in the diode or detector. The physical model of the device, when properly constructed, is in essence a crystal in which there is no net charge on which electric field lines will terminate. In practice it is necessary to form electrical contacts, and at least one of these must be rectifying.

Other symbols may be utilized in connection with alternative methods of compensation and as other techniques for making contacts are developed. Also, if crystals can be suitably refined, then preparation by use of compensation methods will not be necessary.

A. Simple Physical Description of the Detector

Although many steps are involved in the preparation of the Ge(Li) detector, conceptually it is quite easy to construct the device from a crystal of intrinsic germanium. The construction of a diode requires the addition of a rectifying contact or impurity junction to one side of the crystal and an ohmic contact to the other. This diode structure is illustrated in Fig. 69(a) before addition of the contacts; in Fig. 69(b), the contacts are in place. The symbols n^+ , i, and o are used to denote the rectifying contact, intrinsic region, and ohmic contact, respectively. This basic diode or detector structure can serve as a model for illustration of its use or as a guide in the work of preparation.

A question that may arise at this point in the discussion is in regard to the nature of the o contact shown in Fig. 69.

Usually ohmic contacts are difficult to form on an intrinsic crystal and it may be desirable to designate this as a p^+ contact. The symbols n^+ and p^+ refer to the electrical nature of donor and acceptor impurities that are used to form the contacts. The $+$ superscript on n denotes a high concentration of n -type (donor) impurity in the crystal, and similarly for the $+$ superscript on p . If the n^+ contact is a highly rectifying one, such as is produced by diffusing lithium atoms into intrinsic germanium, then it may not be necessary to have the other contact highly doped with acceptors—whether it is necessary or not depends upon the size and symmetry of the crystal. Whether a given crystal is $n^+ - i - o$, $n^+ - i - p$, or $n^+ - i - p^+$ can be decided only by measuring the electric potential in the crystal, as determined by the impurities. The detectors now in use are closer to the $n^+ - i - o$ and $n^+ - i - p$ types.

Fig. 69. Intrinsic monocrystal of germanium (a) before and (b) after addition of contacts to form the diode structure which is to be used as a detector. The dashed lines in (b) mark the boundaries between the contact regions and the region in which the crystal structure remains unaltered.

When the concentration of an impurity in the crystal is altered, the free-electron concentration changes. This causes the mean potential of an electron to shift from the value corresponding to the energy E_F in the energy diagram (Fig. 70) to a higher (i. e., n -type or donor impurity) or lower (i. e., p -type or acceptor impurity) value. In the complete absence of impurities, the mean energy of a free electron is equal to the Fermi energy E_F of the electron distribution.

Fig. 70. Simplest representation of the energy gap in a semiconductor crystal. The energies E_V and E_C are the values for an electron in the valence band and at the lower boundary of the conduction band, respectively, and e is the electron charge. In the absence of donors and acceptors, or for the condition of compensation, the mean energy of the electron is the Fermi energy E_F . The values of the potential $V = E/e$ corresponding to these energies are also shown.

For such an electron in intrinsic Ge the electric potential V_i , measured from the valence band, is

$$V_i = \frac{E_F - E_V}{q},$$

where q is the electron charge.

The temperature at which Ge(Li) detectors are operated is close to 77°K, and sometimes the use of further reduced temperatures may provide improved operation. At 77°K the free-electron concentration in intrinsic germanium is 10^{-4} per cm^3 or less. For intrinsic crystals that have been prepared by Li^+ -ion drift through Ge, the total concentration of neutralized impurities is of the order $10^{14}/\text{cm}^3$. Compensation with Li^+ at this concentration is effective in masking the effects of undesired impurities at the concentrations of $10^{12}/\text{cm}^3$ present in most crystals now in use. Since it is found possible to introduce $10^{17}/\text{cm}^3$ or higher concentrations of valence impurities (i.e., either donors or acceptors) into germanium and have them retain their role as electrical impurities to low values of temperature, it is quite easy (in concept) to adjust the free-electron potential in the crystal from V_i to

$$V_n \approx \frac{E_C - E_V}{q}$$

in the case of a donor impurity. In practice, it is necessary to use a donor that has an ionization energy close to E_C —as is the case for Li.

Fig. 71. Idealized $n^+ - i - p^+$ structure illustrated in terms of the potential V determined by the impurity content in each region. The regions are the intrinsic material (i) and the highly-doped donor (n^+) and acceptor (p^+) material forming the electrical contacts to it.

Similarly, the free-electron potential in an acceptor-doped region may be adjusted from V_i to

$$V_p \approx \frac{E_F - E_V}{q}.$$

For the $n^+ - i - p^+$ structure shown in Fig. 71, the potential (arbitrarily set equal to zero on the p^+ surface) will be approximately $\frac{1}{2}(V_C - V_V)$ in the intrinsic region and approximately $V_C - V_V$ in the n^+ region.

If there were an o region instead of a p region at the right in Fig. 71, then (since an ohmic contact would not cause a change in potential) there would be only one potential step within the thickness of the crystal instead of the two steps shown. However, the studies of electrical contacts suggest that ohmic behavior at a contact is a quite idealized concept that is extremely difficult to realize in practice. It will be sufficient, in practice, to maintain the potential of the p^+ or o layer anywhere below that in the i region. Studies of collection limitations should resolve any possible need for p^+ instead of o. Detailed examinations of useful detectors must be carried out to avoid or eliminate other problems, such as charge injection, that may be caused by some contacts and not by others.

For the diode structure represented in Fig. 71, when the applied potential makes the n^+ surface positive relative to the p^+ surface, a redistribution of free charge will occur. Figure 72 illustrates how the electric field $\mathcal{E}$ is caused to increase in the i region. Free electrons from the n^+ region will be transferred to the p^+ region.

Fig. 72. An $n^+ - i - p^+$ diode structure with an applied potential V_A after transfer of electrons from the n^+ layer to the p^+ layer. For a true p^+ layer a similar transfer of holes occurs in the opposite direction.

The transfer may be less effective for an o region than for a p , but in either case (provided also that there is no net charge in the i region) the electric field intensity in the i region will increase from approximately $\frac{1}{2} (V_C - V_V)/x$ to a much higher value determined by the conditions of leakage at the periphery. Present Ge(Li) detectors are sufficiently thick that ordinary dielectric breakdown will not occur within the crystal, and fields of from 30 to 200 V/mm are generally used.

There are two relatively simple but extremely important properties of such a diode to consider both in preparation and in use. These properties are current I and capacitance C . In the ideal case of noninjection, I will be determined by charge-generation and charge-recombination processes in the i region and will saturate at a voltage sufficient to avoid recombination. If some holes are injected from the n^+ region and electrons from the p^+ region, there will be some departure from charge-generation current as the voltage is increased. In Fig. 73(a) the current behavior of some diodes used in experiments is represented. Note that the reverse current is given as proportional to volume, whereas the forward current is given in terms of the area of the diode.

As shown in Fig. 73(b), a finite external voltage must be applied to the diode to establish the condition of collection throughout the intrinsic region. We find that the capacitance at zero voltage is usually 2—5 times that at higher voltage. Some departure from the expected capacitance may be caused by contamination or by departure from the intrinsic condition or both.

Fig. 73. Voltage dependence of the current and capacitance of a Ge(Li) diode of the type used as a γ -ray spectrometer. (a) Current-voltage characteristic. The apparent discontinuity at the origin is an artifact arising from the abrupt change in scale (pA for backward currents, mA for forward). (b) Capacitance-voltage characteristic as observed for planar Ge(Li) diodes 1 cm thick. When $V = 0$, the junction potential is not high enough to withdraw thermally-generated charges from the interior.

The thickness x of the detector is limited by the carrier mobility; if x is too large, the time τ to collect the charge in the detector becomes larger than the limiting time that would be acceptable in present pulse amplifiers. Since this limiting time (and therefore τ) is about 300 nsec and the velocity v_L of the carriers is about 10^7 cm/sec, this limiting thickness is

$$x = v_L \tau = (10^7 \text{ cm/sec}) (3 \times 10^{-7} \text{ sec}) = 3 \text{ cm}.$$

The resolving time of a detector can be expected to be comparable to τ . Thus, thick detectors should not be relied upon for measurements that require the closest uniformity in the length of pulses.

The above considerations serve as an adequate and simple picture of the operation of the diode as a detector. To produce a pulse, we need only introduce an ionizing event such as would be produced by a γ ray. This is shown in Fig. 74. As a consequence of interactions in the crystal, the radiation releases a quantity of charge

$$Q = E_i / \epsilon,$$

where E_i represents the energy deposited within the intrinsic region and ϵ is the mean energy per electron-hole pair. For different

Fig. 74. Interaction of an incoming γ ray to produce an energetic electron which, in turn, loses its energy in releasing electron-hole pairs in the detector. The fluctuation ΔN_{RMS} in the number of charges released is determined from the mean energy ϵ required per ion pair produced and the total energy E so deposited.

semiconductors it has been found that $\epsilon \approx 3 E_g$, where E_g is the energy gap ($E_g = 0.78$ in Ge).

B. Preparation of the Detector

There are three major steps in the preparation of the lithium-compensated germanium detectors. First, lithium is deposited onto the crystal. The second step, which may be combined with the first, is to diffuse lithium into the crystal to form an n-p junction with sufficient lithium to maintain the junction and compensate the crystal volume. Third, lithium ions are caused to drift into the p-type volume from the n-type lithium-diffused layer. Considerable attention has been given to development of this device in several geometrical configurations, and a wide variety of techniques exist for carrying out the preparation.

Each of the above major steps consists of a large number of individual ones, each of which must be carefully controlled and evaluated to achieve success and ensure reliability. The selection of the material requires close examination of the material and measurements of its electrical and diode properties since the conditions used in preparation of the detector must sometimes be adjusted in accordance with the observed behavior of the material or diode. This will become clear in the following detailed description of preparation.

1. Selection of the crystal. —The general requirements for any semiconductor to be useful in this application are well understood. There must be complete collection of both positive and negative charge carriers that are produced by an ionizing event, and the time for collection must be small compared with the integration time of the apparatus used to record each event. The simplest representation of an ionizing event is the separation of an electron-hole pair under the influence of the electric field of intensity $\mathcal{E}$, as shown schematically in Fig. 75. Under the influence of $\mathcal{E}$, each carrier is accelerated to a limiting velocity v_e (or v_h) determined by the crystal. It then spends most of the time-in-transit at this velocity. If a trapping center is encountered, the carrier will be slowed down. The material can be evaluated in terms of dimensions related to the trapping and recombination of carriers.

Fig. 75. Basic charge-collection process.

Others have studied the trapping of charge released in various semiconductor crystals. The effects are commonly interpreted in terms of the mean drift length

$$\lambda_e = v_e \tau_e^* \quad \text{or} \quad \lambda_h = v_h \tau_h^*, \quad (1)$$

where τ^* is the mean time between traps and the subscripts e and h refer to electrons and holes, respectively. As a first approximation we can assume, as shown by Day et al.,²⁴ that the fraction $\Delta Q/Q$ of trapped charge is equal to the ratio of detector thickness x to mean trapping length λ . Thus

²⁴R. B. Day, G. Dearnaley, and J. M. Palms, IEEE Trans. Nucl. Sci. NS-14 (No. 1), 487 (1967).

$$\frac{\Delta Q}{Q} = \frac{x}{\lambda}. \quad (2)$$

If we then require that not more than 0.1% of the total charge be lost as a result of trapping, then $\lambda \geq 10^3 x$.

For a potential $V = 10^3$ volts applied to a crystal 1 cm thick, the requirement that $\lambda \geq 10^3 x$ means that the product of mobility μ and lifetime τ should be approximately unity for both electrons and holes, i. e. ,

$$\mu_e \tau_e^* \approx \mu_h \tau_h^* \approx 1. \quad (3)$$

This is satisfied in silicon and germanium when $\tau_e^* \approx \tau_h^* \approx 10^2 - 10^3$ sec, depending upon temperature.

Of more than 40 known semiconductors, only a few satisfy the requirement that the mean trapping length $\lambda = v\tau^*$ be large in comparison with the useful thickness for detection. Some materials that have been considered²⁵ are shown in Table X. All of the Group IV

TABLE X. Properties of selected semiconductors.

Group	Material	Energy gap E_g at 300°K (eV)	Energy ϵ per e-h pair (eV)	Atomic number Z	Typical values for $\mu_e \tau_e$ and $\mu_h \tau_h$
IV	C	5.4	15.5 — 16.7	6	0.1 — 1.0
	Si	1.09	3.61 ± 0.01	14	
	Ge	0.66	2.98 ± 0.01	32	
	α -Sn	0.08	0.60	50	
III-V	GaAs	1.52	0.60	31, 33	
	InSb	0.17		49, 51	
	AlSb	1.60		13, 51	
II-VI	CdTe	1.44	4.65 ± 0.2	48, 52	$10^{-5} - 10^{-6}$
	CdS	2.4	7.3	48, 16	

²⁵ E. M. Gunnensen, Rep. Progr. Phys. 30, part 1, p. 27 (1967). In this review is a similar tabulation that includes additional semiconductors.

semiconductors are listed so as to illustrate that the empirical approximation

$$\epsilon = 3 E_g \quad (4)$$

between the energy gap E_g and the energy ϵ per e-h pair produced is useful for them and also for III-V and II-VI compounds. This covers a wide range in energy gap and atomic number, as well as composition. In silicon and germanium the values for $\mu\tau^*$ are about 6 orders of magnitude higher than has been found for other semiconductors.²⁶

CdTe has been extensively investigated as a γ -ray detector,²⁷ but size limitations presently prevent its use for γ -ray spectrometry. The trapping time for holes is of the order of 10^{-7} sec, and dimensions limit the useful volume to 30 mm^3 . The mean drift lengths λ_e and λ_h for electrons and holes, respectively, in a crystal of thickness $x = 1.2$ mm were found to be

$$\begin{aligned} \lambda_e &= 0.8 x, \\ \lambda_h &= 0.2 x. \end{aligned} \quad (5)$$

InSb has been studied²⁸ but trapping was found to be serious at the low temperature ($4\text{--}24^\circ\text{K}$) required for its use. Investigation of AlSb revealed serious problems associated with

²⁶ Summaries of the properties of compound semiconductors are given by R. K. Willardson and H. L. Goering, Compound Semiconductors (Reinhold Publishing Corp., New York, 1962); M. R. Lorenz, in Physics and Chemistry of II—VI Compounds, edited by M. Aven and J. S. Prener (North-Holland Publishing Co., Amsterdam, 1967).

²⁷ J. W. Mayer, in Semiconductor Detectors, edited by G. Bertolini and A. Coche (North-Holland Publishing Co., Amsterdam, in press). In the chapter entitled "Search for Semiconductor Materials for Gamma-Ray Spectroscopy," Mayer points out that any new material considered for spectroscopy should provide 1-keV resolution; for use in medical, reactor, or industrial applications (where new materials might first be used), a 50—100-keV resolution width might be acceptable.

²⁸ This remains the most promising compound semiconductor for nuclear spectrometry (J. W. Mayer, Ref. 27), but it could be used only at temperatures close to that of liquid helium.

trapping.²⁹ Te, with $E_g = 0.4$ eV and $Z = 52$, has also been considered.³⁰

The temperature required for operation depends on the band gap and would be estimated from the temperature dependence of the intrinsic carrier concentration³¹ in each semiconductor. If the band gap is 0.17 eV (as in InSb), then the temperature of operation should be close to 20–25°K. For a band gap of 0.02 eV, this temperature should be about 2°K. If there were complete absence of trapping in the material, it would be of interest to use the semiconductor that has the lowest band gap and the highest atomic number. If, for example, conditions similar to those in germanium could be obtained for some other material with a band gap of ~ 0.1 eV, then under proper conditions of temperature and electric field intensity the energy resolution could be improved by a factor of 3.

Germanium is the only semiconductor presently useful for γ -ray spectrometry at energies greater than 1 MeV. The lithium-drift method provides a means for achieving close to exact compensation as judged from our observations of current and capacitance. This is achieved even though the drift compensation is carried out at a temperature roughly 225°K higher than that at which the detector is used.

Other methods under consideration for achieving the same result insofar as the detector is concerned, but with the possible additional advantage of stability at room temperature, are purification³² to a donor

²⁹N. G. Blamires and P. E. Gibbons, United Kingdom Atomic Energy Research Establishment, Harwell, Report No. AERE-PR/EL (1966).

³⁰The use of tellurium in γ -ray spectrometry has been considered by J. S. Blakemore, Florida Atlantic University. See also J. W. Mayer, Ref. 27.

³¹W. Shockley, Electrons and Holes in Semiconductors (D. Van Nostrand Co., Inc., Princeton, N. J., 1950), p. 245.

³²R. N. Hall, in Ref. 3, p. 27.

and acceptor concentration less than $10^9/\text{cm}^3$, and compensation of n-type samples by means of γ irradiation.³³ The highest purity that has so far been achieved in germanium is approximately $3 \times 10^9/\text{cm}^3$ at 77°K .³² This sample is represented in Fig. 76, which shows the Hall coefficient as a function of temperature. These measurements show the presence of impurities with ionization energies close to the center of the band gap. In Fig. 77 a similar set of measurements for a sample of n-type germanium is shown. In this sample, the flatness of the curve at low temperature indicates most of the impurity content is low in ionization energy (i. e., so-called shallow impurity levels close to the conduction band). We would expect a p-type sample containing $\sim 10^{14}$ acceptor impurities per cm^3 and not more than $\sim 10^{12}/\text{cm}^3$ donors to be quite useful in preparing Ge(Li) detectors. The true composition of the samples we have used remains to be determined.

The disadvantage of a bombardment method is that trapping centers are usually formed. In the work that has been carried out (see O. A. Matveev in Ref. 13, p. 32), the germanium crystal was first encapsulated with an n^+ (i. e., lithium-diffused) contact on one side and a p-type region produced by bombardment with heavy particles on the other. An integrated flux of 10^7 gammas/ cm^2 was found to produce

Fig. 76. Plot of the Hall coefficient for use in determining the impurity content of a high-purity p-type germanium crystal. [From F. Aurich, H. P. Kleinknecht, A. Renz, K. Schuegraf, and K. Seiler, *Ann. Physik* 11, 83 (1963)].

³³ O. A. Matveev, in Ref. 13, p. 32.

Fig. 77. Plot of the Hall coefficient for use in determining the impurity content of an n-type germanium crystal with predominantly valence impurities. [From R. N. Hall, Ref. 3, p. 32.]

as the lower limit of resistivity for this material. The lifetime τ of carriers should be as close as possible to 10^3 sec. As shown in theoretical studies of the effects of resistivity variations in crystals compensated by ion-drift,³⁵ the gradient of resistivity in the direction of drift should be as low as possible; i.e., less than 10 or 20% per cm can be obtained and seems adequate. As yet, there is no known correlation between detector characteristics and etch-pit density.

³⁴M. B. Prince, Phys. Rev. 92, 681 (1953); 93, 1204 (1954).

³⁵P. E. Gibbons and P. Iredale, United Kingdom Atomic Energy Research Establishment, Harwell, Report No. AERE-R5339 (1957).

a thickness of 2.5 mm. From measurements of capacitance, the net impurity concentration $|N_D - N_A|$ was found to be in the range $10^6 - 10^8/\text{cm}^3$. The resolution width was observed to be 2.7, 3.8, and 4.5 keV for γ rays at energies of 122, 662, and 1333 keV, respectively. At room temperature there was no observable deterioration, and at 77°K the performance was stable for 6 months.

Drift mobility

measurements³⁴ for holes in germanium show a reduction of mobility as the concentration of ionized impurities is increased above $2 \times 10^{14}/\text{cm}^3$. We can therefore set $N_A = 2.5 \times 10^{14}/\text{cm}^3$, corresponding to $\rho = 6.5 \Omega \text{ cm}$,

However, the difficulties encountered in the use of some germanium crystals have led several manufacturers to determine lithium-drift rate in selected samples, usually the end-pieces, from each crystal. The possible presence of oxygen in some crystals that were found to exhibit a retarded rate of drift of Li^+ ions led to consideration of methods for obtaining oxygen-free germanium.³⁶

The shape and area of the cross section of germanium crystals grown for use in lithium-drift preparation of the detector is illustrated in Fig. 78. The areas for the three sizes shown are 5, 12, and 22 cm^2 and the weights per length are 25, 60, and 120 g/cm, respectively. These crystals are grown by means of a horizontal, zone-leveling process. End pieces from each crystal are tested by the manufacturer to determine the (1) resistivity, (2) etch-pit density, (3) lifetime of the minority carrier, and (4) mobility of the lithium ion. An approximate price for these three sizes of crystal (in order of increasing size) is \$1.00, \$2.50, and \$4.50/g, respectively, for crystals that appear to be the most suitable for this application.

The loss of material in preparing a planar detector from such

Fig. 78. Cross sections of commercial, horizontally-grown monocrystals of germanium. The circles show the approximate areas expected if a cylindrical detector is prepared from the crystal. Vertically-grown crystals (not shown) of uniform and larger diameter have been successfully used.

³⁶ W. D. Edwards and C. Wilburn, Nucl. Instr. Methods 48, 357 (1967).

crystals has varied widely but has sometimes not exceeded 0.5 mm from each face. If, however, a cylindrical shape is required, then the losses are a substantial fraction of the original crystal. The approximate diameter of the cylindrical detector that can presently be prepared from these crystals is indicated in the drawing to be about 17, 24, and 29 mm, respectively.

From the consideration of shape, vertically-pulled crystals of uniform diameter are preferred. Those that are presently available and tested range in diameter up to 4—5 cm and the approximate price range is \$2.00—\$5.00/g when the diameter is larger than 25 mm and approximately \$1.00/g for a diameter of about 2 cm.

Some of the crystals from which detectors have been prepared are listed in Table XI, together with values for resistivity, etch-pit density, and minority-carrier lifetime that were determined by the manufacturer and used as a guide in our selection. Until the preparation of the crystal is complete, we still cannot tell whether it will provide a detector that meets the specifications for energy resolution, efficiency, and electric-field intensity. Moreover, at the present time, we find it difficult to be sure which effects may be caused

TABLE XI. Some germanium crystals used in preparation of Ge(Li) detectors.

Our crystal No.	Manufacturer reference ^a	Dopant	Resistivity (Ω -cm)	Lifetime of minority carrier (μ sec)	No. of etch pits per cm ²
31	(S-6); 361-C	In	1.12—1.45	30	800—900
38	(S-6); 327-2	In	5.2 — 6.8	50	2800—3500
39	(S-4); 420H-4	In	9.8 —11.0	120	2200—2400
44	(S-4); 449G-7	Ga	9.2 —10.0	115	800—1700
49	(H20-30); 2467A	In	25 $\pm$ 20%	> 500	0—200
50	(H20-30); 2468A	In	24 $\pm$ 10%	$\geq$ 500	0—200
75	(H25-30); V2679	In	20.5 —30	370—500	800—1400
81	(H30-35); V2573/B	In	8.2 — 9.0	400—430	700—2200
93	(H-5 cm ²); 6841/A	Ga	13.5 —16	430—460	700—1100
99	(H31-38); V3214	Ga	9.3 —15.5	400—430	3000—4200

^aIn the parentheses, S-6 = Sylvania Electronic Products Company No. 6 ingot, H20-30 = Hoboken vertically-pulled crystal of diameter 20—30 mm, obtained from Nucleonic Products Company, Inc. H-5 cm² denotes a horizontally-grown crystal of area 5 cm²

in preparation and which arise from defects initially present in the crystal. Our selection of the crystal is therefore based in part upon the uniformity and properties of the crystals that are available.

Although the resistivity of the crystals listed ranges from 1 to 35 Ω cm, a lower limit $\rho \geq 6.5 \Omega$ cm should be set for most applications of Ge(Li) detectors as stated earlier. This lower limit corresponds to the concentration of valence impurities above which an observable reduction of carrier mobility was found. An upper limit of resistivity for use of lithium-ion drift methods is governed by the maximum drift temperature that is used. The drift temperature must be adjusted to avoid a significant thermal (i. e. , intrinsic) carrier concentration in the diode during drift, for this will lower the drift field. We find 35 Ω cm to be the maximum value of resistivity for use at a drift temperature of 25°C. At this temperature the thermal carrier concentration in such a crystal is about 10% of the acceptor concentration.

We have used both zone-leveled and vertically pulled (i. e. , Czochralski) crystals with either indium or gallium as the acceptor impurity. Comparable results have been obtained for crystals containing indium or gallium irrespective of the growing method.

Photographs of some samples are shown in Fig. 79. The relatively long crystal (~20 in.) was manufactured by the Societe General des Minerais, Metallurgie Hoboken, Belgium and was purchased through Nucleonic Products Co. , Inc. The three samples at the upper left were freshly cut from other crystals from the same manufacturer. The fourth small sample (rectangular) is from a crystal grown by the Sylvania Electronic Products Co. Not all crystals have shapes well suited to this application, so it is sometimes necessary to remove material in order to achieve a cylindrical form.

Fig. 79. Samples from vertically pulled and zone-leveled germanium crystals. The weight of the long crystal is 2948 g.

2. Preparation of the sample for diffusion. —The sample is initially cut 2 mm longer than the desired thickness of the detector. An equal excess is allowed on the periphery for possible losses in preparation. If the detector dimensions are not critical some of this excess may be left on the sample after preparation is completed, provided only that it was not necessary to remove it during preparation. If dimensions are critical, any excess is easily removed later by lapping.

A precision wafering machine with a diamond-impregnated cutting wheel is used in routine work. The diamond grit size is usually $120\ \mu$ and the speed of rotation is 5000—5500 rpm. For small-scale cutting, an abrasive-wire cutting machine is used, together with 1—5- μ Al_2O_3 abrasive powder. After cutting, the crystal is first cleaned in trichlorethylene to remove wax used as a cement to secure the crystal during cutting. Then, a thickness of 150—200 μ is lapped from each cut surface. Successively finer abrasives, down to 12.5 μ , are used in lapping.

The crystal is then cleaned in trichlorethylene to remove all traces of oil and wax from the machine lapping. All subsequent lapping is done by use of the 12.5- μ abrasive powder and a flat glass plate. The glass plate is discarded after approximately ten lapping operations.

Resistivity measurements are then made on both faces of the sample and its periphery by means of a 4-point probe. At least five measurements are made on each face and four on the periphery, but for most samples the minimum number stated is a satisfactory record for future reference, as well as to note any significant departure from the manufacturer's specifications. Upon completion of the resistivity measurements, all surfaces receive a final lapping with the 12.5- μ abrasive.

An electrical contact to the p-type surface of the diode is desired during drift and for operation of the detector. This contact is usually applied, by either electrolytic or electroless techniques, during the preparation of the sample for diffusion. Alternatively, it may be applied later. Application prior to diffusion may enhance the integrity of the contact, and has the added advantage of minimizing the handling between diffusion and observation of the initial drift behavior.

In previous work we have used gold contacts. More recently we have adapted electrolytic plating methods to the preparation of the contact, and we use either indium or gold. Indium has the obvious advantage of being a substitutional acceptor impurity in germanium and its possible superiority to gold is being tested. Details of the electrolytic plating procedure must be further delineated before they are published. A detailed description of the electroless gold plating procedure is given in Appendix B.

After plating, the metal contact is first covered with acid-resistant tape. Undesired metal is then removed by chemical means. The periphery and one face are again lapped as before and then etched for 30—90 sec in the chemical polishing solution CP4.

3. Deposition and diffusion of lithium. —Lithium is deposited on the sample by use of any one of three different methods: (a) brush application of fine-grained lithium dispersed in mineral oil,

(b) vacuum evaporation, or (c) electrolytic plating. The dispersion is applied with the sample at room temperature. Evaporation is carried out by use of a tantalum or molybdenum boat with the sample either at room temperature or elevated to 180°C since at the melting point of lithium the adherence and uniformity in thickness appear to be more easily controlled. The temperature for deposition by electrolytic means has a lower limit determined by the salt, and is usually the same as the diffusion temperature. Other methods, such as decomposition of an oxygen-free compound of lithium, might prove to be useful and have been considered in our work.

The diffusion is carried out either in vacuo or in an argon atmosphere. In some work, the sample with an evaporated layer on it is transferred to a tube furnace for diffusion. If desired, diffusion can be carried out in the evaporator, but care must be taken to protect the periphery against lithium vapor when a planar diode is constructed. For this purpose a coating of colloidal graphite (i. e. , aquadag or alkadag) is used. A diffusion temperature in the range $350\text{--}400^{\circ}\text{C}$ is used for a time sufficient to give a diffusion depth of 0.4 ± 0.1 mm.

The furnace used for diffusion in an argon atmosphere is shown in Fig. 80. The apparatus employed for diffusion in vacuo is identical to that employed earlier for preparation of Si(Li) detectors.

4. Drift apparatus and procedure. —After diffusion, the sample is cooled in 15—30 min. A longer time is sometimes used for large (i. e. , $>20\text{ cm}^3$) samples in order to avoid thermal stress. When cooled the sample is cleaned by immersion and ultrasonic agitation first in ethyl alcohol and then in deionized water. The periphery is then lapped, etched in CP4 by use of our standard cleaning procedure, and then installed in the drift apparatus (Fig. 81) so that reverse bias can be applied to drift the lithium ions.

In most present Li-drift processing, the diode is examined at one or more intermediate stages of drift. From a chart of the drift

Fig. 80. Furnace for the diffusion of lithium into samples of germanium. Either argon gas (1 atm, 1.5 liter/min) or a vacuum (10^{-5} — 10^{-6} Torr) may be used. For evacuation, additional apparatus (not shown) including a mechanical and oil-diffusion pumping system is used.

Fig. 81. Apparatus for drifting lithium through samples of germanium. The lower block may be cooled by means of tap water to as low as 15°C . A heater is sometimes used on top of the sample. For dual drifting, the heater (upper block) and the lower block are held at the same temperature. Refined apparatus consisting of a thermoelectric cooler, and other apparatus for measurement of capacitance during drift, are in use but are not shown in the figure.

distance x for Li^{+} (Fig. 82), where the quantity Vt is used as a variable and V is assumed constant, a thickness of 6.2 mm will be expected at 40°C for $Vt = 10^5$ volt-hours.

Since it is usually possible to maintain $V = 500$ V or higher, such a thickness can be obtained within 200 h (~ 9 days). It is usually practical to limit the drift-processing time to 3 months,

Fig. 82. Drift distance $x = \sqrt{2\mu Vt}$ in germanium as a function of Vt , where V = diode potential in volts, t = time, and μ = mobility of lithium ions.

corresponding to 10^6 volt-hours for a drift potential of 500 V. During drift the temperature must be adjusted progressively lower than the temperature at which the starting material would exhibit intrinsic conductivity. Although the quantitative aspects of the selection of drift temperature for a given crystal are quite involved, it sometimes is desirable to reduce the temperature to 20°C throughout drift, if the initial resistivity is about $15\ \Omega\ \text{cm}$. For the wide range of resistivity values that are now used (i. e., $6.5\text{--}45\ \Omega\ \text{cm}$ at room temperature), Fig. 82 shows that the practical upper limit of drift distance should range from 20 to 40 mm.

The largest distance of drift in one direction that has been achieved in our work is 16 mm, and this seems to be the largest value achieved anywhere up to the present. We expect, however, to be able to obtain a larger distance as refinements in materials and methods are continued.

In the ion-drift process, lithium ions Li^+ are transferred from the region of high concentration in the lithium-diffused region to the p-type material across the intrinsic (i) region as indicated in Fig. 83.

Fig. 83. Illustration of p-i-n diode structure during drift of lithium ions.

Fig. 84. Schematic illustration of the impurity concentration for lithium ions that are caused to drift into a crystal containing 6×10^{13} acceptors per cm^3 . The distance x represents the compensated thickness.

If the drift proceeds uniformly through material with small fluctuations in acceptor concentration, then the impurity profile during drift will resemble that shown in Fig. 84. Although indium is shown, gallium atoms may have also been used.

During drift it is important to preserve the diode characteristics and to confirm that the drift is proceeding satisfactorily. Confirmation is obtained either by use of a copper stain to delineate the distance reached, or by measurement of capacitance. The latter method, which has the advantage that the diode need not be removed from drift for examination, is preferred over staining. Furthermore, the present staining method is inadequate in that it does not readily identify the boundary between the n and i regions.

5. Final cleaning and encapsulation. — Completion of drift is confirmed by means of capacitance measurements, or by

copper staining, or both. Additional measurements by use of a 4-point resistivity probe and a thermal probe serve to locate the boundaries between the n and p regions and the i region.

Encapsulation consists primarily in mounting the detector in a cryostat for determination of detector characteristics. The procedure is the same whether the cryostat is one used solely for such testing or is designed for a particular experiment. Improvements are being attempted in the design of the cryostat, with emphasis on both simplicity of mounting and use and versatility in regard to detector dimensions. Although groups elsewhere have mounted the detector in a small capsule that can then be placed in a cryostat, this has not been generally useful in nuclear physics experiments because it introduces added capacitance and scattering.

The diode is installed in the cryostat only if: (a) its capacitance changes less than 1 pF over the range from 100 to 900 V at room temperature, (b) the current changes less than 5% in the range from 100 to 600 V at room temperature (except for thin-window construction, for which this requirement is ignored), (c) the resistivity of the n region is $\leq 0.35 \Omega \text{ cm}$, and (d) the intrinsic resistivity is confirmed on the periphery.

The standard cleaning method is used, except that both the n region and the periphery are cleaned before the diode is installed in the final cryostat, whereas only the periphery need sometimes be cleaned for installation into the test cryostat. The need for cleaning the surface of the n region can be determined by means of measurements of diode properties after cooling the diode to 77°K .

C. Dual-Drift and Thin-Window Detectors

The major advantage of the coaxial drift technique is the reduction of time for preparation of a large-volume detector. In this

method, the increased electric field intensity toward the axis of the sample gives a faster rate of drift than that achieved at a corresponding drift distance in the uniform field of a planar structure. Quantitatively, the same volume can then be compensated by coaxial drift in one-fourth the time required for planar drift. The disadvantage of the coaxially drifted device is two-fold: first, there is a dead region 0.3—0.5 mm thick covering the periphery and one flat surface of the detector; second, the electric field in the coaxial detector is nonuniform and this may lead to a larger spread in time of arrival of pulses at the electrodes than would be found in a planar detector prepared from the same sample. Also, for a detector 3 cm in diameter and 3 cm thick the capacitance of the planar detector is one-fourth that of the coaxial detector.

As a compromise between the planar and the coaxial configuration for drifting, and also to exploit large thickness and low capacitance in the detector, we chose first to investigate a dual-drift technique, wherein two diodes on opposite faces of the sample are used to drift lithium ions toward the center. Upon completion of the merger of the two regions undergoing compensation, one junction was removed and the crystal with the other junction is the detector. This has proved to be successful, and has allowed us to achieve a detector thickness of 26 mm with a sensitive volume of 17.7 cm^3 , limited by the diameter of the sample used.

For the same size of the detector, whether it is in axial or coaxial form, the per cent dead region associated with the lithium-diffused layer is significantly greater than if it were planar. Such a dead region should be made as small as possible; furthermore, the p-type core of axial and coaxial detectors should also be made as small as possible.

In an effort to find the best use of the various methods at our disposal, we studied the conversion of the coaxially drifted diode

into a planar structure. This has been successful, but there have been other problems to be identified and these are not obviously related to the particular methods employed.

Both the dual-drift method and the conversion of axially- or coaxially-drifted samples to planar form have required development of reproducible techniques for preparation of electrical contacts on lithium-compensated intrinsic germanium samples. We find replacement of the n^+ (or lithium-diffused) and p (or ohmic) contact on such samples to be routine operations when the proper control procedures are utilized.

1. Dual drift. —It is of interest for us to review here our initial approach to dual drifting. We purposely chose partially drifted samples for which copper staining of the periphery showed gross nonuniformity in the thickness of the compensated region. Thus, we were concerned that the merger of two n-i diodes might stop when a small area of contact between them had been made. We found this was not the case, and that merger does indeed continue. Perhaps it is caused to continue in part by diffusion, but this must be resolved in further studies. Our findings, which will be illustrated, are that the merged-dual-drift device is identical to the one prepared by drift in one direction; this has been confirmed for a thickness up to 16 mm.

We selected diodes such as the one illustrated in Fig. 85(a) that had been compensated nonuniformly to a depth of 6.5 ± 1 mm in a crystal 10 mm thick and to a depth of 9.5 ± 1 mm in a crystal 16 mm thick. The junction was removed [Fig. 85(b)] by lapping, leaving the lithium-compensated region and a known thickness of uncompensated material. A new junction was then prepared on the opposite face and its compensated region was extended by drift toward the first region. Despite nonuniformity of the diodes selected, the intermediate region of p-type material was thereby compensated.

Fig. 85. Schematic representation of the investigation and use of dual drift. In (a), the diode ① is partially drifted from one direction to a depth that is nonuniform, and then fully compensated ② by drifting from the opposite direction with a new junction. The steps are illustrated in (b) as they were carried out on six samples. In subsequent work (c), simultaneous drifting from two directions was employed.

At intervals of approximately 1 week, the edge of each of the crystals was copper stained. Near completion of drift, a thin p-type trace 0.1 mm thick was observed. With further drift for 3—7 days at 25°C this was caused to vanish. Similar tests were performed on other samples, and merger was confirmed by observation of an increase of current as merger occurred and also by measurement of capacitance as a function of voltage after completion of merger. Both ac and dc dual drift [Fig. 85(c)] were used in subsequent work.

In an effort to find the best use of the various methods at our disposal, we then studied the conversion of the coaxially-drifted diode into a planar structure. Coaxially-drifted samples were obtained from Nuclear Diodes, Inc. All of the electrical contacts were removed and new ones were formed on opposite faces, each of which is 3.0×3.0 cm. The total thickness of the sample was 21.5 mm upon completion of the reconstruction. The detector capacitance, plotted as a function of voltage in Fig. 86, was found to be 6.0 ± 0.3 pF, after subtraction of that due to mounting. The performance for γ rays from a ^{208}Tl source is illustrated in Fig. 87. The tail extending toward low energies

Fig. 87. Upper portion of spectrum for γ rays from a ^{208}Tl (or thorium) source as observed with a coaxially drifted planar detector. We expect that the tailing, evident on the low-energy side of the peaks shown, will be eliminated by further drifting.

Fig. 86. Capacitance-voltage curves at different stages of clean-up drift for a coaxially drifted diode after reconstruction in planar form. After 400—500 hours of drift at -3°C , the change of capacitance with voltage suggested that further drift was required for this sample.

may be due to deficiencies in the diffusion; the techniques used are being examined further.

We have used both dc and ac drift methods. Diagnosis during drift is possible with either method. For the dc method, the capacitance and current are used. For the ac method, the waveform of the diode voltage or current is used.³⁷ Such waveforms are shown in Fig. 88.

³⁷M. A. Jamini, IEEE Trans. Nucl. Sci. NS-14 (No. 1), 492 (1967).

Fig. 88. Typical sequence of waveforms observed during ac drift.

Here τ = time after start of drift, T = temperature, V = applied voltage, and I = diode current. (a) Waveform at start of drift in the fluorocarbon liquid FC 43: $\tau = 1$ min, $T = 25^\circ\text{C}$, $V = 100$ V, $I = 8$ mA. (b) $\tau = 0.75$ hr, $T = 25^\circ\text{C}$, $V = 200$ V, $I = 8.2$ mA. In 45 min the decay of the spike is less abrupt as current becomes limited by the diode. (c) $\tau = 24$ hr, $T = 25^\circ\text{C}$, $V = 300$ V, $I = 38$ mA. During drift the waveform changes as the diode capacitance decreases and the resistance of the intrinsic region increases. (d) $\tau = 44$ hr, $T = 48^\circ\text{C}$, $V = 140$ V, $I = 1$ A. At higher temperature, the saturation current in the diode increases and may lead to excessive heating. (e) $\tau = 45$ hr, $T = 44^\circ\text{C}$, $V = 165$ V, $I = 0.854$ mA. As drift proceeds, the spike continues to become more rounded. (f) $\tau = 140$ hr, $T = 44^\circ\text{C}$, $V = 140$ V, $I = 0.5$ A. When rediffusion is necessary, the spike is nearly completely rounded. (g) $\tau = 140$ hr plus the 4—6 hr required for rediffusion, $T = 25^\circ\text{C}$, $V = 100$ V, $I = 10.5$ mA. After rediffusion at 450°C , the waveform shows restoration of the junction. (h) $\tau = 232$ hr, $T = 46^\circ\text{C}$, $V = 100$ V, $I = 0.8$ A. The waveform shows the effect of a high drift temperature. (i) $\tau = 280$ hr, $T = 25^\circ\text{C}$, $V = 100$ V, $I = 0.5$ A. One of the two junctions in the dual-drift structure is shorted out as a result of contaminant in the bath.

Further work is under way to compare the results of the preparation by different methods.

Although we have used a sinusoidally varying voltage for ac drift, a square waveform is preferred to facilitate interpretation. It is important, regardless of the waveform, to avoid forward bias on either diode.

2. Thin window. — The method used for obtaining a thin window with an equivalent thickness of germanium in the range 1—10 mg/cm^2 has been described in a previous publication.³⁸ Usually we determine the effective thickness of the dead layer by use of the ratio of the 22- and 88-keV lines from ^{109}Cd , which we have observed to be as high as 20/1 with a Be foil 0.23 mm thick between the source and the detector. Figure 89 illustrates the use of a thin-window detector (a) for electrons and γ rays from ^{207}Bi and (b) for the low-energy x rays from ^{57}Co .

Fig. 89. Illustration of the thin window that is obtainable by plating a gold layer directly onto a lapped surface of lithium-compensated germanium. In (a) the low-energy tailing observed for electrons at an energy of ~ 1 MeV is fully accounted for by a 0.23-mm-thick Be foil between the source and the plated surface. (b) Low-energy x rays from ^{57}Co as observed with a similar arrangement.

III. The Cryostat

The design, construction, and operation of the cryostat has been described by Miner.³⁹ Detector dimensions cannot be precisely

³⁸F. J. Janarek, H. W. Helenberg, and H. M. Mann, Rev. Sci. Instr. 36, 1501 (1965).

³⁹C. Eugene Miner, A Semiconductor Detector Cryostat, University of California, Lawrence Radiation Laboratory, Berkeley, Report UCRL-17201 (December 15, 1966).

Fig. 90. Typical assembly drawing of a Ge(Li) detector cryostat equipped with a hollow cold finger (a) to serve as container for liquid nitrogen, and a flange (b) for an external reservoir. The cryostat is evacuated through valve (c) by adsorption pumping and then through valve (d) with the aid of a vac-ion pump. The pumps are not shown.

controlled, and it is sometimes desirable to locate the field-effect transistor and other components in proximity to the detector. In order to assure adequate cooling capacity for a wide variety of physical arrangements and a wide range in detector dimensions, the detector is mounted on a hollow cold finger containing liquid nitrogen as shown in Fig. 90. Chasman⁴⁰ has described an alternative construction wherein a solid cold finger is used. The need for standardization to permit ease of assembly, minimum amount of external absorbers, and flexibility among experimental applications requires further design improvements. At present there is a wide range in diameter and length of cryostat housing suitable for particular experiments.

Cryostats constructed at Argonne were initially equipped with 1-liter/sec vac-ion pumps. Some of these were later replaced with the larger 8-liter/sec pump in order to eliminate the possible need for replacement of the smaller pump during an experiment. Satisfactory operation for 2 years or longer can be achieved with either size of pump, and the larger one is generally used to avoid uncertainty that could arise

⁴⁰ C. Chasman and R. A. Ristinen, Nucl. Instr. Methods 34, 250 (1965).

when a good detector is to be quickly removed, cleaned, and reinstalled. A small (i. e. , < 3 liter) cryostat properly cleaned and assembled will not require the larger pump if the installation is not repeated more than a few times. The larger pumps can be returned to the manufacturer for repair at nominal cost after a period of use.

The disadvantages of the vac-ion pump are the need for a power supply or battery pack for operation, and the resulting additional mass due chiefly to the magnet. For these reasons the internal pumping scheme (i. e. , molecular sieve or charcoal absorbing material) is desirable. However, these materials do not permit as low a pressure in the cryostat as can be maintained with the vac-ion pump. We have evidence that some detectors can be more satisfactorily operated in the higher pressure environment, and cannot as yet state clear design criteria to resolve the choice of pumping scheme except as a preference based on limited experience.

A. Construction and Assembly of the Cryostat

In order to ensure cleanliness and satisfactory operation of the completed cryostat, great care is taken to clean the various parts as they are assembled. The cryostat is then tested under actual conditions of operation prior to installation of the detector.

In construction, type-304 stainless steel is used because of its low outgassing in vacuo—except when aluminum is required (e. g. , for mounting parts to minimize nuclear scattering outside the detector). All internal joints are welded by the burn-through technique to avoid the outgassing that might occur if pockets were formed in the weld material. Silver-solder joints are completely filled to avoid trapping residue and the solvents used for cleaning. All completed welds and joints are cleaned and vacuum checked before beginning the next step. Silver-solder joints are immersed in boiling water to remove excess

Fig. 91. Cryostat parts before assembly.

flux. Before the final weld seals the cryostat, the assembly is degreased in the standard way with trichloroethylene.

When the cryostat has been assembled, it is evacuated by a sorption pump and the interior surfaces are baked out. The baking temperature is limited to 100°C when Viton-A O rings are used, but may be as high as 300°C for systems with metallic gaskets.

Some experiments impose special design requirements. The individual parts of one cryostat designed for insertion into an anticoincidence spectrometer, or simply into a lead shield, is shown in Fig. 91. The long narrow tube at the bottom of this illustration is the cold finger which, when filled with liquid nitrogen, cools the detector. Toward the right and just above the cold finger is an end cap equipped with a 0.010-in. Be window.

A similar chamber, different only in regard to the end cap, is shown in Fig. 92 with the outer jacket removed. After assembly, and after installation of an FET-equipped input stage, the chamber must be further baked out before the detector is installed. For bake out and use, the vacuum and cleanliness requirements are met by use of sorption and ion pumping, in preference to oil-diffusion or oil-mechanical pumps.

B. Vacuum and Electrical Performance Requirements

Operation of the detector at the highest possible voltage and the absence of contamination by outgassing of materials in the

Fig. 92. Assembled cryostat with outer jacket removed.

cryostat are the major aims in preparing the cryostat for the detector. With care in assembly, an operating voltage up to 8400 V for a 2.5-cm-thick detector has been achieved. We do not feel this voltage is desirable and for general use the high-voltage connection is checked for negligible leakage up to 5000 V.

To prepare the cryostat for installation of the detector, it is first filled with 1 atm of nitrogen and then evacuated to $\sim 1-5 \mu$ by means of a sorption pump. The valve to the vac-ion pump is then opened. If the pump current falls to $\leq 50 \mu\text{A}$ (corresponding to $\leq 4 \times 10^{-7}$ Torr) in $\sim \frac{1}{2}$ h, the cryostat is regarded as ready for use and is kept evacuated until time to install the detector.

IV. The Ge(Li) Spectrometer System

A complete system assembled for use in nuclear spectrometry consists of a detector and cryostat, a preamplifier, a linear amplifier, and a multichannel analyzer. A voltmeter and oscilloscope for monitoring detector leakage current through the feedback resistor in the detector circuit and associated current noise is extremely useful both in setting up the apparatus and in diagnosis of difficulties that may arise during an experiment. To some systems a threshold

(biased) amplifier and a scaler may be added. Additional apparatus is required for timing, coincidence, or anticoincidence measurements.

The assembly requires preselection of components such as the field-effect transistor (FET), capacitors, and resistors for the detector-input section. Direct (dc) coupling of the detector to the gate of the FET is preferred, since capacitive (ac) coupling usually causes higher noise. The detector is isolated electrically but connected thermally to the cold finger by means of sapphire in the mounting arrangement. Up to now a large proportion of our systems have been assembled with the components of the input section inside the cryostat. Recent improvements in design and selection of the FET by the manufacturer make this unnecessary for many experiments involving γ rays with energies of 1–10 MeV or higher.

A. Detector Circuit

The components of the detector circuit are shown schematically in Fig. 93. The first stage of the preamplifier is the FET together with the components C_F and R_F in the feedback loop. The value of C_P is chosen according to the amplitude of the pulses from the pulse generator and is typically 1.1 ± 0.1 pF for systems that are to be used with energy values ranging up to 10–12 MeV. The feedback resistor R_F is $2-4 \times 10^8 \Omega$ for a detector leakage current in the range 0.5–1.0 nA. For smaller currents, R_F may be chosen to be $\sim 10^9 \Omega$.

Fig. 93. Circuit diagram of the first stage of the preamplifier with the detector, calibration capacitor C_P , feedback capacitor C_F , and feedback resistor R_F connected to the gate of the field-effect transistor FET.

The value of C_F is fixed by R_F and stability requirements of the amplifier.

In earlier work the detector alone was inserted into the cryostat, and usually a single electrical connection was provided for connection to the preamplifier. This required that the detector voltage be provided at the detector with capacitive (ac) coupling to the preamplifier. This arrangement makes it difficult to measure or confirm the relatively low values of detector current (i. e. , < 1 nA) required in satisfactory operation. Thus, the cryostat would be at ground potential and ground loops or stray pickup of external electrical signals could not be easily avoided. For these reasons—and in accord with more sophisticated electronic design considerations for a low-noise, high-stability system—the use of ac coupling and the earlier vacuum-tube preamplifiers are now obsolete.

A block diagram of the apparatus in a low-noise high-resolution system is shown in Fig. 94(a). In such a system, either commercial apparatus or laboratory-made instruments may be used—depending in part upon availability and also upon need for further development. At present the monitor of deposited charge and leakage current shown coupled to the preamplifier is a voltmeter (0—2.5 or 0—10 V) which measures the voltage across the load (or feedback) resistor in series with the detector. In this arrangement, the detector is direct-coupled to the preamplifier. Both the detector and the first stage (input section) of the preamplifier are usually mounted close together inside the cryostat and cooled to 77°K . In use, the temperature of the field-effect transistor (FET) in the first stage is higher than 77°K as determined by its mount and the drain current in the FET. For comparison, a modified system for use at counting rates in the range from 10^4 to 10^5 counts/sec is shown in Fig. 94(b).⁴¹

⁴¹M. G. Strauss, I. S. Sherman, R. Brenner, S. J. Rudnick, R. N. Larsen, and H. M. Mann, paper C-6; Rev. Sci. Instr. 38, 725 (1967).

Fig. 94. Block diagrams of Ge(Li) spectrometer systems for high resolution of γ -ray energy at counting rates (a) less than 10^4 counts/sec, and (b) in the range from 10^4 to 10^5 counts/sec.

B. Preamplifier²¹

Previously we used a vacuum tube for the amplification of detector pulses, and required the linewidth for 1333-keV gamma rays to be ≤ 3.5 keV (FWHM). For the same detectors, the FET allows the upper limit on the linewidth to be reduced to 2.5 keV (FWHM). Both of these preamplifiers were designed by I. S. Sherman of this laboratory.

Fig. 95. Performance characteristics of a low-noise FET preamplifier. In (a) the noise is expressed in terms of the linewidth (FWHM) for a germanium detector (on the assumption that $\epsilon = 2.96$ eV) and is plotted as a function of the capacitance C_{added} which is external to the FET (SF 5868). Curve (b) shows the effect of counting rate on the feedback voltage.

The preamplifier noise performance is shown in Fig. 95(a) for a selected FET (SF 5868) in the input section of the detector circuit. For these measurements, a time constant of $1.6 \mu\text{sec}$ was used in the single exponential integration and differentiation. When cooled to $\sim 90^\circ\text{K}$, the noise intercept at zero added capacitance was 610 eV and increased with capacitance at the rate of 37 eV/pF. When operated at 25°K , the intercept increased to 1 keV and the slope was reduced to ~ 30 eV/pF. The limit of noise is determined by the particular FET used, and has been observed to be 420 eV with about the same slope.

The rise time is limited by the FET, and is 30 nsec when the detector-FET connection is several centimeters in length. This time is short in comparison with the transit time for charges produced throughout the relatively thick Ge(Li) detector.

In normal use the detector leakage current is continuously monitored. If desired, the current monitor can be calibrated for use as a counting-rate meter, as illustrated in Fig. 95(b). This dc output

TABLE XII. Principal characteristics of the PASD-4 preamplifier (The energy deposited has been computed on the assumption that $\epsilon = 2.96$ eV per ion pair produced in germanium.)

Sensitivity	0.6 V/MeV unterminated, 0.3 V/MeV terminated with 91Ω .
Maximum signal level	At least 12 MeV.
Gain stability	10 ppm drop in closed-loop gain for 1% reduction in gain of charge-sensitive amplifier with 5-pF detector. Feedback capacitor temperature coefficient = 25 ppm/ $^{\circ}\text{C}$. Expect less than 10 ppm/ $^{\circ}\text{C}$ from output circuit when adequate resistors are used in feedback loop.
Output pulse shape	50 μsec tail. 20 nsec rise time for low capacitance, increasing to 30 nsec for 100 pF
Overload characteristics	50 μsec exponential recovery of overload pulses up to 68 MeV
Counting-rate capability	At 1.33 MeV, the resolution width was 2.5 keV at 50 000 pulses/sec, but increased to 3.5 keV at 100 000 pulses/sec
Noise with input stage cooled	400 eV at zero added capacitance, noise increase of 35 eV per picofarad added capacitance with Texas Instrument FET types SF 5868A, 2N2823 (selected), 2N3819 (selected). The FWHM of a pulser signal was broadened only by preamplifier noise.
Noise with input stage at room temperature	600–700 eV at zero capacitance, increase of 50 eV per picofarad added capacitance. With a special TIS42 field-effect transistor, the values were 1 keV at zero capacitance; increase of 30 eV per picofarad added capacitance.
Noise at preamplifier output	Less than 15 keV with 40 nsec rise time with a 5 pF Ge(Li) detector. Cold FET

is a linear function of the product of counting rate and γ -ray energy, and consequently is useful for anticipation of spectral distortion in the remainder of the system at a high counting rate.

The principal characteristics of this preamplifier are listed in Table XII. The circuit diagram is shown in Fig. 96. There

PASD 4

Fig. 96. Circuit diagram of the Model PASD-4 low-noise transistorized preamplifier with a field-effect transistor in the detector circuit. A field-effect transistor is used also in the amplifier section to obtain a high value of gain $\times$ bandwidth.

are two sections: a high-gain charge-sensitive amplifier and a voltage-sensitive amplifier capable of driving a $93\text{-}\Omega$ terminated line.

1. The charge-sensitive section. —The charge-sensitive section has a very high internal gain (more than 60 000 at room temperature). This gain increases by about a factor of two with the input stage cooled. Direct coupling was used to simplify counting-rate problems, and consequently this section can be used as an electrometer to monitor the total detector current. The only stages with little or no local degeneration are the input transistor and the difference amplifier. Though the first two transistors form a cascode, this configuration was not chosen for its low noise, which can be achieved just as well in other ways, but for over-all design considerations. A germanium microalloy transistor is used after the input FET because it exhibits good gain-bandwidth characteristics as well as low noise. The current in this transistor is only 0.2 mA. The cascode gain is almost 500 at room temperature.

A source follower (rather than an emitter follower) is used to avoid loading the cascode while providing a high product of gain and bandwidth. Relatively noisy FET's can be used at this point. The gain of the source follower is 0.8 and the gain of the difference amplifier is 200. A fast emitter follower drives the capacitance of the wiring in the feedback loop and output amplifier.

2. Output amplifier. —The output amplifier is capable of driving two $91\text{-}\Omega$ terminated lines to about 4.5 V before overloading. It has a rise time of 11 nsec for either positive or negative pulses. Its closed-loop gain up to the source terminating resistors is 5, while its open-loop gain is about 2500. The last four transistors are already well degenerated, and the over-all gain stability is high.

The total capacitance between base and emitter at the point in the circuit where the diode bias string is located is almost 20 pF. For a pulse with an 11-nsec rise time at full output, the peak

charging current is about 20 mA. One of the sides of the push-pull input stage (the choice depending on the polarity of the pulse) provides this current. The quiescent current is 1 mA; a low current is desirable for low base-current noise. After this capacitance is charged, the input stage returns to more linear class-A operation.

3. Pulse shaping. —Examination of the output-amplifier feedback loop, which is shown in simplified form in Fig. 97, shows that

Fig. 97. Simplified diagram of PASD 4 preamplifier to illustrate selection of pulse-shaping time constants. The capacitor C_2 is chosen to produce a pole having a 50- μ sec time constant. A resulting zero at 110 μ sec is then canceled by adding

the coupling network. This network has a 110- μ sec pole (canceling the 110- μ sec zero) and a zero at 1 msec that cancels the time constant of the charge-sensitive section.

it produces a response equivalent to a pole-zero coupling network.⁴² The capacitor is chosen to produce a pole having a 50- μ sec time constant, the value desired for the final output pulse. The resulting zero, whose time constant is 110 μ sec, is canceled by adding the coupling network shown in Fig. 97. This network has a 110- μ sec pole (canceling the 110- μ sec zero) and a zero at 1 msec that cancels the time constant of the charge-sensitive section. Figure 98 illustrates the pole-zero cancellation scheme in terms of the frequency response. The effect of the large coupling capacitors that remain at the input of the driver is easily removed by a dc restorer later in the system.

⁴²C. H. Nowlin and J. L. Blankenship, Rev. Sci. Instr. 36, 1830 (1965).

The current contribution to noise is given by

$$(\Delta E)_I = 0.96 \sqrt{I_d},$$

where $(\Delta E)_I$ is in keV (FWHM) and the current I_d is expressed in nA. Thus, in a system in which the pulser is to have an energy resolution width not greater than 1 keV, the detector current should not exceed 1 nA.

C. Amplifier

Several commercial amplifiers have been used in measurements on detectors and in experiments. These and also an amplifier designed at Argonne⁴³ have been found to be satisfactory.

D. Threshold (Biased) Amplifier

A biased amplifier designed for reduction of pile-up and high stability has been utilized.²² Its deviation from stability was found to be $\leq 10^{-5}/^{\circ}\text{C}$ and the deviation from differential linearity did not exceed $\pm 1\%$ in 94% of the 9-V amplitude range. The biased amplifier includes a pulse stretcher. Special attention was given to minimizing effects of temperature on the components used to establish the bias level. Effects of high repetition rate were compensated for without degrading the instrumental signal-to-noise ratio.

Fig. 98. Schematic illustration of pole-zero cancellation as used in the PASD 4 preamplifier. Frequency values f_3 , f_2 , and f_1 refer, respectively, to the 50- μsec , 110- μsec , and 1-msec time constants of Fig. 97.

⁴³ This is a pole-zero compensated amplifier designed by M. G. Strauss. Its use is described in Ref. 41.

A good test of the performance of this instrument was provided in its use by H. R. Bilger, who measured the energy resolution very accurately over a period of up to 10 hr. During this time a reference pulse showed the instability to be 64 parts per million, including the instability of the pulse generator (40 parts per million per $^{\circ}\text{C}$). These measurements, which were made without a stabilizer, gave 25 parts per million for the root-mean-square deviation from linearity at energies of several MeV.

E. Multichannel Analyzer

Various multichannel analyzers are in use. Those routinely used in the preparation and development of detectors are the RIDL 34-12 (400-channel), Victoreen ST 800 M (800-channel), and the Victoreen SCIPP 1600 (1600-channel ADC and 3200-channel memory).

F. Pulse Generator²³

In experiments, artificially produced pulses are used for stabilization and for calibration of the energy scale. In studies of the energy resolution of detectors, the artificial pulses are also used for determination of the system contribution to the linewidth. It is important that the repetition rate of pulses be unsynchronized with respect to the frequency of the line voltage; otherwise the system noise may be underestimated.

We have found that it is advantageous to use special capacitors made with Teflon dielectric for calibration and stabilization pulses. Furthermore, it now appears most desirable to install such capacitors in the cryostat with the detector and cool them to 77°K as an aid to achieving stability.

Previously we have used a Berkeley Nucleonics Corporation pulser with specified drift of 0.003% per $^{\circ}\text{C}$. During the past year we

have used a more versatile Argonne-designed double pulse-generator with higher stability.

G. Present Limitations and New Areas

Refinements in the electronic apparatus allow the energy-resolving capability of the Ge(Li) detector to be fully utilized at an energy of 10 MeV or higher. At lower energies, as shown in Fig. 99, the resolution is limited by electronic noise. Otherwise the resolution width should decrease to about 150 eV (FWHM) at an energy of 10 keV. The smallest pulser width represented in the figure corresponds closely to the theoretical limit set by the FET, and would provide a resolution width of 300 eV at an energy of 10 keV.

The principal noise limitations in the FET are (a) thermal noise due to charge fluctuations in the channel, and (b) shot noise associated with gate current. Thus, it is possible that with this type of device a substantial reduction of operating temperature would be required for improved energy resolution.

Another limitation is associated with the size of the detector. As a result of the spatial distribution of events leading to

Fig. 99. Energy resolution width as a function of energy deposited in the detector for different values of the pulser width. In the figure, $(\Delta E_D)^2 = 2.355 \sqrt{\epsilon F E}$, where $\epsilon = 2.98$ eV/pair and $F = 0.129$.

Fig. 100. Idealized curves to show time of arrival of charge at the electrodes of a planar Ge(Li) detector for the case of equal mobility of electrons and holes. The charge may be produced (a) at the center, (b) at either electrode, (c) close to one electrode, or (d) close to the center. A real pulse for spatially distributed charges will be smoothed as shown in (e).

pulses, the amplitude at any given time after the event has a spread related to detector thickness. This spread in pulse amplitudes has been studied by Strauss.²⁰ For a real detector, the time dependence of the distribution of pulse amplitudes is as indicated in Fig. 100. The time spread of the pulse is larger at the end than at the beginning. Pulse-shaping networks now in use are not the best means for handling widely different pulses from the detector.

Since the time of arrival at the electrodes depends upon the position of the event in the detector, there is a spread in pulse shape for different pulses of the same energy and amplitude. In the "ideal" case (Fig. 100), the differential spread in time for the last pair to be collected is approximately

$$t \approx \frac{1}{2} \frac{W}{v} \approx \frac{W}{2 \times 10^7} \approx 50 \text{ nsec}$$

for a detector 1 cm thick.

Loss in amplitude due to pulse shaping of the distributed pulses from the detector, known as ballistic deficit, has been analyzed by Roddick.⁴⁴ This would not be a problem if all of the detector pulses had the same shape. In consequence of the ballistic deficit, the fluctuations in the detector-current pulse shape will contribute amplitude fluctuations of the order of 1 part in 10^4 when the PASD-4 preamplifier is used.

⁴⁴R. G. Roddick, "Analysis of the Ballistic Deficit in Solid State Detector Systems," in Ref. 7.

In the studies of pulse shape (Ref. 20), the pulses were examined by use of a 2-dimensional pulse-height and pulse-time analyzer system. The number of pulses at each amplitude was displayed at each of several selected times after the pulse generator had fed a pulse into the system. Figure 101 is a composite representation of these results. The spread in detector pulses was examined for a 10.6-mm-thick detector. For a detector bias of 2240 V, the spread [Fig. 102(a)] was found to be 60–70 nsec at full collection. When the bias was reduced to 550 V, this spread increased to about 110 nsec as shown in Fig. 102(b).

By examination of such spectra the initial rate of charge collection and the total charge-collection time (Fig. 103) was obtained.

Fig. 101. System response to signals from a pulse generator. This is a superposition of runs at selected times (Ref. 20).

Fig. 102. Pulse-shape distribution (Ref. 20) for 662-keV gamma rays in a germanium detector 10.6 mm thick: (a) with a bias field of 2300 V/cm; (b) with a bias field of 500 V/cm.

Fig. 103. Charge-collection time as a function of electric field intensity for a 10.6-mm-thick detector (Ref. 20).

at high counting rates was tested and confirmed by use in a system with counting rates up to 100 000 cps.⁴¹ This particular system was developed for use at a detector counting rate of up to 100 000 pulses/sec. At this detector rate, obtained by placing ^{60}Co and ^{137}Cs sources in proximity to the detector, the 1.33-MeV γ -ray peak from ^{60}Co was resolved to 3.4 keV (FWHM) with a spectral shift not greater than 0.1%. At a low rate (1000 pulses/sec) the resolution width at the same energy was 2.3 keV (FWHM).

New electronic methods, such as the use of current amplifiers and gating techniques, have been suggested by Arbel to attempt to overcome problems introduced by pulse shaping.⁴⁶

V. Spectrometer Performance

The spectral response (pulse-height distribution) obtained by use of the Ge(Li) detector for photons at an energy E_γ is determined by the energy $E \leq E_\gamma$ transferred to electrons within the detector. The subsequent collisions of these primary electrons (the

The detector response

has been found to be linear within $\leq 0.05\%$ for energies over the range 500 keV—10 MeV.⁴⁵ The FET preamplifier was designed to have a gain that was stable within $10^{-5}/^\circ\text{C}$. With the input stage close to (but not integral with) the remainder of the preamplifier, a rise time of ~ 30 nsec has been obtained. Its suitability for use

⁴⁵ A. J. Levy and R. C. Ritter, University of Virginia (to be published).

⁴⁶ A. Arbel, in Ref. 7.

ones directly ejected by the photons) release a quantity of charge $Q = Ne$, where N is the number of electron-hole pairs produced and e is the electron charge. The ratio of the energy deposited to the charge produced is the mean ionization energy ϵ . In germanium at 77°K , $\epsilon = 2.96$ eV/pair⁴⁷ or simply 2.96 eV. The limits of performance of the detector are determined by (a) fluctuations associated with the energy-transfer processes, (b) the finite time for movement of electron-hole pairs to the electrodes of the detector, and (c) trapping and recombination of charge in the detector.

The usefulness of a detector depends on its energy resolution and efficiency. Also, for some experiments, it is important to seek the most rapid motion and most uniform arrival time of charge at the electrodes.

A. Energy Resolution and the Fano Factor

Our earliest results in evaluating and using the detector showed the need for determining the limit of its energy resolution. There was a significant discrepancy, amounting to 50% at an energy of 1 MeV,² between the energy resolution we obtained and that reported by others. The difference was sufficiently large to influence both the design of electronic apparatus for use with the detector, and the design of the experiment. We attributed the improved energy resolution obtained then to both the detector and the apparatus used. Subsequent measurements, on the detector and the system have established the limit of energy resolution—for the detector, as well as the requirements on stability, linearity, and resolution of electronic apparatus. The results obtained in these studies of energy resolution have stimulated theoretical studies

⁴⁷Richard H. Pehl, Fred S. Goulding, Donald A. Landis, and Martin Lenzlinger, Accurate Determination of the Ionization Energy in Semiconductor Detectors, University of California, Lawrence Radiation Laboratory (Berkeley), Report UCRL-17770 (September 1967).

and show also the need for further experimentation to identify the mechanisms involved in charge generation in a semiconductor crystal.

1. Experiment. — The Fano factor F is the constant of proportionality between the variance σ^2 (the square of the statistical fluctuation σ) and the mean of the number N of charge pairs released in an ionizing event. That is,

$$\sigma^2 = F \bar{N}. \quad (6)$$

As originally introduced by U. Fano^{4 8} in his study of ionization in gases, this was a defining equation for the variance of an otherwise unknown probability distribution function. But since measurement of the quantity of charge $Q = Ne$ in an ionizing event is equivalent to measuring N , both σ^2 and $\bar{N}$ are measurable quantities—so Eq. (6) can alternatively be used to define the Fano factor.

The experimental problem is that of measuring precisely the energy resolution for a known energy E_γ deposited within the detector, and the resolution of the electronic apparatus used. In terms of the variances, the observed γ -ray line width σ_γ is given by

$$\sigma_\gamma^2 = \sigma_d^2 + \sigma_p^2, \quad (7)$$

where the subscripts d and p refer to detector and pulser, respectively.

The result of one measurement for γ rays near 4.5 MeV is shown in Fig. 104. Events corresponding to γ -ray interactions in the detector and to the artificial pulser events were simultaneously recorded in order to obtain a reliable measure of the linewidth associated with the electronic apparatus. Two γ rays were used for the purpose of determining the energy scale. Similar measurements were made for γ rays at energies in the range 0.122–10 MeV. Thus, the detector contribution to linewidth was determined on the assumption that the

^{4 8}U. Fano, Phys. Rev. 70, 44 (1946); 72, 26 (1947).

Fig. 104. Pulse-height distribution for γ rays at two energy values near 4.5 MeV, together with a pulser peak. Such spectra from the detector were used to determine its limit of resolution from the measured linewidths for the pulser and the γ ray (Ref. 19).

pulser provided a valid measure of the electronic noise and that both the electronic noise and the detector processes contributed independently to the total width. The reliability of these assumptions was thoroughly tested and assured in the highly refined measurements described by Bilger.¹⁴ The results of these measurements show conclusively that the Fano factor in germanium at 77°K has the value

$$F = 0.129 \pm 0.003$$

for γ rays with energies from 0.122 to 4.8 MeV. Earlier work (Ref. 14) has shown $F \leq 0.16$ for γ -ray energies up to 10 MeV, but the lower value is a more reliable determination. We therefore represent the detector limit of energy resolution in Fig. 105. We can expect to obtain a resolution width of 1.5 keV at an energy of 1 MeV and 4.5 keV at 10 MeV.

The erroneous value $F = 0.3$ determined elsewhere appeared to agree with theory.⁴⁹ This illustrates both the lack of basic knowledge and the existence of experimental limitations. Thus, the interaction processes by which an energetic electron loses energy as it moves through a crystal are not known; the experiments to determine the detector limit of resolution always give an upper limit despite the standard error assigned to the measurement. In the most refined measurements there may still be systematic errors that are not identified.

⁴⁹ W. van Roosbroeck, Phys. Rev. 139, 1702 (1965).

Fig. 105. Limit of energy resolution for a Ge(Li) detector as a function of the energy deposited in the detector.

Knowledge of ϵ , which is a determinable quantity, and the range of energies over which ϵ is constant, leads automatically to the acceptance of statistical considerations in analysis of the charge-generation processes. This is quite analogous to the statistical fluctuations observed in the ionization of a gas. Thus the amount by which the number of ion pairs produced in one event departs from the average number $N = E/c$ is expected to be $\sqrt{N}$, the variance associated with N events. It has, in fact, been observed that the statistical fluctuation for ionization events is not determined solely by the number of events. This was first noted by U. Fano in his study of ionization in gases. Yet, the only approach to the problem of explaining the observed resolution has been to determine departure from $\sigma = \sqrt{N}$. As additional knowledge is gained, we can hope to replace the statistical approach with a more direct one.

2. Theory. — The successively smaller values for F found over a period of several years have led to a closer examination of the models of the ionization process in semiconductors. One widely used theoretical model has been constructed in close analogy with Fano's model for gases. He assumed three classes of interaction: (1) ionization in which the energy E of the resulting electron or hole did not exceed

the gap energy (i. e. , $E \leq E_g$), (2) ionization with $E > E_g$, and (3) excitation without ionization ($E = 0$).

The theoretical studies^{49,50} are based upon assumed models for the ionization processes. Clearly, the ionization events do not fall into a Poisson distribution, for then we would have $F = 1$, and there would be no Fano factor. The events seem to obey some other statistical distribution, simply because $F \neq 1$ according to experiment. Two kinds of energy transition do exist; namely, one for which $F = F_0 = 0$ (corresponding to complete absorption of the incoming energy) and another for which $F = F_1 = 1$ (corresponding to completely random absorption of any fraction of the incoming energy). When $F_{\text{exp}} = 0.13$, we can infer 87% of the incoming energy is consumed by events in class 0 and 13% by events in class 1. This means that the statistical fluctuation is reduced as the incoming energy is more completely transferred (in our case) to electron-hole (ion) pairs. Thus, the limit of energy resolution (of the detector) is not determined by ionization events, but by the discrete quantities of energy too small to produce ion pairs. These residual energy losses are small enough that they produce no significant departure from linearity of the detector response over a wide range of energy values.

The problem of correlating the ionization energy ϵ with the band gap has been studied by Klein,⁷ who found that the relationship

$$\epsilon = E_g + \frac{9}{5} E_g + r\hbar\omega_R \quad (8)$$

represented the values for ten different semiconductors. The apparent range of validity may extend to $E_g = 6$ eV, as shown in Fig. 106. Over the range of values considered, the phonon-loss term $r\hbar\omega_R$ in Eq. (8) is constant and has a value in the range $0.5 \leq r\hbar\omega_R \leq 1.0$ eV. On the

⁵⁰ C. A. Klein, J. Appl. Phys. (to be published).

Fig. 106. Ionization energy ϵ as a function of band gap E_g for different semiconductors (Ref. 50).

Fig. 107. Schematic representation of the ionization energy ϵ as a sum of three terms according to Klein (Ref. 50). It is possible to consider $F = F_0 = 0$ for transitions that do not involve optical phonons, and $F = F_1 = 1$ for those that do.

basis of these findings, we have constructed the schematic representation of the energy loss shown in Fig. 107. The experimental findings are consistent with this picture. However, it is not established that the interactions can be classed according to the F values shown.

It is interesting that F is independent of the energy of the primary electrons in the measurements made so far. Perhaps F does decrease with increase in E_g . This would be consistent with the dependence of ϵ on E_g ,⁵⁰ which shows a larger proportion of phonon loss at the lower values of E_g . Up to now most of the developers of detectors have looked to low E_g for further reduction of line width. This may not be a valid path. C. A. Klein has suggested that one should go to higher values of E_g for improved resolution.

Fig. 108. Model of a transition scheme with a band gap ΔE , and a valence band and conduction band of width $\beta\Delta E$ and $\alpha\Delta E$, respectively. For many ($m \rightarrow \infty$, $n \rightarrow \infty$) equidistant energy levels and for the case of no phonon losses, the model results in $0 \leq F \leq \frac{1}{3}$ (Ref. 19).

Bilger has noted that under the assumption that phonon production made a negligible contribution to F , Fano's calculations could be used to obtain expressions for F and ϵ in terms of two parameters α and β governing the widths of the valence and the conduction bands, respectively. Thus,

$$F = \frac{1}{3} (\alpha^2 + \beta^2) / (\alpha + \beta + 2)^2$$

and

$$\epsilon = \Delta E + \frac{1}{2} \alpha \Delta E + \frac{1}{2} \beta \Delta E,$$

where ΔE , as shown in Fig. 108, is equal to the width E_g of the band gap. Using $F = 0.129$ and $\epsilon = 2.97$ eV, we find that the width of the conduction band is 3.7 eV and that of the valence band is 0.5 eV. The transition scheme suggested appears to be a satisfactory one for the case of small phonon interactions and correspondingly high ionization efficiency.

In summary, the limit of energy resolution and the numerical value for the Fano factor are determined by residual energy losses that play little or no role in ionization. The physical phenomena—particularly the impact-ionization threshold and transfer of energy to phonons—require further investigation. It now appears necessary to consider revision of our earlier conclusion that a material with a lower band gap than that in silicon and germanium would provide better energy resolution than is obtained with the Si(Li) and Ge(Li) detectors that are now in use. On the contrary, as noted by Klein, for $E_g \approx 0.2$ the phonon excitation would represent the largest of the

three terms from which ϵ may be calculated. Although ϵ for this material would be smaller than that for Ge, the statistical fluctuation governing energy resolution would very likely be higher. It is now of interest to look toward the higher-band-gap materials both for improved (best possible) energy resolution and higher temperature of operation.

It has been noted by Alkhazov et al.⁵¹ that $F \approx E_g / \epsilon$, but this was based upon earlier erroneous values of F . It seems important to point out that E_g / ϵ is a measure of the ionization efficiency, and this latter quantity would seem to play the decisive role in determining F . Thus, for a low value of E_g the ionization efficiency would be low because ϵ would level off as E_g decreases, as shown in Fig. 106. Hence it would seem better to go to high E_g in order to obtain high ionization efficiency.

B. Efficiency and Size of the Detector

The full-energy-peak (FEP) efficiency for a γ ray of energy E_γ is defined as the ratio of the number of events in the full-energy peak to the number of γ rays at this energy which strike the detector. This and other parameters (peak-to-total ratio, single- and double-escape-peak efficiency) of the detector response may be computed.⁵² For an energy close to 1 MeV, the parameters are useful both for comparing the performances of detectors with different dimensions and for interpreting measurements of absolute efficiency. With a calibrated source, or with the same source always at the same distance from the detector, such measurements have been useful in determining departures from expected size as inferred from staining the periphery of a planar diode. For example, if the detector is in

⁵¹ G. D. Alkhazov, A. P. Komar, and A. A. Vorob'ev, Nucl. Instr. Methods 48, 1 (1967).

⁵² William J. Snow, The Response of Monoenergetic γ Rays in Finite Media, Argonne National Laboratory Report ANL-7314 (April 1967).

Fig. 109. Relative efficiency curves as obtained with selected planar Ge(Li) detectors. In (a) the electric field intensity required for saturation of the relative efficiency curve with increasing field for a thin (5.5-mm) detector is shown to be nearly twice that required for the thicker (14-mm) detector. Also, in the thin detector a slight difference in γ -ray energy resulted in a shift of the curve but no noticeable effect for the thicker one. Comparison of curves (b) for two detectors with volumes of 3.5 and 8 cm³ (as inferred from staining of the periphery) shows the larger detector to have, in effect, a smaller detector volume. The effects shown in (a) and (b) are believed to be caused by faulty preparation techniques, or improper identification of the sensitive volume, or both.

the form of a right circular cylinder of face area 7.06 cm² and thickness 2.2 cm, the computed FEP efficiency is 5.3% at 1173 keV and 4.6% at 1333 keV. These values have been closely approached (i.e., to within 10–15%) for some detectors of this size; but usually the effective volume has been much less than the physical volume. For example, detectors with a physical volume of 30 cm³ (as estimated by staining) have been found to have as little as 20–25% of the efficiency expected if the entire volume were effective. We therefore have not relied on staining as an indication of the effective detector volume.

Departure from the efficiency expected on the basis of the dimensions of the compensated volume may arise from either (a) too low an electric field intensity or (b) incorrect determination of the effective dimensions. The first of these causes of low efficiency is illustrated in Fig. 109(a), a plot of efficiency as a function of the

electric field intensity for two detectors. To bring the efficiency up to the saturation value, the relatively thin detector (5.5 mm thick) required an electric field intensity of 700 V/cm; a thick detector (14 mm) required only 400 V/cm at the same γ -ray energy. The discrepancy between effective and physical dimensions is illustrated in Fig. 109(b), which shows the results of experiments at γ -ray energies up to 10–12 MeV. For this comparison, the relative double-escape-peak efficiency of the larger detector [Ge(Li) 78 with a volume of 8 cm^3] was arbitrarily normalized to that for the smaller one [Ge(Li) 34 with a volume of 3.5 cm^3] in the low-energy region. It is seen that the supposedly larger detector [Ge(Li) 78] had in fact a smaller effective volume than Ge(Li) 34, as indicated by the rate of decrease of efficiency with increasing γ -ray energy and the total number of counts in a fixed time at 7 MeV.

Both of these effects seem to be attributable to the methods of preparation, but the quality of the material may also be a factor. Both as a diagnostic tool in gaining a better fundamental understanding of these departures and as a practical method of predicting the performance of a detector under its normal conditions of use, we find it convenient to estimate the sensitive volume of a detector by measuring the capacitance. These size estimates have been found reliable for detector volumes up to 20 cm^3 and perhaps larger. Gross departures from the expected capacitance correlate with reduced efficiency. The advantage of this method is illustrated in Fig. 110, in which the number of events in the 1333-keV gamma-ray peak of ^{60}Co is plotted as a function of the detector volume computed from the measured capacitance. When the "stained volume" was used, there was no correlation.

Some observations of FEP efficiencies reported by others are shown in Fig. 111. Most of our measurements yield only the relative efficiency, but in a few instances we have determined the absolute efficiency at 1333 keV. As can be seen by interpolating between the

Fig. 110. Number of events observed in the full-energy peak of the 1333-keV γ rays from a ^{60}Co source at a distance of 20 cm from the detector. The detector volume v was computed from measured capacitance C according to $v = Ax_C$, where $x_C = 1.38 (C/A)^{-1}$ and A is the area.

Fig. 111. Intrinsic full-energy-peak efficiency as a function of energy for selected Ge(Li) detectors. The three uppermost lines represent observations on coaxial detectors of volume 17, 30, and 54 cm³ for comparison with a single data point $\otimes$ at 1333 keV as obtained with a 16 cm³ planar detector prepared at Argonne. The two lower lines show a significantly higher efficiency for a 4 cm³ planar detector prepared at Argonne than is obtained with one of the same volume prepared earlier by Tavendale. A single data point Δ at 1333 keV (obtained with a 1 cm³ planar Argonne detector) is seen to be between the two lines representing measurements on the 4 cm³ planar detectors. [Observations on the 30 cm³ detector were reported by H. L. Malm in IEEE Trans. Nucl. Sci. NS-13 (No. 3), 285 (1966); the others were reported by H. L. Malm and I. L. Fowler in IEEE Trans. Nucl. Sci. NS-13 (No. 1), 62 (1966).]

curves for the 16- and 54-cm³ coaxial detectors in the figure, the efficiency of a good 16-cm³ planar detector is comparable to that of a 30-cm³ coaxial detector.

Acknowledgments

The author is extremely grateful to workers too numerous to be mentioned by name—both at this laboratory and elsewhere—for direct and indirect contributions to the efforts described here. He is also grateful to F. E. Throw for valuable assistance in the preparation of the manuscript. The efforts of all persons in the Semiconductor Detector Group, and staff members of other groups in the Electronics Division at Argonne are gratefully acknowledged. Many of the users have contributed valuable information obtained in pursuit of their experiments. Special acknowledgment is due L. M. Bollinger and his colleagues for their interest and support.

Appendix A

The following companies constitute our present list of suppliers of Ge(Li) detectors and germanium monocrystals. (Other possible suppliers are not included.)

Ge(Li) Detectors

Nuclear Diodes, Inc.
P. O. Box 135
Prairie View, Illinois 60069
312-634-3870

Princeton Gamma-Tech
Box 641
Princeton, New Jersey 08540
609-924-7310

Isotopes, Inc.
50 Van Buren Place
Westwood, New Jersey 07675
201-664-7070

Ortec
102 Midland Road
Oak Ridge, Tennessee 37830
615-482-1006

Nuclear Equipment Corporation
931 Terminal Way
San Carlos, California 94070
415-591-8203

Solid State Radiations, Inc.
2261 South Carmelina Avenue
Los Angeles, California 90049
213-478-0557

S. A. I. P.
(Société d'Applications Industrielles de la Physique)
38, Rue Gabriel-Crié
Malakoff (Hauts-de-Seine-92)
France

RCA Victor Company, Ltd.
1001 Lenoir Street
Montreal 30, Canada

Amperex Electronic Corporation
230 Duffy Avenue
Hicksville, Long Island, New York 11802
516-931-6200
(N. V. Philips, Eindhoven)

Germanium Monocrystals

Geoscience Instrument Corp.
435 East 3rd Street
Mount Vernon, New York 10553
914-664-5100

Societe Generale des Minerais
Metallurgie Hoboken
Olen, Belgium
(U.S.A., NPC Metals and Chemicals,
3133 E. 12th St., Los Angeles,
California 90023; 213-268-3464)

Sylvania Electronic Products
Towanda, Pennsylvania 18848
717-265-2121

Tokyo Denshi Yakin Kenkyusho
2-18 Nichirokugo-cho
Ohta-ku, Tokyo, Japan

Societe de Mines et Fonderies du Zinc
de la Vieille Montagne
Angleur, Belgium
(U.S.A., Harmon and Lichtenstein,
26 Broadway, New York, N. Y. 10004
212-422-8395 or 914-834-5012)

Appendix B

In our discussions with visitors, manufacturers, representatives, and other persons interested or engaged in preparation of the Ge(Li) detector, we find one of the problems most often encountered is that of making an electrical contact to either the p or i region of the detector. This is easily and reproducibly done by a technique we have previously published.^{3 8} According to our interpretation of difficulties encountered by others, the importance of avoiding oxidation of the surface onto which the contact is applied must be strongly emphasized. The step-by-step procedure for applying a gold contact is as follows.

1. Prepare the gold-plating solution for use.

(a) Pour 50 cc of Atomex immersion gold plating solution (available from Engelhard Industries, Inc.) into a 1-liter plastic bottle

and then fill bottle to the 1-liter mark by adding deionized water. Mix thoroughly.

(b) Use any desired quantity of the diluted solution, and add an equal volume of acetic acid.

(c) To the solution (b) containing acetic acid, add 10% by volume hydrofluoric acid (electronic grade, assay 49%).

(d) Heat solution (c) to $85-90^{\circ}\text{C}$.

2. Plate gold onto the germanium crystal.

(a) Immerse the cleaned crystal into concentrated nitric acid at room temperature for 1 min.

(b) Rinse thoroughly with distilled water.

(c) Immerse the crystal in concentrated hydrofluoric acid for 1 min.

(d) Transfer the crystal from the hydrofluoric acid to the gold-plating solution, maintaining a meniscus of hydrofluoric acid on the surface to be plated.

(e) Allow 2—5 min for completion of plating.

(f) Remove the crystal from the plating solution and rinse thoroughly with deionized water.

Prior and subsequent steps in preparation vary somewhat from one laboratory to another. An enlarged version of our preparation procedures is being assembled.

* * *

L. M. BOLLINGER, Argonne National Laboratory: Did I correctly understand that you feel that we are at the end of the road in getting better resolution than is already realized in existing systems?

MANN: Yes. I think we are close to the end of the road in detector resolution. Insofar as the detector is concerned, there is

at present no basis for expecting a linewidth less than 4.5 ± 0.1 keV (FWHM) at a deposited energy of 10 MeV. However, while we can say that we are close to the end of the road in detector energy resolution, we are also limited in our understanding of the processes that govern energy resolution in a semiconductor detector. Measurements to determine the limit of energy resolution always give an upper limit, and the standard error of a measurement does not include any so-far undetectable systematic error. If further improvement is obtained, then it would have to be associated with 0.1% of the charge produced, since this is the quantity of charge that remained uncollected in our measurements.

R. K. SMITHER, Argonne National Laboratory: Even though you are reaching the end of the line with germanium, is it not true that improved resolution might be obtained by use of better materials?

MANN: An improvement in energy resolution is expected to occur as the ionization energy is reduced since $\Delta E_d \propto \sqrt{F \epsilon E}$, where F is the Fano factor, ϵ is the ionization energy, and E the deposited energy. Indium antimonide is considered of interest primarily because $\epsilon(\text{InSb})/\epsilon(\text{Ge}) = E_g(\text{InSb})/E_g(\text{Ge}) \approx 0.2/0.79 = 0.25$. A factor-of-two improvement in linewidth might result—possibly a factor of three over the range of values for E_g that can be considered. The low energy gap would require operation at about $5-20^\circ\text{K}$.

SMITHER: This improvement would mean that a 5-MeV gamma ray could be measured to a linewidth of 1 keV?

MANN: I would say so—to 1—2 keV. Reducing the energy gap by a factor of ten would improve the resolution by a factor of three; but the gap is not reduced by a full factor of ten in going from germanium to indium antimonide.

R. C. GREENWOOD, Idaho Nuclear Corporation: That, of course, assumes that the Fano factor remains the same. Is there any basis for this assumption?

MANN: There is some basis for expecting the Fano factor to be higher as the band gap is lowered (Ref. 50 and Sec. V.A of paper C-3). It would be interesting to answer this question experimentally by use of InSb, primarily because the technological development of this material places it close to germanium and silicon in regard to purity and the degree of crystalline perfection. This means that it is easier to define and control the work of preparing the detector. There is no basis for expecting the Fano factor to be independent of band gap; available information shows it is indeed higher in germanium than in silicon. (It should be evident from the paper that a knowledge of the dependence of F on E_g is required.)

J. R. TATARCZUK, Rensselaer Polytechnic Institute: What are the absolute efficiencies of these detectors?

MANN: For a volume of 16—18 cc, we obtain a full-energy-peak intrinsic efficiency of 4% at 1.3 MeV. This figure is to be compared with the 1.8% full-energy-peak intrinsic efficiency at 1.28 MeV for the most recently prepared 30-cc coaxial structure, reported by Orphan and Rasmussen⁵³ at the Thirteenth Nuclear Science Symposium.

D. S. GEMMELL, Argonne National Laboratory: Would you say something about the best timing you are now able to get with some of these large detectors?

MANN: This has been in the range 5—10 nsec for detectors (2 cm thick) used in the muonic x-ray studies of Coté and coworkers.

⁵³ V. J. Orphan and N. C. Rasmussen, IEEE Trans. Nucl. Sci. NS-14 (No. 1), 544 (1967).

~~C-4.~~ ^(H) PULSE-HEIGHT DEFECT DUE TO ELECTRON
INTERACTION IN THE DEAD LAYERS OF ^(H)Ge(Li)
^(H)γ-RAY DETECTORS*~~c~~

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1. Introduction

A γ ray interacting in a lithium-drifted germanium [Ge(Li)] detector imparts part or all of its energy to an electron (or electron-positron pair) which in turn loses its energy by releasing a large number of electron-hole pairs. These drift to their respective electrodes and thereby induce a current which, if integrated on a capacitor, gives rise to a voltage pulse proportional to the number of electron-hole pairs collected. If the primary electron loses its entire energy in the sensitive volume of the detector, the entire charge is collected (assuming there is no trapping and recombination in the intrinsic region) and the pulse height is proportional to the energy of the primary electron.

The region near the electrodes of a Ge(Li) detector is often poorly compensated. The field in this region is weaker than that in the intrinsic region, thereby enhancing carrier recombination and trapping.¹ Gamma-ray events which occur in this region or in the intrinsic region, but result in electrons whose path extends into the poorly compensated region (electron escape), produce charge which is not fully collected. Thus, the poorly compensated region represents a section in the detector which is degraded or dead and hence is referred

* Work performed under the auspices of the U. S. Atomic Energy Commission.

¹ G. Dearnally and D. C. Northrop, Semiconductor Counters for Nuclear Radiations (E. F. N. Spon Ltd., London, 2nd Edition, 1966), pp. 115-118.

to as dead layer. Events interacting in this layer give rise to pulses with a reduced amplitude which is not proportional to the energy of the primary electrons. Similarly, γ rays interacting in the material supporting and housing the detector may result in electrons that scatter into the dead layer and thereby give rise to defective pulses.

Charge carriers created in the weak-field region have longer collection times than those created in the intrinsic region and therefore result in slower pulses. The amplitude of the already defective pulses may in turn be further degraded by the shaping network in the main amplifier. Thus, the defective pulses degrade the energy spectrum as well as the coincidence resolution. Energy spectra are affected by having reduced full-energy and escape peaks as well as an increased continuum which is most pronounced at low energies. The residual continuum observed with 3-crystal pair spectrometers and with spectrometers employing an anti-Compton annulus is also due in part to pulses degraded by electron interaction in the dead layers. This study was made to determine the extent to which electron interaction in the dead layer near the electrodes affects γ -ray energy spectra.

Slow pulses can readily be identified by pulse-shape discrimination. We determined the effects of such pulses on spectra from single planar and coaxial Ge(Li) detectors and from a Ge(Li)-NaI(Tl) 3-crystal pair spectrometer. It is shown that the continuum is increased significantly, but this increase can be minimized by rejecting the slow pulses as reported by Alexander *et al.*² and Tamm *et al.*³

²T. K. Alexander, J. D. Pearson, A. E. Litherland, and C. Broude, Phys. Rev. Letters 13, 86 (1964).

³V. Tamm, W. Michaelis, and P. Coussieu, Nucl. Instr. Methods 48, 301 (1967).

2. Pulse-Shape Distributions from γ Rays in Ge(Li) Detectors

Before discussing the pulse-shape discrimination technique, it is instructive to briefly review the waveforms resulting from the interaction of γ rays in a planar Ge(Li) detector. To simplify the discussion, the detector is assumed to be ideal; i. e., it is assumed to have a uniform field throughout its volume (no dead layer), and therefore also constant drift velocity. Effects due to such imperfections as leakage current, recombination, and trapping are ignored at the present.

The interaction of γ rays in such a detector gives rise to pulses whose shape depends upon the location of the interaction as well as the spatial distribution of the charge in the detector volume. In turn, the spatial distribution depends upon the energy of the incident γ ray and upon the interaction process. Gamma rays can interact in the detector at one or more locations. The photoelectric processes or Compton interactions in which the scattered photon escapes the detector are considered as interactions occurring at a single location. Gamma rays below 1 MeV which interact at a single location produce charge which is localized in a spot small compared with a 1-cm-thick detector. (The range of 1-MeV electrons in germanium is ~ 0.8 mm.) The electrons and holes contribute to the pulse amplitude in proportion to the fractional distance they travel to reach their respective electrodes. Thus, if the interaction takes place in the center of the detector, the two charge-carrier types would contribute equally to the resulting pulse; whereas if the interaction takes place at one of the electrodes, the resulting pulse corresponds to the charge induced by only one type of carrier. Since the mobilities of holes and electrons in germanium at 77°K are approximately equal,⁴ it is apparent that in the former case (in which

⁴F. S. Goulding, Nucl. Instr. Methods 43, 1 (1966).

Fig. 112. Dependence of the pulse shape on the location at which the gamma ray interacts within the detector volume. A. Waveforms resulting from the interaction of γ rays in an ideal planar Ge(Li) detector. When the charge is localized in a spot that is small compared with the detector width, the pulse shapes are like a, b, c, or d depending on the location of the interaction. When the charge is distributed in the detector volume, the pulses have shapes similar to e. B. Pulse-height distribution at time t_1 . The solid line shows the distribution corresponding to pulse shapes a through d; the dashed line represents all pulse shapes, including e.

the charge carriers travel only half the detector width), the pulse has a fast rise as depicted by waveform a in Fig. 112 A. If one type of carrier crosses the full width of the detector, as in the latter case, it requires twice as much time and results in a slower pulse as described by waveform b. Most signals have collection times which are longer than a but shorter than b and therefore have waveforms similar to c and d. Their initial slope is the same as that of a but as the holes or electrons reach their collecting electrode the slope changes by approximately a factor of two—which corresponds to changing to the drift velocity of a single carrier type.

Gamma rays in the range 0.1—1 MeV interacting at a single point in a 1-cm detector produce waveforms a, b, c, and d with nearly equal probability. The pulse-height distribution expected at time t_1 is shown as a solid line in Fig. 112 B. The sharp peak at 65%

is due to events occurring in the center region of the detector, where they give rise to fast pulses with rise times falling in the range between d and a. The flat continuum is due to events occurring in the outer regions of the detector, where they give rise to pulses slower than d, e. g., like b and c.

Gamma rays interacting at two or more locations in the detector produce charge which is not localized at one point but at several points. This would occur when Compton-scattered photons, annihilation quanta, or bremsstrahlung are reabsorbed. Furthermore, the range of electrons or positrons above ~ 1 MeV is not negligible compared with a 1-cm detector. Thus, the charge produced by high-energy γ rays and by γ rays interacting at several locations, tends to be distributed in the detector volume. The shape of pulses resulting from such events will depend upon the spatial distribution of the charge, including the length of the ionization tracks relative to the detector width and their orientation with respect to the collecting electrodes. The resulting pulse is therefore likely to be a superposition of a number of waveforms like a, b, c, and d in Fig. 112 A. Such a pulse would initially rise at the same rate as waveform a but would then assume a mean shape similar to e. A typical pulse-height distribution at time t_1 due to all interaction processes, including all pulse shapes (a through e), is shown as the dashed line in Fig. 112 B. This distribution exhibits a somewhat more uniform pulse shape than the other (solid line) distribution, as would be expected when the charge is not localized but distributed in the detector volume.

Studies of the pulse-shape distributions resulting from the interaction of γ rays in planar Ge(Li) detectors⁵ strongly support

⁵M. G. Strauss, R. N. Larsen, and L. L. Sifter, Nucl. Instr. Methods 46, 45 (1967).

the model shown in Fig. 112. Barring edge effects, it appears that the performance of planar detectors⁶ closely resembles the behavior of an ideal diode. Edge effects introduce anomalies which are the subject of this paper.

3. Pulse-Shape Discrimination System

Electrons that interact in the dead layer or near it, but have a path that extends into it and perhaps beyond the crystal (electron escape), produce slow pulses of reduced amplitude. To identify these pulses, the charge collected in the first 20 to 100 nsec is compared with the total charge as Brooks⁷ did. The comparison is made by using Bennett's⁸ pulse-shape discrimination technique, implemented with the system shown in Fig. 113. The integrated pulses from a fast preamplifier are routed into two branches. In the upper branch, the fast channel, they are clipped by a shorted delay line and then amplified and stretched at their peak amplitude. In the bottom branch the pulses are amplified and shaped in a conventional linear amplifier. The fast and slow signals are then applied to an analog pulse computer⁹ to calculate the ratio of the two pulses. This ratio represents the rate-of-rise of the detector pulse in percent of final amplitude per 2τ , where τ is the length of the clipping line. A fast pulse produces a larger "ratio" pulse than a slow pulse, independent of its amplitude. The pulse computer is gated for the energy range of interest. Pulse-shape discrimination is

⁶ The planar detectors used in these experiments were fabricated at Argonne by H. M. Mann, F. J. Janarek, and H. W. Helenberg, IEEE Trans. Nucl. Sci. NS-13, No. 3, 336 (1966).

⁷ F. D. Brooks, Nucl. Instr. Methods 4, 151 (1959).

⁸ E. F. Bennett, Argonne National Laboratory Report ANL-6897 (1964).

⁹ M. G. Strauss and R. Brenner, Rev. Sci. Instr. 36, 1857 (1965).

Fig. 113. Pulse-shape discrimination system. The pulse-height distribution of the fast/slow "ratio" pulses is similar to that shown in Fig. 112 B. Pulse-shape discrimination is accomplished by gating the multichannel analyzer with "ratio" pulses corresponding to γ rays interacting in the interior of the detector and not near the electrodes.

accomplished by gating the multichannel analyzer with pulses having "ratios" or rise times corresponding to γ rays interacting in the interior of the detector and not near the electrodes.

4. Interaction of Internal-Conversion Electrons in Planar Ge(Li) Detectors

Pulses produced by events occurring in the dead layer can best be studied by measuring the pulse-shape and pulse-height distributions resulting from the direct interaction of electrons in the detector, rather than the interaction of γ rays. A partial spectrum from ^{207}Bi with two conversion-electron lines is shown in Fig. 114. The spectrum was obtained¹⁰ with a thin-window planar Ge(Li) detector which was compensated to within $10\ \mu$ from the front electrode. The apparent reduction in the energy of the electrons is primarily due to losses in an air path of 8.5 cm and in a 0.25-mm-thick Be foil which

¹⁰F. J. Janarek, H. W. Helenberg, and H. M. Mann, Rev. Sci. Instr. 36, 1501 (1965).

served as window on the detector chamber. Since all conversion electrons interact within 1 mm of the electrode, some electrons, no doubt, escape the detector and thereby produce defective pulses which do not fall in the peaks. However, the fact that the conversion electrons appear in two pronounced and well defined peaks at the expected amplitude indicates that when the electrons do not escape and the dead layer is very thin, charge collection near the electrodes is virtually complete.

Most Ge(Li) γ -ray detectors are not fully compensated throughout; a substantial region near one or both electrodes is often rather poorly compensated.

The pulse-height distribution resulting from the radiation of ^{207}Bi on a planar detector having a thin window on the chamber (0.25-mm Be foil) but a dead layer 0.3 mm thick at the front electrode and one 0.2 mm thick at the back electrode is shown in Fig. 115. The conversion-electron peaks which were so pronounced in the spectrum obtained with the thin-dead-layer detector (Fig. 114), completely vanished from the spectrum obtained with this detector. The distribution of "ratio" pulses or rise times from this detector (Fig. 116) is similar to that shown in Fig. 112 B. The abscissa represents the fraction of the final amplitude reached in $2\tau = 40$ nsec.

Fig. 114. Part of a spectrum of internal-conversion electrons and γ rays from ^{207}Bi , obtained with a thin-window planar Ge(Li) detector which has a dead layer $10\ \mu$ thick. (Measurement by Janarek *et al.*, Ref. 10.) The apparent reduction in the energy of the electrons is primarily due to losses in an 8.5-cm air path and in a 0.25-mm-thick Be foil which served as a window on the detector chamber.

Fig. 115. Part of a spectrum of internal-conversion electrons and γ rays from ^{207}Bi , obtained with a planar Ge(Li) detector which has a window consisting of a dead layer 0.3 mm thick. Note that the electron peaks seen in Fig. 114 have completely vanished.

Thus, fast pulses are represented by the right peak and slow pulses by the left peak. The distribution due to γ rays only is shown in Fig. 116 A; the conversion electrons were blocked with an aluminum absorber.

When the absorber was removed, the distribution due to both γ rays and electrons was obtained as shown in Fig. 116 B. Comparing the two spectra (Fig. 116 C), it appears that the conversion electrons result in slower pulses than those due to γ rays—as indicated by the left peak. This, in turn, suggests that the conversion electrons encounter a thicker detector than do the γ rays. That this is not the case can be seen by remembering that the $\sim 1\text{-MeV}$ conversion electrons lose their entire energy in and near the dead layer and therefore result in pulses of

Fig. 116. Distribution of "ratio" pulses from γ rays of ^{207}Bi (spectrum A), and from γ rays and internal-conversion electrons of ^{207}Bi (spectrum B). The peak on the right is due to fast pulses resulting from events interacting in the interior of the detector, whereas the peak on the left is due to slow pulses resulting from events interacting in the dead layer near the electrodes. Since the conversion electrons interact in the dead layer near the front electrode, they give rise to "ratios" or rise times which are represented by the left peak in B.

reduced amplitude. Gamma-ray-produced electrons of 1 MeV interacting at the same location as the conversion electrons are assumed to result in pulses of about the same amplitude and rise time, as suggested by the tail of the spectrum in Fig. 116 A at $\sim 30\%$. Most γ rays in the range 0.6—1.06 MeV produce one or more Compton electrons with energy less than $E_c \approx 850 \text{ keV}$. Unlike conversion electrons, Compton electrons in this energy range are generated nearly uniformly throughout the crystal and therefore should result in a distribution similar to that shown in Fig. 112 B. However, slow pulses due to Compton interactions near the face of the detector apparently are degraded in the dead layer below 590 keV and therefore are not recorded in Fig. 116 A. The left peak in this spectrum represents a departure from the expected distribution shown in Fig. 112 B. This peak is attributed primarily to energetic Compton electrons which lost some charge in the dead layer, yet not

Fig. 117. Spectrum of ^{207}Bi internal-conversion electrons and γ rays that produced electrons in and near the dead layers. The spectrum was obtained by recording pulses with "ratios" or rise times below the discrimination level shown in Fig. 116. Note that the spectral features characteristic of the conversion electrons and γ rays are barely apparent.

enough to fall below 590 keV. Thus, most γ -ray-produced pulses recorded in Fig. 116 are faster than those due to conversion electrons.

The pulse-height distribution resulting primarily from electrons interacting in the dead layer is shown in Fig. 117. It was obtained by recording only those pulses that are below (slower than) the discrimination level shown in Fig. 116. Most γ rays that interacted in the sensitive region were rejected, as evidenced by the fact that in Fig. 117 the γ -ray peaks are highly attenuated and the Compton edges (E_c) virtually vanished. Thus, the spectrum in Fig. 117 represents predominantly the pulse-height distribution from the conversion electrons as well as from γ rays that produced electrons in the dead layers. However, the features characteristic of the conversion electrons and γ rays are barely apparent in the spectrum; this clearly indicates that

γ rays producing electrons in the dead layer give rise to defective pulses which increase the continuum. This effect is most pronounced at the low-energy end of the spectrum.

5. Degradation of γ -Ray Spectra as a Result of Electron Interaction in the Dead Layers

The effects on γ -ray spectra resulting from electrons interacting in the dead layers of Ge(Li) detectors have been observed in single planar and coaxial diodes as well as in a Ge(Li)-NaI(Tl) 3-crystal pair spectrometer.

5.1. Single Planar Detector

Measurements were made to determine the pulse-height distribution resulting from γ -ray-produced electrons that interact in the dead layers. The distribution of rise times or "ratio" pulses of γ rays in the full-energy peak was compared with that of events in the continuum. The distribution in Fig. 118 A was obtained by gating the system on the ^{60}Co full-energy peak. The peak on the right, due to fast pulses, and the quasi-flat region on the left are characteristic of γ rays interacting in the sensitive region of planar detectors as shown in Fig. 112 B. The distribution of rise times of pulses from a typical continuum at the same energy is shown in Fig. 118 B. Events in the ^{60}Co full-energy peak result predominantly from reabsorption of Compton-scattered photons, and therefore produce γ -ray interactions in two or more locations in the crystal. On the other hand, events in the continuum are predominantly due to interactions of Compton electrons at a single location. While these two processes would result in somewhat different pulse-shape distributions, this effect would not account for the difference observed in Fig. 118 C, especially since the γ -ray energy ranges in Figs. 118 A and 118 B are the same. The distribution from the pulses in the continuum

Fig. 118. Distribution of "ratio" pulses or rise times from γ rays in the full-energy peak of ^{60}Co (spectrum A) and from γ rays in the continuum of ^{24}Na at the same energy (spectrum B). The two spectra are normalized for approximately equal counts in the right peak. The left peak in B is due to defective pulses resulting from electron interaction in the dead layers.

(Fig. 118 B) has a peak on the left (due to slow pulses) which is clearly not present in Fig. 118 A.

On the basis of the results obtained with conversion electrons, we conclude that the left peak is due to Compton electrons, photoelectrons, and electron-positron pairs with energies above 1.33 MeV which interacted in the dead layers and thereby produced defective pulses with amplitude equivalent to 1.33 MeV. Temporary trapping of charge carriers¹¹ in the sensitive region also results in slow pulses of reduced amplitude. However, no evidence of trapping, such as low-energy tails,¹² was observed in this detector. The distance between the end points of the two distributions at $\sim 30\%$ in Fig. 118 C reflects the width of the dead layer. However, since the field in the dead layer is highly nonuniform, this distance is not proportional to the thickness of this layer.

¹¹ For a general discussion on trapping of charge carriers in semiconductor detectors, see Ref. 1, Chaps. 3 and 4.

¹² A. J. Tavendale, IEEE Trans. Nucl. Sci. NS-12, No. 1, 255 (1965).

Fig. 119. Gamma-ray spectrum from ^{24}Na in a planar Ge(Li) detector, with and without rejection of pulses degraded by electron interaction in the dead layers. The spectrum with rejection was obtained by recording pulses with "ratios" or rise times above the discrimination level shown in Fig. 118. The two spectra are normalized for equal counts in the 1.37-MeV peak. Note that with rejection the continuum at 1.33 MeV is reduced by $\sim 25\%$, as expected from Fig. 118.

If the pulses in the continuum were all due to Compton interactions in the sensitive region, they would have had a distribution of rise times similar to that shown in Fig. 118 A. Yet Fig. 118 B shows that the distribution from pulses in the continuum is quite different. In fact, the difference between the spectra shown in Figs. 118 B and 118 A amounts to 26% of the area of the spectrum in Fig. 118 B. That is, 26% of the pulses in the continuum (at 1.33 MeV) from ~ 3 -MeV gamma rays in this particular detector are defective.

The fraction of the continuum due to electrons interacting in the dead layers can largely be rejected by accepting only those pulses that are above (faster than) the discrimination level shown in Fig. 118. At 1.33 MeV the background would be reduced by 35%, and the full-energy peak by 16%. Below the discrimination level there are more defective pulses than bonafide pulses, but above it the two spectra are virtually identical. Thus, the point at which the two distributions begin to overlap (Fig. 118 C) is the level that yields the optimum peak/background ratio consistent with high peak efficiency. Two spectra of ^{24}Na , taken with and without rejection of defective pulses, are shown in Fig. 119. They

were normalized for equal counts in the 1.37-MeV peak. At 1.33 MeV, the continuum is reduced from an ~ 800 count level to ~ 600 . This reduction of the background to 75% of its initial value increases the peak/background ratio at the 1.37-MeV peak by $\sim 30\%$, as expected from Fig. 118 ($84/65 \approx 100/75$). Degraded events raise the low-energy end of the continuum as already observed in Fig. 117. The high-energy end of the spectrum is virtually unaffected, as is evident from Fig. 119.

Gamma rays above 3 MeV give rise to electrons and positrons which have a longer range in the detector and therefore are more likely to interact in the dead layers. We studied the γ -ray spectrum resulting from the capture of slow neutrons in beryllium nitride. The planar detector used in this experiment has a smaller volume but approximately the same compensated thickness as the previous detector. However, the dead layers are considerably different. The dead layer in this detector was ~ 3.5 mm thick in the front and ~ 0.3 mm in the back. The γ rays were incident normal to the electric field rather than to the front electrode as in the previously described experiments. The "ratio" or rise time spectrum of fully absorbed γ rays was again compared with the rise-time spectrum of γ rays in the continuum. The distributions obtained were similar to those shown in Fig. 118. The comparison was done with ^{60}Co at 1.33 MeV and ^{24}Na at 2.75 MeV using a clipping line with $2\tau = 25$ nsec. Once these distributions were obtained, the discrimination level was established and the energy spectrum was measured with and without pulse-shape discrimination as shown in Figs. 120 and 121. At 1.33 MeV, 50% of the pulses in the continuum are defective and therefore rejected. At 2.7 MeV, the continuum is reduced by 30%. At higher energies the reduction gradually becomes less pronounced, as in Fig. 119, and at 10 MeV the two spectra are virtually identical. The fraction of the continuum due to defective pulses depends on the energy and intensity of the measured γ rays as well as on the detector width. The highest reduction in continuum observed with γ rays from

Fig. 120. Three low-energy regions of the γ -ray spectrum from the $^{14}\text{N}(n,\gamma)^{15}\text{N}$ reaction, obtained with a planar Ge(Li) detector. In each region the spectrum is shown with and without rejection of pulses degraded by electron interaction in the dead layers. Each pair of curves is normalized for equal counts in the most prominent peak. With rejection, the continuum at 1.33 MeV is reduced by 50% and at 2.7 MeV by 30%. The broadening of the 1.29-MeV peak (with rejection) is attributed to drift in the zero intercept, since only the gain was stabilized. The area of the 1.29-MeV peak with and without rejection is nevertheless the same.

Fig. 121. Two high-energy regions of the γ -ray spectrum from the $^{14}\text{N}(n,\gamma)^{15}\text{N}$ reaction, obtained with a planar Ge(Li) detector. In each region the spectrum is shown with and without rejection of pulses degraded by electron interaction in the dead layers. Each pair of curves is normalized for equal counts in the most prominent peak. Note that degraded events result in pulses of reduced amplitude which raise the continuum, mostly in the low-energy regions (Fig. 120).

the reaction $^{14}\text{N}(n, \gamma)^{15}\text{N}$ in an 11-mm-thick detector was 50%. In a thinner detector one would expect a more pronounced spectral degradation and consequently a greater reduction in the continuum. Alexander *et al.*² and Tamm *et al.*³ measured different high-energy spectra (8–11 MeV) with 2–5-mm-thick detectors. By rejecting slow pulses they observed a factor of 2–3 reduction in the continuum. Since the pulse shape is a function of the γ -ray energy, the fraction of peak events rejected also varies with energy. With a given discrimination level, low-energy peaks suffer greater loss than high-energy peaks.

5.2 Single Coaxial Detector

The effect of electron interaction in the dead layers was also studied in a 20-cm³ coaxial detector.¹³ Since the electric field in such a detector is not uniform as it is in planar diodes, the pulse shapes are different and so are the rise-time spectra. Measurements with ^{24}Na similar to those shown in Figs. 118 and 119 were made with the coaxial detector. The optimum clipping time was $2\tau = 90$ nsec, as compared with 25 and 40 nsec for the planar detectors. It was found that 40% of the continuum at 1.33 MeV was due to defective pulses, whereas in planar detector No. 54 only 26% of pulses were degraded. When pulses slower than the discrimination level were rejected, the continuum at 1.33 MeV was reduced by 30%, which is somewhat less than expected. It was not determined if the defective slow pulses were due only to electron interaction in the dead layers or were also due to other phenomena such as carrier trapping in the sensitive region. Low-energy tails due to slow collection times have been observed with this detector.

¹³ The coaxial detector used in this experiment was manufactured by Nuclear Diodes Inc., Prairie View, Illinois 60069.

5.3. Ge(Li)-NaI(Tl) 3-Crystal Pair Spectrometer

Spectra of high-energy γ rays can be greatly simplified by using a 3-crystal pair spectrometer. We constructed a system using a 10.6-mm-thick planar Ge(Li) detector (No. 54) in the center, and two 5X5-cm NaI crystals placed at 180° to each other on either side of the center crystal. The incident γ rays were collimated so that they impinged on the Ge(Li) detector and not on the two NaI crystals. Events in the center crystal were recorded only if two annihilation photons were detected in coincidence in the NaI detectors. Thus, only γ rays interacting by pair production were registered. The resulting spectrum obtained from ^{24}Na is shown in Fig. 122. The continuum between the

Fig. 122. Gamma-ray spectrum from ^{24}Na , as obtained with a Ge(Li)-NaI(Tl) 3-crystal pair spectrometer. The spectrum is shown with and without rejection of pulses degraded by electron and/or positron interaction in the dead layers. The spectrum with rejection was obtained by recording pulses with "ratios" or rise times above the discrimination level shown in Fig. 123. The two distributions are normalized for equal counts in the upper peak. With rejection, the continuum between the two peaks is reduced by 45% as expected from Fig. 123. The high-energy shoulder on the 2.75—1.02-MeV peak is attributed to the fact that the energy windows on the NaI side channels were about 85 keV wide. Thus, annihilation photons losing 42 keV (by Compton scattering) in the center detector were accepted by the side channels and therefore resulted in a 12-channel (3.5 keV/channel) shoulder.

two double-escape peaks is attributed to several processes. Gamma rays scattered in the lead collimator arrive at the Ge(Li) detector with reduced energy. If these γ rays interact by pair production, the resulting pulses are registered below the double-escape peak and thus contribute to the continuum. Electrons or positrons emitting bremsstrahlen which are not fully absorbed in the detector result in pulses of reduced amplitude which contribute to the continuum and not to the double-escape peak. Gamma rays which are Compton scattered from the Ge(Li) detector into the surrounding material, where they interact by pair production, also result in degraded pulses. Similarly, electrons or positrons interacting in the dead layers, or escaping the detector volume, or scattering into it from the surrounding material (where they interact by pair production) produce defective pulses and therefore contribute to the continuum.

The fraction of defective pulses in the continuum was determined by comparing the rise-time spectrum from events in the 2.75—1.02-MeV double-escape peak (Fig. 123 A) with the rise-time spectrum from events in the continuum between the two peaks (Fig. 123 B). The energy of the events in the two spectra is not the same and therefore one would expect some differences in the distributions. However, the shape of these spectra is not a very strong function of energy and thus would not account for the difference observed in Fig. 123 C, namely the peak on the left due to slow pulses. As in previous experiments, this peak is attributed to electrons and/or positrons that are created in the dead layers or elsewhere but have a path that extends into the dead layer. This peak (the difference between the two spectra) amounts to 46% of the area of the spectrum shown in Fig. 123 B. Perhaps it is even somewhat higher than that, since the small peak on the left in Fig. 123 A is thought to have resulted from the fact that γ rays from the continuum were inadvertently included in this spectrum. When the energy range includes only fully absorbed events, as in Fig. 118 A, the left peak is not apparent.

These observations indicate that about half of the continuum between the two double-escape peaks in Fig. 122 (without rejection) is solely due to defective pulses. Virtually all of these can be rejected by accepting only those pulses that are faster than (above) the discrimination level shown in Fig. 123. Thus, 50% of the continuum is rejected while the double-escape peak is reduced by only 14%. The spectra with and without rejection are shown in Fig. 122, normalized for equal counts in the 2.75—1.02-MeV peak. The area of the continuum between the two peaks is only 55% of the original area as expected from Fig. 123 ($86/50 \approx 100/55$). At higher γ -ray energies, the electrons and positrons have a longer range in the detector and therefore are more likely to interact in the dead layers. Thus, at higher energies spectral degradation would be more pronounced than is observed in Fig. 122 from ~ 3 -MeV gamma rays.

Fig. 123. Distribution of "ratio" pulses or rise times from events in the double-escape peak (spectrum A) and in the continuum (spectrum B) of ^{24}Na , as obtained with a Ge(Li)-NaI(Tl) 3-crystal pair spectrometer. The two spectra are normalized for approximately equal counts in the right peak. Note that nearly 50% of the pulses in the continuum are defective (left peak in B) because of electron and/or positron interaction in the dead layers.

6. Discussion

Pulse-height defect due to electron interaction in the dead layers of Ge(Li) detectors is not inherent in the detector properties, but is merely a result of the current techniques of detector fabrication. The factors affecting spectral degradation include the thickness of the dead layer relative to the compensated region, the field intensity in the dead layer, and the pulse-shaping time constants in the main amplifier. In Fig. 114 it was shown that when the dead layer near one electrode was reduced to $10\ \mu$, charge collection near that electrode was virtually complete. If a detector could be made to have a very thin dead layer near each electrode, the fraction of γ -ray events occurring in the dead layers would be very small and spectral distortion due to that effect would be negligible. Events occurring in the intrinsic region but giving rise to electrons that escape into the dead layer and beyond are also responsible for the degradation observed in the spectra presented. However, most of these can be identified and rejected (by pulse-shape discrimination) even when the dead layers are only $10\ \mu$ thick.

We sought to determine if spectral degradation could be minimized by collimating the γ rays so that their direction of incidence is parallel to the electrodes rather than normal to them. This was done by comparing the rise-time spectra from ^{24}Na at 0.66 and 1.5 MeV (in the continuum) when the γ rays were normal to and parallel to the electrodes of planar detector No. 34 whose diameter is 2.1 cm, thickness 1.1 cm, and dead layer at the front 3.5 mm. Any difference between these spectra might have been indicative of a preferred direction; yet no significant difference was observed. The fact that the left peaks, those due to electron interaction in the dead layers, were virtually identical confirms that γ rays in this energy range interact uniformly in the detector volume.

The pulse-shape discrimination system shown in Fig. 113 is most effective for studying pulse-shape distributions as well as for rejection of defective pulses. However, when the prime interest is not the study of pulse-shape distributions but only the rejection of slow pulses, one can use a less elaborate system. The simple pileup-rejection circuit¹⁴ in use at Argonne rejects slow pulses whenever their zero-crossing is delayed with respect to the leading edge of the pulse. Thus, pileup pulses as well as defective pulses, due to electron interaction in the dead layers or trapping in the sensitive region, are rejected with the same circuit.

Acknowledgments

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¹⁴M. G. Strauss, Rev. Sci. Instr. 34, 335 (1963).

G-5. MULTIPARAMETER DATA ACQUISITION AND ANALYSIS AT THE HFBR FAST CHOPPER*†

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1. Introduction

The computer system used for collecting data of the neutron-capture gamma-ray experiments with the fast-chopper facility at HFBR is described. Details of the on-line data acquisition and off-line data analysis are given and illustrated with some results.

2. Description of the System

a. On-Line Data Acquisition

A flow-chart of the system is given in Fig. 124. A chopped neutron beam from the fast chopper is incident on the sample

Fig. 124. Flow-chart of the system.

*This work was supported by the U. S. Atomic Energy Commission.

†A more detailed report on this work has now been published [M. R. Bhat, B. R. Borrill, R. E. Chrien, S. Rankowitz, B. Soucek, and O. A. Wasson, Nucl. Instr. Methods 53, 108 (1967)].

at the end of a flight path 21.66 m long. The neutron-capture gamma rays are detected by either a 10-cc or a 30 cc Ge(Li) detector placed close to the sample but out of the direct beam. The nominal resolution widths of these detectors are 9 and 12 keV, respectively, at about 7 MeV. Pulses from the solid-state detector and from a stable pulser and those corresponding to the zero of the time of flight (TOF) are fed into the pulse-height and time-of-flight encoder. The pulse-height and TOF information are coded into 2048 channels (11 bits) and 1024 channels (10 bits), respectively. The pulses from the stable pulser are used to correct for any gain drift of the pulse-height spectrum, as will be described later. The pulse-height and TOF information of a particular event are then fed into the SDS-910 computer.¹ This is a computer with a word-length of 24 bits, cycle time of 8 μ sec, and an 8 k core memory. It has attached to it a magnetic tape unit, a paper tape punch, a typewriter output, and a photoreader as peripheral equipment. It also possesses a 20-channel "priority interrupt" feature enabling its time-shared use. A signal on any one of these lines forces the computer to interrupt its current operation and enter into a subroutine unique for the particular interrupt line and thus "service" the input data on it. The data-analysis subroutine currently being used takes about 550 μ sec/event.

At the beginning of an experiment, the storage locations of the various input parameters are zeroed, and the experiment is turned on by use of the typewriter. It is also possible to get a typeout of the current status of the experiment from time to time. The data thus obtained include the time interval for which the experiment has been on, data rates, and the chopper rpm. This information is typed out without in any way interrupting the incoming data. Data rates of 2000 counts/min give a dead time of about 4%. In the two-parameter

¹ A product of Scientific Data Systems, Inc., Santa Monica, California.

Fig. 125. Time-of-flight spectrum with W^{182} .

experiments discussed here, the data of a particular event fed into the computer are stored in one memory location (24 bits) with the 10 bits of TOF occupying the first half and the 11 bits of the pulse-height occupying the second half of the computer word. The data are stored in either of the two "ping-pong" buffers, each 515 words long. The first word of such a buffer stores the elapsed time, the second word the run number, and the third the pulser channel number, while the rest of the 512 locations store the data. A special interrupt routine inhibits the superposition of the pulser pulses on the recorded spectrum. As soon as one of the buffers is full, the incoming data are routed to the other buffer while the contents of the filled buffer are dumped onto the magnetic tape as a "record" without interrupting the experiment. One reel of tape can contain about 2600 such records at 200 bits/in. $\approx 1.4 \times 10^6$ events/tape. The usual rate at which the records are written on the tape is about 2 to 4/min.

While the data are being accumulated and stored on the magnetic tape, a live CRT display of the spectra corresponding to either of the parameters and showing 512 channels at a time is available. Such a TOF display obtained with a 100-g sample of W^{182} is shown in Fig. 125. When the experiment is turned off, it is possible to do a limited amount of scanning on the SDS-910 at 7 min/scan.

No incoming data can be stored during such scanning. A scan corresponding to definite limits on the TOF channels on either

side of a resonance can be set by use of the light pen and the CRT display. An example of this is shown in Fig. 126 where the peak corresponds to the 4-eV resonance in W^{182} , and the two brightened spots on either side of it are the TOF limits corresponding to channels 707 and 771 set by the light pen. The result of this scan is seen in Fig. 127, which shows a part of the pulse-height spectrum obtained. A paper tape punch-out or a typeout of such a spectrum could be obtained if desired. It should also be mentioned that while the TOF display during an experiment corresponds to all the 1024 channels, the pulse-height display corresponds to the limits of the TOF set by the light-pen at the beginning of an experiment. It should be emphasized that these light-pen limits govern only the live display of the pulse-height spectrum and do not in any way limit the events that are stored on the magnetic tape.

Fig. 126. Time-of-flight spectrum with scan limits set by the light pen on the 4-eV resonance of W^{182} .

Fig. 127. Pulse-height spectrum of W^{182} for the scan on the 4-eV resonance.

b. Off-Line Data Analysis

The data tape thus obtained is scanned on a CDC-6600 computer.² There are three distinct programs utilized in the extraction of spectra from the data tape:

1. SCANMAG—to assemble spectra from the data tape (with or without gain-drift correction) and store them on a magnetic tape.
2. SEARCH—to search for spectra from different runs from the storage tape and add them with drift correction.
3. PLOT RUN—to produce a line plot and/or a CRT photograph of the spectrum.

The scan program takes about 30 sec of the central processor time per spectrum. The spectra thus obtained are stored on magnetic tape, and one could also get a print-out or punch-out of the data. In scanning the tape, corrections may be applied for long-term drifts within a run by using the pulser tags written at the beginning of each record. The pulser is assumed to be stable, and its peak has a full width at half-maximum of 9 keV. At the beginning of every run the pulser peak corresponding to about 5.3 MeV is set to fall at about channel 1536. The pulser pulses are not actually stored superposed on the pulse-height spectrum, but are stored on the magnetic tape as a tag word. If the gain drift has been appreciable during the course of a run, the spectrum is corrected for these gain drifts as it is being scanned. The first group of a hundred records is scanned; their mean pulser tag is determined. If the mean pulser tag of the next hundred records is different from that of the first group, their corresponding spectrum is suitably shifted and added to the spectrum of the first group, and so on for the rest of the tape. In Fig. 128 is shown part of a pulse-height

²Manufactured by Control Data Corporation, Inc., Minneapolis, Minnesota.

Fig. 128. Pulse-height spectrum of tungsten with and without gain-drift correction.

spectrum of a 20-mil foil of tungsten taken over a 16-h period with and without gain-drift correction. Such a spectrum is stored on magnetic tape along with its pulser tag. The SEARCH program searches for several of these runs taken over a period of days and adds them if so desired after correcting for any day-to-day gain drifts depending on

Fig. 129. CRT display of part of a holmium spectrum.

Fig. 130. Calcomp plot of a tungsten spectrum.

their pulser tags. In such a summed run it has been possible to obtain a resolution width of about 12 keV with the 10-cc detector. This is to be compared with a resolution width of 9 keV seen in a short-time run.

The summed spectra are stored on magnetic tape and may be recalled and plotted on a Calcomp plotter by use of the PLOT RUN program. This program gives a picture of the spectrum as displayed on a CRT for preliminary examination (Fig. 129) and a physical plot for further analysis (Fig. 130).

Using these programs, we have scanned about one hundred reels at the rate of about 2 reels/day. Also it is found that the only practical way to handle the large number of assembled spectra is to store them on magnetic tape.

* * *

M. G. STRAUSS, Argonne National Laboratory: When you search the tape, does the computer make a complete search? Or does the experimenter specify what he would like to have searched?

BHAT: The scan limits are specified to include the resonances you want to study. Those resonances then are shown on a plot of the time of flight.

STRAUSS: Have you ever tried to monitor what is recorded on tape by programming the computer for an associative store? I know you have developed that technique at Brookhaven. It would be interesting to see the complete array of time of flight vs gamma-ray energy as a matrix.

BHAT: We have not used associative programming for this experiment. I think associative programming is most useful when you have an extremely peaked spectrum. If the spectrum is formed of quite a large number of peaks, then you cannot win anyway.

211-2-162

676. HIGH RESOLUTION AT HIGH INPUT RATES IN Ge(Li)
 γ -RAY SPECTROMETERS*

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I. Introduction

The recent development of cooled-FET low-noise preamplifiers resulted in a considerable improvement in the energy resolution obtainable with Ge(Li) γ -ray spectrometers. The 1.33-MeV ^{60}Co line has been resolved to $\text{FWHM} \approx 2$ keV at low counting rates by a number of workers. However, at rates above a few thousand pulses/sec, spectral distortions due to pulse undershoot, baseline shift, and pulse pileup usually masked the resolving power of the spectrometers. In many experiments, such as γ - γ coincidence experiments, high counting rates are unavoidable. Even though the coincidence rate is usually low, the high singles rate incident on the linear gate in the multichannel analyzer is sufficient to cause considerable line broadening and shift.

It is possible to build a spectrometer system in which the rate-dependent distortions are quite small at high rates. Pole-zero cancellation can be used to minimize pulse undershoots due to multiple time constants; baseline restoration can be used to further improve resolution and prevent spectral shifts; and pulse-shape and baseline discrimination can be used to reject pileup pulses. In this paper we show that a system incorporating these features in conjunction with a preamplifier in which the input stage is a cooled field-effect transistor, can measure spectra at rates up to 100 000 pulses/sec with a full width at half maximum at 1.33 MeV of $2-3\frac{1}{2}$ keV and spectral shift of no more than 0.1%.

* Work performed under the auspices of the U.S. Atomic Energy Commission.

II. Pulse-Height Measuring System

The Argonne three-parameter multichannel magnetic-tape recorder-analyzer was originally designed for use with NaI. Recently the system was converted to a two-parameter analyzer for use in γ - γ coincidence experiments with two Ge(Li) detectors. The logic of the original analyzer¹ as well as the circuit details of the encoding system² have already been reported. Therefore this paper concentrates only on the techniques used for obtaining high resolution at high rates.

The detector used is a 3.5 cm³, 13-mm-thick, lithium-drifted, planar germanium diode housed in a cryostat and cooled to 77°K. The preamplifier consists of two sections, a charge integrator and an output driver. The input stage of the integrator is a field-effect transistor (FET) which is direct coupled to the detector and also cooled to 77°K. The amplifier consists of two 3-transistor feedback loops with a gain of 16 per loop. Unipolar RC pulse shaping is used because of its outstanding simplicity and good signal-to-noise-ratio characteristics. To prevent undershoots due to the multiple differentiations, pole-zero cancellation³ is used. The amplifier output pulses therefore return to the baseline gracefully, as shown in Fig. 131(a). The baseline following the output pulses is shown in Fig. 132. When the resistor associated with the last pole-zero cancellation network is adjusted properly [Fig. 132(a) and 132(b)], the pulses return to the baseline promptly without undershooting. However, when the resistor is too large [Fig. 132(c)] undershoot occurs, and when the resistor is too small [Fig. 132(d)], the pulses fail to return promptly to the baseline. In the last

¹ C. C. Rockwood and M. G. Strauss, Rev. Sci. Instr. 32, 1211 (1961).

² M. G. Strauss, Rev. Sci. Instr. 34, 335 (1963).

³ C. H. Nowlin and J. L. Blankenship, Rev. Sci. Instr. 36, 1830 (1965).

Fig. 131. Response of baseline restorer to pulses from ^{60}Co in a Ge(Li) detector. Note that the restorer recovers in about one pulse width, and that the baseline at the output is quieter than that at the input.

Fig. 132. Response of amplifier to pulses from ^{60}Co in a Ge(Li) detector. The waveforms show the effect of proper and improper pole-zero cancellation.

two cases spectral distortion is likely to result. After going through the differentiators and integrator, the pulses emerge from the amplifier with equal rise and decay time constants of $1.2 \mu\text{sec}$.

The integrating section in the preamplifier produces about 0.1 V per MeV of γ -ray energy absorbed in the detector. This corresponds to 0.25 V per MeV at the input to the amplifier. The noise induced in the preamplifier cable is usually small compared to this signal level, and therefore has negligible effect on the resolution. The amplifier has a maximum over-all gain of about 95 and so is useful for γ -ray energies from 50 keV to 20 MeV. The peak-to-peak noise at the output of the amplifier is about 100 mV. When the preamplifier is disconnected, the noise observed is ~ 50 times smaller. Thus the amplifier-noise contribution to the line width in the above energy range is negligible.

After amplification the pulses are encoded by a system which includes a baseline restorer, pileup rejector, linear gate, and analog-to-digital converter (ADC). The ADC measures a pulse amplitude as the difference between a fixed reference level and the peak of the pulse. If the baseline on which the pulse is superimposed does not fluctuate with respect to the reference level, the amplitude measurement is perturbed only by noise on the peak of the pulse. To prevent rate effects and possible dc drift at the output of the amplifier from affecting the baseline and thereby causing fluctuations in the measured pulse amplitude, the amplifier is followed by a baseline restorer which superimposes each pulse on a stable dc level. The baseline restorer used here is a version of the Robinson⁴ two-diode restorer. The input and output waveforms of the restorer are shown in Fig. 131. Each pulse is followed by an undershoot [positive excursion in Fig. 131(b)] which occurs while the restorer is recovering. Note that the recovery time (undershoot duration) is approximately equal to the pulse duration, as it would be in a system using symmetrical bipolar pulses. This quick recovery is desirable because it reduces the number of pulses superimposed on the undershoot⁵ and, hence, recorded in a channel lower than they should be. The baseline restorer also has a substantial effect on the signal-to-noise ratio. Note that in Fig. 131 the baseline at the output of the restorer is considerably quieter than at the input.

Before a pulse is encoded it is inspected for pileup. A discriminator in the system-gated single-channel analyzer is triggered every time an input pulse exceeds the noise level (~ 50 mV), and hence it is referred to as a baseline discriminator. Once triggered, the

⁴L. B. Robinson, Rev. Sci. Instr. 32, 1057 (1961).

⁵Note added in proof: The baseline discriminator has been revised to extend the deadtime for the entire undershoot duration. This eliminates the low-energy shoulder [Fig. 5(b,c)] due to pileup.

Fig. 133. Response of baseline discriminator to pulse-generator pulses. A pulse which "rides" on the tail of a previous pulse fails to trigger the discriminator [(a) and (b)], thereby rejecting "tail pileup" pulses. Once a pulse returns to within 50 mV of the baseline, a second pulse is accepted (c).

discriminator remains paralyzed as long as the pulse waveform is above the noise. The output of the discriminator strobes an internal gate. If all gating conditions are satisfied, a single-channel analyzer output is generated. When a second pulse occurs before the tail of the first one has returned to within 50 mV of the baseline, the discriminator is not triggered a second time. Thus, "tail pileup" pulses are rejected. Such a case is illustrated in Fig. 133(a) and in more detail in Fig. 133(b). The first pulse was not distorted and therefore it was accompanied by an output from the discriminator. However, the second pulse occurred before the tail of the first pulse returned to within 50 mV of the baseline. Since the discriminator was still paralyzed by the first pulse it did not trigger again, but its deadtime was nevertheless extended for the duration of the second pulse. In Fig. 133(c) the second pulse occurred just as the first pulse reached the 50 mV level. Since the discriminator was no longer paralyzed, it generated a second output. The baseline discriminator is also effective in preventing tail pileup due to overload pulses. Despite the fact that these pulses are wider than non-overload pulses, they do not result in excessive tail pileup distortion. The baseline discriminator, and consequently the entire system, is paralyzed until the overload pulse returns to the baseline.

discriminator remains paralyzed as long as the pulse waveform is above the noise. The output of the discriminator strobes an internal gate. If all gating conditions are satisfied, a single-channel analyzer output is generated. When a second pulse occurs before the tail of the first one has returned to within 50 mV of the baseline, the discriminator is not triggered a second time. Thus, "tail pileup" pulses are rejected. Such a case is illustrated in Fig. 133(a) and in more detail in Fig. 133(b). The first pulse was not distorted and therefore it was accompanied by an output from the discriminator. However, the second pulse occurred before the tail of the

A pulse that starts on the baseline rather than on the tail of a previous pulse may still have a second pulse superimposed on its leading edge and therefore be distorted due to "peak pileup." These pulses are identified by the peak pileup detector in which input signals are differentiated in order to produce a zero-crossing. Since the zero-crossing for pileup pulses occurs later than that for normal pulses, the former are readily gated out by the single-channel analyzer, as illustrated in Fig. 134.

Once it is established that a pulse is not contaminated by pileup, that it is within the amplitude range of interest, and that it is accompanied by a signal from a fast coincidence circuit, it is ready to be measured. If the system is no longer busy processing a previous pulse, the linear gate opens and the selected pulse is digitized and stored.

III. System Performance

The system can best be evaluated by observing its performance at several input rates. Typical spectra of ^{60}Co with input rates up to 50 000 pulses/sec are shown in Fig. 135. The rates were measured at the baseline discriminator (i. e. , all pulses above the noise level were counted) and then corrected for the deadtime of that discriminator. To simplify the corrections, an average deadtime of 6 μsec was used instead of the actual extendable deadtime of the baseline

LINEAR GATE OUTPUT

(a)
PEAK PILEUP PULSES
NOT REJECTED.

(b)
PEAK PILEUP PULSES
REJECTED.

VERTICAL SCALE: 4V/cm

HORIZONTAL SCALE: 1 μsec /cm

Fig. 134. Pulses from ^{60}Co in a Ge(Li) detector at the output of the linear gate: (a) without and (b) with rejection of "peak pileup" pulses.

Fig. 135. Spectrometer response to ^{60}Co for various input rates (with pileup rejection). Note that with rates up to 25 000 pulses/sec the resolution is nearly rate-independent, and at 50 000 pulses/sec it is only slightly degraded.

discriminator. The $\text{FW}_{1/2} M$ at 25 000 pulses/sec is virtually the same as that at 1000. At 50 000 pulses/sec, the $\text{FW}_{1/2} M$ is greater by about 10%. In many spectrometers, a low- or high-energy shoulder often develops at high rates. To measure its extent in these spectra, we use the $\text{FW}_{1/10} M$. At 25 000 counts/sec, the $\text{FW}_{1/10} M$ is approximately 10% greater than that at 1000, and at 50 000 it is $\sim 40\%$ greater. Thus,

one can conclude that for rates up to 25 000 counts/sec the resolution of the system is nearly rate-independent.

The low-energy shoulder noticeable at the higher rates is attributed to pileup on the pulse undershoot caused by the baseline restorer.⁵ The extent of this shoulder can readily be estimated from Fig. 131(b). The highest undershoot is ~ 0.2 V; at 2.5 mV/channel the shoulder should extend about 80 channels—as it does. If every pulse is accompanied by an undershoot which lasts on the average 6 μ sec, one would expect that at a rate of 25 000 pulses/sec $\sim 15\%$ of the events which should have been in the peak would fall on the shoulder. Calculation of the number of counts in the shoulder in Fig. 135(b) verifies this assumption.

When these spectra were accumulated, it was noticed that data taken immediately following a change in the ^{60}Co source strength exhibited a spectral shift. However, after about 30 min the peaks returned to nearly their original position. This transient initial shift was thought to be due to drift in the electronic apparatus, the cause being a temporary lack of thermal equilibrium as a result of the change in duty factor. It would be difficult to ascertain whether the slight centroid shift observed in Fig. 135 is due to a rate effect or a thermal effect.

This study was extended to rates up to 100 000 pulses/sec. However, in order to obtain this rate we had to resort to some ^{137}Cs sources in addition to the ^{60}Co , and therefore the spectra obtained cannot be compared directly with Fig. 135 in which only ^{60}Co was used. It is nevertheless worth noting that at 100 000 pulses/sec the $\text{FW}_{\frac{1}{2}}\text{M}$ of the 1.33-MeV line was only 3.4 keV.

In the spectra shown in Fig. 135, most peak and tail pileup pulses were rejected. The continuum above the peak is thought to be due primarily to residual pileup. The effectiveness of the pileup-

Fig. 136. Spectrometer response to ^{60}Co at an input rate of 50 000 pulses/sec, with and without pileup rejection. Note that pileup pulses cause spectral shift, peak broadening, and considerable increase in the continuum.

rejection circuits can be judged by noting that at a rate of 50 000 pulses/sec the high-energy continuum is barely higher than that at 1000 pulses/sec. Figure 136 illustrates the relative distortion due to peak pileup and tail pileup at 50 000 pulses/sec when the rejection circuits are disabled. The top spectrum is reproduced from Fig. 135(c). When peak pileup pulses are not rejected [Fig. 136(b)], the continuum above

the peak increases tenfold; below the peak it also increases. When none of the pileup pulses are rejected [Fig. 136(c)], the continuum is higher yet. In addition to increasing the continuum, pileup also causes line broadening and shift. The 8-channel shift observed when pileup pulses were not rejected [Fig. 136(c)] is attributed primarily to the relatively long tail of the RC shaped pulses. Figure 136 clearly shows the spectral distortion that pileup pulses cause when not rejected. However, when they are rejected, one must bear in mind that the data rate decreases and that eventually, as the input rate is increased, a point of diminishing returns is reached.

In conclusion we wish to stress that to obtain performance such as illustrated here, the entire system must be carefully designed. A low-noise preamplifier and a well designed amplifier would not yield these results unless the baseline restorer, pileup rejector, linear gate, and ADC have also been carefully considered.

Acknowledgments

We are indebted to L. M. Bollinger and H. H. Bolotin for the support and encouragement they have given us in this study. R. W. Bannon carried out many of the spectral measurements with dedication and perseverance. The assistance of C. H. Freese in checking out and optimizing the system was most valuable.

* * *

R. E. SEGEL, Argonne National Laboratory: It seems to me that there are two major effects at high counting rates. One is pulse pileup which you have described, and which your system apparently eliminates very nicely. The other effect may be called paralysis due primarily to unwanted events. If you have even 1000 wanted events

per second, you are doing very well. One usually wants to run at 50 000 to 100 000 counts/sec merely because some other requirement rejects all but a very small number of these. Thus if you have only pileup rejection, then above a certain rate you preserve the nice line shape as the rate goes higher and higher but do not really take data faster — you just throw more and more away. The question is: can anything be done to reduce the paralysis time—the effective time lost on unwanted events? It seems to me that the solution of this problem will be the next real gain in this sort of system.

STRAUSS: You are 100% right. We do not count as fast as we would like to at 100 000 events/sec. This is primarily due to the careful rejection of the very numerous distorted pulses. The only way to correct it is to make the pulses narrower. The width of the pulse is a whole subject in itself.

To some degree the pulse width will depend on the size of the detector. The rate of collection of charge in the detector is approximately 10 nsec/mm. If you want a detector with a linear dimension of 1 cm, the time to collect all of the charge is in the neighborhood of 100—150 nsec. For a 2—3-cm detector, the collection time may be as much as 0.5 μ sec; you clearly will have to integrate the pulse over a time considerably longer than that.

Another point to consider is the shaping of the pulse. After the integration, the pulse has to be shaped in such a way as to filter out the noise due to the preamplifier. The optimum condition for this depends on the preamplifier input stage. With the present field-effect transistors (FET), the optimum shaping time constant for minimum noise is in the neighborhood of 1—3 μ sec, which results in a pulse width of ~ 10 μ sec. If you want to sacrifice noise suppression, then you can make the pulse narrower (as one of the participants here has reported) by clipping it at 200 nsec.

SEGEL: I should like to pursue this a little further. The pulses you want to count have to be treated much more carefully than the unwanted ones. In NaI, where it is very much easier, we have been successful in doing this—and I am sure others have also done so. Is it possible in germanium to integrate only the wanted events, and just throw the others away quickly so they do not bother you?

STRAUSS: We have also built such a system for NaI. Instead of integrating all the pulses, we integrated only selected ones. The selection was based on logic; a telescope told us which of the many pulses we wanted to integrate. Once this was established, we opened a linear gate and integrated and shaped the current pulses. In a gated system such as this, the pulses can be narrow and therefore the paralysis time would be reduced and the data rates increased. Such a system would be particularly useful in coincidence experiments. However, noise filtering may present formidable problems which must be carefully studied so as not to degrade the Ge(Li) resolution.*

G. G. SLAUGHTER, Oak Ridge National Laboratory: Your rates were amplifier rates?

STRAUSS: They were rates in the amplifier—above noise level.

SLAUGHTER: What percentage of the pulses did you count in the analyzer at 100 kc/sec?

STRAUSS: I do not know; but the paralysis time of the system was appreciable.

SLAUGHTER: Yes, that is what would be expected with an extendable deadtime. Another question. Is it feasible to apply a pole-zero cancellation throughout an amplifier such as a TC-200?

*Note added in proof: This subject was discussed at some length at the Conference on Semiconductor Nuclear Particle Detectors and Circuits, Gatlinburg, Tennessee, 15—18 May 1967.

STRAUSS: Rudnick has shown that it is feasible and that at high rates it improves the amplifier performance considerably relative to the original TC-200.

SLAUGHTER: Was this applied to all of the time constants or to just one?

STRAUSS: I think it was applied throughout.

S. J. RUDNICK, Argonne National Laboratory: I have taken a TC-200 and modified each of its time constants to provide either pole-zero compensation or direct coupling. But I found that this made the resolution worse if it were done in a system with the normal preamplifier and the normal analog-to-digital converter. You have to treat the whole system, not just the amplifier.

SLAUGHTER: Is it possible to do this?

RUDNICK: Yes. We did it and obtained an order-of-magnitude improvement at high rates.

SLAUGHTER: Was your amplifier direct coupled throughout?

STRAUSS: Yes. It has one differentiating time constant which is pole-zero compensated.

R. C. GREENWOOD, Idaho Nuclear Corporation: On most of our germanium systems with the TC-200 amplifier, we also have pole-zero correction. As Rudnick indicated, it is also necessary to go into the preamplifier and correct the whole system. But there was a considerable improvement at the higher counting rates.

O. W. B. SCHULT, Technical University, Munich and Brookhaven National Laboratory: I have another kind of question. In your figures, the line position seems to be shifted by something like 2 keV—depending upon the counting rate. Was this 2-keV shift of the peak position due to the germanium detector alone, or did it originate in the electronics?

STRAUSS: No significance should be attached to the shift; I can show you data in which there is virtually no shift in the range from

1000 to 100 000 counts/sec. The shift is due to thermal drift. The circuits were subjected to a rapid change in counting rate which upset the thermal equilibrium. For example, we found that if we wait long enough to establish thermal equilibrium at 1000 counts/sec, take a spectrum at this rate, and then immediately take a second spectrum at 50 000 counts/sec, we notice a considerable shift. Yet if the measurement is repeated after counting at the high rate for about half an hour or an hour, there is virtually no shift. This is due to the fact that the circuits have reached a new thermal equilibrium. In order to finish the measurements in time for this meeting and to avoid long-term drifts, we took the spectra I showed without waiting for final equilibria to be established.

SESSION D

2 NOVEMBER 1966

SPECTRAL ANALYSIS

T. J. KENNETT, CHAIRMAN

~~D-I.~~ AUTOMATIC ANALYSIS OF SPECTRA FROM Ge(Li) DETECTORS*

M. Mariscotti

Brookhaven National Laboratory, Upton, New York

I will describe a method that we have been using since one year ago to analyze our single γ -ray spectra obtained with Ge(Li) detectors.

Due to the high resolution of these detectors, in many cases it is possible to analyze each line individually and obtain its position and intensity by least-squares fitting of the peak and its neighboring channels. Such a procedure is more straightforward than those used to study spectra obtained with NaI crystals.

The complication in the present case, however, arises from the large number of peaks that one gets in one single spectrum; in fact, it takes much longer to analyze it than it takes to run it. For this reason faster techniques become necessary if one really wants to avoid the accumulation of unprocessed data.

One year ago we used to plot our spectra to locate the peaks and choose the interval of channels that we thought should undergo fitting. Then we had to estimate initial parameters and punch out the input data for the least-squares fitting program.

All this seemed to be a very inefficient procedure—especially when, as in our case of recording on magnetic tape, the data were already taken from the analyzer in a very suitable way to send them directly into a computer. What we wanted, therefore, was to have a program that after reading the data from the magnetic tape would be able to find the peaks and set the required parameters to link automatically into the least-squares fitting program.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

The following method makes it possible to have such a program. Currently, the time spent for the analysis of a typical spectrum consisting of about 30 peaks is 15 sec. In this time we get a listing of the positions, heights, and widths with their errors. If desired, in 5 sec more one gets a plot of the experimental points on each peak and of the function fitting them. Some examples of these outputs will be shown later.

The basis of the method is the following. If one assumes that peaks can be described by Gaussian functions and that the background

Fig. 137. A typical spectrum (above) and a comparison between the second difference without averaging ($z = 0$) and the generalized second difference with $z = 5$. The numbered peaks in the spectrum are the ones the computer identified by this method.

may be approximated by a linear function along short intervals (of the order of few times a peak width), then the second derivative of such a function would be zero except where there is a peak. Therefore the computer could easily find it.

Unfortunately, statistical errors are present, and they become very important when one attempts to use the second difference of a real spectrum to find the peaks.

A typical spectrum is shown in the upper part of Fig. 137. The spectrum was taken with a small Ge(Li) detector in the region of 3 to 4 MeV.¹

¹ Gamma rays from the $\text{Cr}^{53}(n, \gamma)\text{Cr}^{54}$, W. R. Kane, M. A. Mariscotti, and G. T. Emery, presented in this meeting (paper F-2).

The background is high, most of the peaks are weak, and in addition, there are doublets. We find that these poor characteristics make this spectrum very useful to test the application of the method.

The central plot represents the second difference of that spectrum. This is taken as

$$S_i = N_{i-1} - 2N_i + N_{i+1}$$

and its standard deviation is

$$F_i = (N_{i-1} + 4N_i + N_{i+1})^{1/2},$$

which is indicated in the plot by a line.

It is clear that this function is not suitable for our purpose because the relative standard deviation (i.e., the ratio F_i/S_i) is very large even for strong peaks such as peak 1 in Fig. 137. In contrast with this plot, however, the one at the bottom shows a function similar to S_i but with a considerably smaller statistical fluctuation. For each peak in the spectrum above we have a group of points clearly deviating from zero. Also the doublets are detected and resolved.

This modified second difference was obtained by iteratively averaging the values of neighboring points. In each iteration we took groups of w channels to get the new value of the central one in that group. We will refer to the value of w as the window width, the number of iterations will be z , and the new function will be called the generalized second difference.

The generalized second difference depends then on two parameters w and z . The best choice for them was found to be

$$z = 5 \text{ and } w = 0.6 \Gamma,$$

where Γ is the peak width at half maximum. These values were obtained by studying the minimum of the ratio $F_i(z, w)/S_i(z, w)$ as a function of these two parameters. Since the results are different when one considers

a doublet instead of a single peak, the adopted pair z, w actually represents a compromise between the values for which, in each case, the minimum of $F_i(z, w)/S_i(z, w)$ occurs.

A convenient definition of the generalized second difference in terms of the independent quantities N_j is

$$S_i(z, w) = \sum_{\text{All } j} c_{ij}(z, w) N_j,$$

with

$$c_{ij}(z, w) = \sum_{\ell=i-m}^{i+m} c_{\ell j}(z-1, w) \quad \text{for} \quad z \geq 1$$

and

$$c_{ij}(0, w) = \begin{cases} 0 & \text{if } |j - i| > 2, \\ 1 & \text{if } |j - i| = 1, \\ -2 & \text{if } j = i, \end{cases}$$

where

$$m = \frac{1}{2}(w - 1).$$

By use of this expression for $S_i(z, w)$, a straightforward computation of its standard deviation gives

$$\overline{\Gamma}_i(z, w) = \left\{ \sum_{\text{All } j} c_{ij}^2(z, w) N_j \right\}^{1/2}.$$

The application of $S_i(z, w)$, with $z = 5$ and $w = 5$, led the computer to recognize the numbered peaks in the spectrum at the top of Fig. 137.

The next step is to establish the procedure to recognize peaks. If the background were strictly a succession of straight sections as we assumed at the beginning, the presence of a peak could be determined by the condition $S_i(z, w) > f F_i(z, w)$, where f is just a factor of confidence. Sometimes, however, as in the case of Compton edges, the background is far from linear. It is then necessary to impose additional conditions based on special characteristics that the second difference keeps exclusively for peaks. The computer uses the function $S_i(w = 0.6 \mu, z = 5)$

to look for sets of channel numbers for each of which the values of S_i fall into three consecutive sections: Section III in which the successive values are positive and larger than one standard deviation, Section II in which the values are positive and less than one standard deviation, and Section I in which the values are negative (Fig. 138).

Section IV in Fig. 138 is

considered in the same way as

Section III. Following the

identification of a sequence like

this, the computer checks whether

certain relations concerning the

number of channels in each section

hold. These relations are set under the assumption that the generalized second difference keeps the basic characteristic features of the second derivative of a Gaussian function.

We will express these relations in the form of conditions that have to be fulfilled. The first one simply requires that

$$|S_{i_0}| \geq 2 F_{i_0}.$$

The second establishes maximum and minimum limits for the number of points in Section I (Fig. 138). It is possible to show that, for $z = 5$ and $w = 0.6 \mu$, the number n_1 of points in Section I should be approximately 1.22μ . Therefore, with allowance for deviations of up to 2 units from this expected value, the second condition may be written as

$$|n_1 - 1.22 \mu| \leq 2.$$

Fig. 138. A doublet and its associated function $S_i(z, w)$. The numbers of points in Sections I, II, and III (or IV) are taken into account to identify a set of points as belonging to a peak.

Fig. 139. Another example, similar to that of Fig. 137, showing that peaks are discriminated from Compton edges.

The third condition establishes that the number n_2 of points in Section II (Fig. 138) must be

$$n_2 \leq \frac{n_1}{2} \frac{F_{i_0}(z,w)}{S_{i_0}(z,w)}.$$

Finally, the fourth condition requires that the number n_3 of points in Section III or Section IV (Fig. 138) must be

$$n_3 \geq n_1 \left[1 - 2 \frac{F_{i_0}(z,w)}{S_{i_0}(z,w)} \right].$$

The application of these conditions makes it possible to discriminate between a peak and a nonlinear section of the background (such as a Compton edge).

Figure 139 shows another spectrum taken at lower energy and its second difference for $z = 5$ and $w = 7$. For both peaks and Compton edges, the values $S_1(z,w)$ are far from zero. The only difference between one and the other remains in their characteristic shapes. The numbers at the top indicate again what the computer recognized as peaks; and as shown, Compton edges were correctly ignored.

Finally, once the peaks are found the program applies a least-squares subroutine.² This subroutine fits a given number of

² This is a general least-squares fitting procedure [E. A. Crosbie and J. E. Monahan, "Arbitrary Functional Fit, Least Squares," Subroutine AN-E208 (for the IBM-704 computer) or ANL-E208 (for the CDC-3600 or 360), Applied Mathematics Division Subroutine Library, Argonne National Laboratory].

experimental values to an arbitrary function, provided that initial estimates for all the parameters entering in such a function are supplied.

At the present time we use a polynomial of second order for the background and one Gaussian function if the interval considered contains a single peak or two if it contains a doublet. The latter option is chosen by the program that checks for peaks lying close together.

The principal parameters are the width Γ of each peak and its position i_0 .

An estimate of the average Γ in the spectrum must be supplied to the program. The position i_0 is taken as the center of gravity of the negative points in Section I of Fig. 138. Given both Γ and i_0 , the program sets the interval of channels as those between channel number

$$i_{\min} = i_0 - 5 \Gamma$$

and

$$i_{\max} = i_0 + 5 \Gamma.$$

If the i_0 value for the next peak is within this interval, then two Gaussian functions will be used and the rest of the parameters (i. e., peak heights, intensity of the background, and shape) will be determined accordingly.

Table XIII lists the results obtained for both examples shown previously. A row is filled with zeros whenever the fitting subroutine did not converge (as in the case of peak 8 in the first example or peak 1 in the second). Figure 140 shows some of the plots for individual peaks and the calculated function that the program carried out for the case of our first example. Figure 141 represents a flow chart of the program.

The program reads the experimental data stored on paper or magnetic tape as they come from the analyzer. Then it reads w , or equivalently an estimate of Γ . With w and $z = 5$, the functions S_i and F_i are computed. Next it sets the limit values for the number of points in Sections I, II, and III in Fig. 138 and searches for those sequences of points that fulfill the four conditions mentioned above.

TABLE XIII. Position, intensity, and width of the peaks in two runs

Peak number	Position ± Error	Height ± Error	Relative	FWHM ± Error	XI	No. of iterations	No. of points			
Run 145014										
1	79.059	0.096	3928	128	1.0000	7 18	0 29	73	6	41
2	183.941	0 582	312	77	0 0794	5 23	1.62	29	11	41
3	208 757	0 926	177	124	0.0451	2.97	2.63	18	6	21
4	229 918	0.335	862	94	0.2195	9.58	1 25	38	5	41
5	313 360	0 851	239	56	0 0608	8.20	2.41	41	9	61
6	379.534	0 348	749	84	0.1908	9.14	1 25	36	7	41
7	473.663	0.520	276	130	0 0703	2 42	1.42	19	6	21
8	0	0.	0	0	0	0.	0.	0	0	0
9	591.279	0.620	401	78	0.1020	6 96	1.72	74	9	60
10	609.569	0.667	371	81	0.0945	6.96	1.72	74	9	60
11	847 729	0.544	236	84	0 0601	3.22	1.40	37	7	41
12	893.735	0.179	1437	69	0.3659	9.50	0.58	64	7	59
13	912 424	0.360	696	81	0.1773	9.50	0 58	64	7	59
Run 035014										
1	0.	0.	0	0	0.	0.	0.	0	0	0
2	182.259	0 431	775	107	0 3022	8 63	1.49	33	5	41
3	249.857	0.290	1610	168	0.6279	10.96	1.24	47	15	41
4	409.863	0.411	446	212	0.1739	1 63	0.87	24	4	21
5	549.883	0.200	1678	112	0.6546	10.16	0.78	49	7	41
6	616.378	0.215	1793	124	0.6992	9 70	0.80	73	7	41
7	660.030	0.097	2564	81	1.0000	10.12	0.37	29	8	41
8	782 065	0.494	311	86	0.1214	3.84	1.30	40	3	41
9	946 043	0.797	327	84	0.1276	8 46	2 71	55	8	41

When the whole spectrum has been scanned and the parameter i_0 is determined and stored for each peak found, the program takes one peak at a time to initiate the fitting procedure. Here we introduce a small change. While a rough estimate of Γ is quite enough for the peak-finding procedure, it is not so for the least-squares fitting subroutine. Usually the latter requires a much better evaluation of Γ to initiate the fitting of each peak. To avoid the undesirable delay of having to estimate carefully the width of each peak, we let the program itself find the more convenient Γ . It starts with the minimum $\Gamma = 2$, and if a fit is not achieved, it adds two units to the last value of Γ until $\Gamma > \Gamma_{\max}$.

Fig. 140. Plots of some of the peaks in the spectrum of Fig. 137 and the functions that fit them best.

The subroutine stops when either a fit is accomplished-- or the maximum allowed number of iterations has been reached. In the first case, the results are stored and the next peak is taken to restart the cycle. The second possibility leads back to the subroutine with a new increased value for Γ . If Γ exceeds the established maximum without a fit having been achieved, the peak involved is disregarded and the cycle restarts with the following one.

Finally the two types of output supplied (a plot and a listing) are indicated in Fig. 141.

* * *

H. H. BOLOTIN, Argonne National Laboratory: The doublets you showed were almost fully resolved. If a closely-spaced pair of gamma rays appears as a peak with a shoulder but with no valley, does your program resolve these lines.

MARISCOTTI: No, it does not.

BOLOTIN: I noticed that the full width at half maximum varied tremendously from one peak to another. One might expect a gradual change in width with energy, but within a narrow energy region the widths should be fairly uniform. When the computer finds that a peak is much too wide, does it try to fit this energy region with two peaks?

MARISCOTTI: No.

BOLOTIN: Another point. The time for the program to make one run over a spectrum is really immaterial; the point is how many times you have to look at the data in order to feel satisfied with the fits you obtain.

MARISCOTTI: We run each spectrum through the computer once, and accept the results. Sometimes peaks are missing, and such peaks ought to be fitted by a simple least-squares program. In general, the

peaks we are more interested in are obtained in the first run—so the effective computer time is actually short.

BOLOTIN: An unsophisticated program for locating peaks was developed by Namenson while he was at Argonne. His program looked for deviations from what the program chose as the average background between peaks. That is, it did what you might do with an unsophisticated eye: it just looked to see if any points go up and down. Just by asking the program "Is there a rise over the general background in this region?" he was able to get 50—60% of even the relatively weak peaks. He, too, was unable to distinguish the component peaks of unresolved doublets, but he was able to pick out the peaks of the stronger doublets.

MARISCOTTI: What happens with Compton edges and bad statistics?

BOLOTIN: The Compton edges you showed would not provide any difficulty at all if you looked at the data by eye. But wouldn't your Compton edges cause difficulty if they were underneath a peak?

MARISCOTTI: Yes.

BOLOTIN: At some point in the analysis, you have to look back at your data to see whether the program had been misled into assigning a Compton edge as a peak or if there was a true peak in this neighborhood.

MARISCOTTI: Of course we look back. But before we had this program we had to fit peak by peak. Punching the experimental values in order to feed them into the computer took a long time, and we felt this was a waste since the data were already on magnetic tape.

O. W. B. SCHULT, Technical University, Munich, and Brookhaven National Laboratory: In case you have to go back to a real peak obtained with extremely poor statistics, the results from fitting it by hand will certainly not be much worse than the results of a computer fit. So you may just as well avoid the inconvenience of putting the data back into the computer. Only a sophisticated program would give a good answer

if the peak comes right under the Compton edge. Such a program would need to store the entire response function of the detector in the computer memory for use in the computer fit.

BOLOTIN: I am not trying to intimate that anyone has such a sophisticated program; I am just saying that the identification of Compton edges is quite meaningless. If a Compton edge is not under a peak, one can see it by eye or can find its equivalent energy and see if it corresponds to the Compton edge of some gamma ray at higher energy. If you never want to look at the data, then you can have the computer identify the Compton edges. But I see little advantage in this; in a complex spectrum you will have trouble in any case.

MARISCOTTI: At low energies Compton edges are a common source of trouble. But in the high-energy spectra from neutron-capture experiments, one really has a smooth background; and here I think the procedure I described is a useful one for automatically fitting spectra with 20—30 peaks.

W. R. KANE, Brookhaven National Laboratory: Bolotin asked what percentage of the peaks are fitted by computer and how this compares with hand fitting of the data. In using this code at Brookhaven, other people engaged in gamma-ray spectroscopy with Ge(Li) detectors have found that the code does miss a few peaks—chiefly those lying right on peaks of Compton distributions. On the other hand, the computer found a number of weak peaks that had not been found by the people who worked on the same data by hand. Thus, in effectiveness in finding peaks, it is just about a standoff between man and machine.

ANALYSIS OF NEUTRON CAPTURE GAMMA-RAY SPECTRA

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1. Introduction

Neutron-capture gamma-ray spectra obtained with high-resolution lithium-drifted germanium detectors may show many peaks which correspond to discrete-energy gamma rays from the capture reaction. In order to interpret these spectra and to determine the level diagrams of the compound nuclides, it is necessary to determine the energies and intensities of these gamma rays. For high-energy gamma rays it is often desirable to determine the differences in their energies to a higher accuracy than the absolute energies of the gamma rays. Although the spectra can be analyzed by hand, we have written a simple computer program to do this tedious task. The computer analysis also gives more accurate results for complicated spectra in which the peaks are not well resolved. To analyze these unresolved peaks it is necessary to consider the shapes of the peaks in order to determine their energies and intensities.

2. Mathematical Formula

High-resolution gamma-ray spectra from many nuclides contain regions where the peaks are quite well separated. As in the analysis of neutron transmission data, we consider a region to be made up of narrow peaks and, between the peaks, a relatively slowly varying part which we shall call the baseline. To fit the points between peaks we have used a least-squares fit by orthogonal polynomials.

*Research sponsored by the U. S. Atomic Energy Commission under contract with the Union Carbide Corporation.

Fig. 142. Asymmetrical function used to fit peaks.

To fit the peaks we have used a function of the form

$$y = h \left(\frac{2}{\exp \left[\frac{-(x - x_0)}{s(1 + a)} \right] + \exp \left[\frac{(x - x_0)}{s(1 - a)} \right]} \right)^2, \quad (1)$$

where, for each peak, x_0 and h are approximate values for the center and height, respectively, s is a measure of the width, and a is the asymmetry parameter ($|a| < 1$). A peak is considered to cover the region from $(1 + a)w$ below x_0 to $(1 - a)w$ above x_0 —hence, a width $2w$.

Figure 142 shows this function for various positive values of a . The width of this function is almost independent of a since one side of the peak comes in the same amount as the other side goes out. When $a = 0$ you will recognize that the function becomes $[1/\cosh^2(x - x_0)s]$. From Fig. 142 we can see that the maximum of the function does not occur exactly at $x = x_0$ unless $a = 0$. Also the maximum of the function changes with a and is equal to h only for $a = 0$. The width w at half maximum depends weakly upon a ; and for $a = 0$, $w = 1.763 s$.

We selected this function rather than a Gaussian function for several reasons.

(1) Much of our experimental data shows asymmetrical peaks so that a symmetrical Gaussian function is not suitable. (2) An asymmetrical Gaussian function appeared to require one or two more parameters than our chosen function and seemed to be more complicated than is justified.

(3) When the asymmetry is zero the function is similar to a Gaussian, as shown in Fig. 143, except that it has longer tails.

(4) The selected function, a special function from a family of functions suggested by T. A. Welton, has several desirable mathematical properties. The real test of the suitability of the function comes in the comparison with the experimental data, as will be shown later. However, I should mention now that the program is written so that if one desires to use another function, a subprogram which calculates that function and its derivatives may be substituted for the present subprogram.

Fig. 143. Comparison of Gaussian and $(1/\cosh^2 x)$ normalized to same peak height and area.

3. Input to Program

Up to 4096 channels of experimental data may be fed in at once. The input may consist of one spectrum of not more than 4096 channels or two sets of data of equal length and not more than 2048 channels each. When one spectrum is input, the program computes the ordinates to be fitted by dividing the number ν of counts in each channel by a constant (for example, the time t in minutes) and assigns to each

point the standard deviation $\sqrt{1 + v}/t$. When two sets of data are input, each set is divided by its appropriate time and the background set is subtracted to obtain the ordinates.

The complete run is divided into regions such that the number of peaks in each region does not exceed 8, and the number of points in the region does not exceed 400. Each region is selected so that there are many more points in the baseline than there are in a peak. For each peak in the region it is necessary to feed in an estimate for the width w at half maximum and the channel number c_0 of the position of the peak. If initial estimates of the area under a peak and the asymmetry are available, these can be fed in also. If estimates of the asymmetry and the area are not fed in, the program computes initial estimates for these parameters for each peak. To estimate the asymmetry, the program first sets a at zero and fits a curve to the baseline. Then, for each peak, a value for a is calculated from the ratio of the area of one half of the peak to the area of the other half. These estimates are used to compute a new baseline and new estimates for a . The process is repeated until the new values for a differ from the previous values by less than 0.05. To estimate the area of a peak, the program sums the points in the portion of the region from $w(1 + a)$ below the center of the peak to $w(1 - a)$ above the center.

The program checks to see whether peaks are well resolved from one another. If two or more peaks overlap, the program does not try to compute values of a for these peaks, but sets a equal to zero for them. It will, however, compute the combined area of these unresolved peaks and apportion separate areas to the individual peaks in proportion to the ordinates above the baseline at the centers of the peaks.

4. Determination of the Baseline

To determine the baseline for a region, a least-squares fit by orthogonal polynomials is made over all the points in the region except those considered to be included in the peaks. If no bound is put on the degree of the polynomial in the input, the program stops at the degree needed for a reasonable fit. After each iteration, the program computes the sum of the squares of the residuals and compares it with the sum from the previous iteration. As long as this sum is < 0.6 of the sum of the previous iteration, the process continues and the polynomial of next higher degree is tried. In general, regions are selected so that polynomials of only the first or second degree are required. However, Fig. 144 shows a fit to a region which contains two Compton edges and requires a polynomial of the 9th degree. This wide region was selected to see just what would happen and the result was very gratifying; however, the detail of the two Compton edges is not reproduced by the program.

Fig. 144. High-energy gamma-ray spectrum from thermal-neutron capture in ^{186}W . These two peaks are full-energy peaks to the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ states of the $[510]$ rotation band.

5. Peak Fitting

The subroutine used to determine accurate values for the function parameters is a modified version of a least-squares routine, called ØRLSQ, written by E. C. Long. The initial estimate for a is simply the input or computed a ; but the other function parameters x_0 , s , and h must be computed from c_0 , w , and the area. The formulas used are

$$x_0 = c_0 + 0.5s(1 - a^2) \ln \left(\frac{1 + a}{1 - a} \right), \quad (2)$$

$$s = \frac{w}{1.763(1 - 0.44a^2)}, \quad (3)$$

$$h = \frac{\text{area} \cdot \sin(\pi a)}{2s(1 - a^2) \pi a}. \quad (4)$$

The subroutine determines the amount of correction to be applied to the initial estimates of the parameters in order to produce the smallest χ^2 with respect to each parameter. Because of this feature, usually only a few iterations are needed and this subroutine is more stable than simple least-squares routines based on applying the full correction of a linear approximation. Separate tests for satisfactory convergence are applied to the four parameters (if not fixed) for each peak. For successive iterations these are: (1) the value of x_0 should change by < 0.01 channel, (2) the height should change by $< 0.1\%$, (3) the width should change by < 0.005 channel, and (4) the asymmetry parameter should change by < 0.01 . If the convergence tests have not been met after 25 iterations, the computations are stopped for this region and the program advances to the next region.

From the converged parameters a new baseline is computed, this time correcting for the contributions of tails of the peaks to the points used in the baseline computation. Finally, another least-squares fit is made to determine more exact values for the parameters, their

variances, and the correlation coefficient between s and h for each peak. Figure 145 shows an example of data of two closely spaced peaks which were fitted by the program.

In the analysis of some data it may be desirable not to allow all the parameters to vary initially but to use a "chain-ing" procedure. Several parameters may be held fixed until a solution is found for the free parameters. Then some or all of the parameters that were held fixed can be turned free by using the results from the previous "chain." The procedure can be continued until all the parameters are turned free (if desired).

After one region has been completed, the program proceeds to the next region until all regions to be analyzed have been processed.

6. Other Computations

From the fitted parameters, the position of the maximum of each peak is computed by use of formula (2) and the standard deviation on c_0 is set equal to the standard deviation on x_0 . The width of each peak is computed from Eq. (3) and the standard deviation on w is set equal to $1.763(1 - 0.44\alpha^2)$ times the standard deviation on s . The area of each peak is computed by use of formula (4) and the standard deviation on the area is computed from the variances of h and s and the correlation coefficient between h and s . Since c_0 , w , and the area are relatively insensitive to α , the variance of α would not give any appreciable contribution to their standard deviations. The χ^2 for each

Fig. 145. High-energy gamma-ray doublet from neutron capture in the 45.8-eV resonance in ^{118}Sn . The transitions are to the $s_{1/2}$ ground state and the $d_{3/2}$ excited state at 24 keV.

peak is computed from the formula

$$\chi^2 = \frac{\sum_{i=1}^N w_i (y_{\text{exp}_i} - y_{\text{calc}_i})^2}{N - n}, \quad (5)$$

where N is the number of points in the peak, n is the number of parameters allowed to vary, and $w_i = 1/(\text{Standard deviation})^2$. The χ^2 for the fit to the baseline is computed from an equivalent formula.

From the position c_0 for each peak, a value of the energy is computed from the equation

$$E_0 = a_0 + a_1 c_0 + a_2 c_0^2 + a_3 c_0^3, \quad (6)$$

where the a 's are input constants for the spectrum.

The standard deviation on the energy is computed from the standard deviation on c_0 and does not include errors arising from uncertainties in the input constants a_0 , a_1 , a_2 , and a_3 .

7. Output

A printed output gives the final parameters c_0 , w , area, α , and E_0 for each peak, their standard deviations, a χ^2 for each peak, and a χ^2 for the baseline fit. A logarithmic plot showing the experimental points and the computed curve is made with a CALCOMP plotter; a linear plot can be obtained on option.

A printout of current estimates of the parameters after each iteration of the peak-fitting routine is optional.

8. Error Checks

The program contains many error checks, especially on the input data. Since all of the input for a region is read in before the checks are made, most errors in input data are found in one run on the

computer. If an error occurs in the processing of a region, the program prints out an appropriate message and proceeds to the next region.

9. Time

The computer time (CDC 1604) to analyze a region of 119 channels with two peaks as shown in Fig. 144 was only 1 min 46 sec. This included 3 "chained" passes of several iterations each, all optional output, and a memory dump.

* * *

H. H. BOLOTIN, Argonne National Laboratory: When you fit two peaks that are not fully resolved, are the resulting asymmetry parameters the same for both peaks?

HARVEY: For the two peaks in the tungsten spectrum shown in Fig. 145, the asymmetry parameters were quite similar. However, for the doublet in ^{118}Sn shown in Fig. 145, they were -0.46 for the upper peak and -0.29 for the lower one. However, the errors were quite large. Our program is not able at present to require the asymmetries to be the same unless they are held constant.

BOLOTIN: If the asymmetry parameters are quite different, is it not possible that there is another peak somewhere in the middle?

HARVEY: Yes, this is very possible. However, I prefer to determine the width and asymmetry for a specific energy region from resolved peaks for the particular experiment, and then hold these parameters fixed in analyzing complex capture gamma-ray spectra.

W. V. PRESTWICH, Argonne National Laboratory: I was also interested in this point. Have you looked at the asymmetry parameters as a function of energy over a relatively wide region?

HARVEY: No. So far our analysis has been restricted mainly to the tin data, which had poor statistics. The apparent variation of the asymmetry parameter occurs because of the poor statistics.

PRESTWICH: Can the asymmetry parameter produce an asymmetry toward the high-energy side of the peak?

HARVEY: Yes.

O. W. B. SCHULT, Technical University Munich and Brookhaven National Laboratory: Does the program compute only the values of the asymmetry parameters, or does it give the errors as well?

HARVEY: The program does compute the errors.

D-5. GAMMA-RAY SPECTRAL ANALYSIS

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The field of slow-neutron capture gamma-ray spectroscopy is one which has benefited enormously from the development and use of Ge(Li) detectors. Virtually every paper presented at this conference demonstrates the revolutionary impact these devices have made. Among the many obvious advantages associated with the use of these detectors, two that stand out are the remarkable energy resolution and the comparative spectral simplicity which allow data of unprecedented accuracy and precision to be obtained. This paper addresses itself to those aspects of gamma-ray spectral analysis that are designed to glean the highest degree of accuracy from the analysis of these data. The two-step procedure to be described is: (1) a fitting technique employed to obtain accurate peak positions and the decomposition of complex pulse-height spectral regions and (2) the utilization of these results to determine gamma-ray energies with high accuracy.

The fitting technique utilizes a program originally written at Argonne, later modified by Shera at Los Alamos, and again modified to some extent at Argonne. The method employs what is known as a variable-metric minimization procedure.¹ The user chooses a line shape of any desired form, and sets up an initial error matrix incorporating his estimates of the various parameters associated with the line shape chosen. A subroutine calculates the value and gradient of χ^2 on the basis of the initial guess. The program then proceeds in the n-dimensional

*Work performed under the auspices of the U. S. Atomic Energy Commission.

¹W. C. Davidon, Variable Metric Method for Minimization (Argonne National Laboratory, Argonne, Illinois, 1966), Report No. ANL-5990 (Rev. 2).

Fig. 146. Two-dimensional schematic representation of the main aspects of the variable-metric minimization procedure. The computer program is shown proceeding from the initial position (1) to a final χ^2 - minimum value (6) in iterative and interpolative steps.

space defined by the total number of parameters corresponding to the peaks to be fitted. This procedure is schematically represented in two-dimensions in Fig. 146. The value and gradient of χ^2 at the initial point, labeled position 1, are used in an iterative progression to a final χ^2 minimum. The code takes steps of virtually arbitrary and variable lengths in this n -dimensional space and proceeds to find a point (position 2) where the value and gradient of χ^2 are again computed. On the basis of these calculated quantities at positions 1 and 2, the program proceeds to interpolate in search of a χ^2 minimum and readjusts the stored error matrix.

Position 3 results. At this point the χ^2 quantities are again calculated and dictate a step to position 4. This procedure is continued until the χ^2 minimum at position 6 is found. At this point a controlled random step is taken to seek a possible better fit. If no improved minimum is found, the initial minimum is adopted. The random step is designed to allow escape from entrapment in local χ^2 minima and provide an access route open to the more general and deepest χ^2 minimum.

The two main advantages of this variable-metric minimization procedure are: (a) Unlike almost all other fitting codes, the error matrix is not inverted after each successive try. Instead, and this is perhaps one of the main advantages, the error matrix is modified in the above-mentioned iteration procedure. This avoids a nonconvergence

and effectively guarantees some solution. (b) Second, it takes controlled but variable steps in the n -dimensional space, thereby leading to a more rapid determination of the χ^2 minimum.

We have chosen to fit gamma-ray peaks with a Gaussian line shape. The Gaussian has three independent parameters—centroid, height, and width. Incorporated into the variable-metric minimization method is the ability to constrain any or all of these parameters, or permit the program to seek its own unconstrained value for the particular parameters involved.

The results of these fits are presented to the user not only as printed output but also in visual form. Figure 147, made directly from a 35-mm film of an oscilloscope trace presented by the computer, shows the final output of the computer program. The vertical lines delineate the various regions of fit. The original data are shown and the curve through these data points follows the computer fit based on the χ^2 minimum. This visual form is of considerable aid in readjusting some of the initial guesses when needed. In analyzing a 4096-channel spectrum, this program is capable of fitting 50 pulse-height regions—each of which may have as many as 10 peaks. A typical run on the CDC-3600 computer takes approximately 3–5 min for a fit of 50 pulse-height regions.

Examples of some typical computer fits to the data are shown in Fig. 148. This figure represents three types of fits made to the same data. The data points shown were obtained after background subtraction. On the left, these data were fitted to a single Gaussian whose width is 5.1 channels, whose centroid is at channel 3035.2, and whose area is 6.37×10^4 counts. For the best fit, the value of χ^2 per degree of freedom is 93. The solid line, representing the fit to these data, is seen to deviate from the points to a marked degree. This fit is not a particularly good one. The normal width of a single peak in this region is expected to be approximately 3.75 channels. After inspection,

Fig. 147. Typical computer output. The oscilloscope trace shows the various gamma-ray spectral regions fitted by the variable-metric minimization procedure. The points represent the initial data, the solid lines are the computer fit to these data, and the pairs of vertical lines extending from the abscissa to the data points mark the boundaries of the regions fitted.

Fig. 148. Results of using the variable-metric minimization procedure to fit identical data under three initial assumptions. At the left, the data are fitted to a single Gaussian. At the right, they are fitted to a pair of unresolved lines. And in the center they are fitted to two unresolved lines whose widths were constrained to be equal. The value of χ^2 per degree of freedom is denoted by $\chi^2/D.F.$, the areas of the component lines are the values given in parentheses, and the numbers associated with arrows pointing to the summits of the component peaks are the centroid positions of these components.

the choice was to fit these data to two unresolved gamma rays. The results appear at the extreme right. The dashed and dotted lines represent the two components obtained. Centroids are found at channels 3034.7 and 3038.3. The larger peak has been assigned a width of 3.83 channels and the smaller one a width of 3.22 channels. The χ^2 per degree of freedom is small and indicates, as does a visual inspection and the smallness of the residuals, that a good fit has been obtained.

However, one expects that two peaks so close in energy would have identical peak widths. A third attempt to fit these data was made by specifying two peaks with the constraint that their widths be

identical. The common value of these widths is free to be assigned by the computer fit. The central portion of Fig. 148 shows the results. The centroids at channels 3034.6 and 3038.0 are virtually the same as those obtained for the case of two unconstrained peaks. The χ^2 per degree of freedom is virtually as good. The resulting widths are now consistent with the value expected. Which of these two-peak fits is to be preferred depends upon the philosophy of the user. I favor the equal-width result as corresponding more to the anticipated physical situation.

Once the user is satisfied with the computer fits, he has at his disposal the centroids of the gamma-ray peaks, the widths of these peaks, and the areas of the lines.

The second facet of this paper is the method by which one may convert these accurate centroid positions to gamma-ray energies. To ensure accurate determinations of the gamma-ray energies, a series of pulser calibration lines (spaced at ~ 60 -channel intervals) is fed into the analyzer before and after each sample run. During the pulser calibration, the sample spectrum is allowed to enter the analyzer; and the spectrum is digitally stabilized by use of the same gamma-ray peak from the sample run as was used for that purpose in the normal spectral runs. This ensures an accurate one-to-one correspondence between energy and channel number in calibration and sample runs. A sensitive and accurate determination of the various calibration pulse heights is made by use of a high-precision digital voltmeter which records the voltage stored on the pulser capacitor immediately ahead of the mercury switch. The series of pulser peaks are used to sensitively trace the over-all linearity of the system.

The underlying assumption of this calibration method is that the digital voltmeter reading varies linearly with the pulse height of the pulser peak. It was observed that contact potentials and/or other effects produced a small but detectable digital voltmeter reading at zero

pulse height. This zero correction required at least two accurately known energy standards to define the linear relationship between pulse height and energy. For this purpose the accurately determined energies of the carbon ground-state gamma ray (4945.4 keV) and the Ar^{41} line (1293.4 keV), present in all spectra, were employed.

Figure 149 shows a fictitious and exaggerated version of the linearity curve for the system, as could be traced out by the series of pulser calibration

Fig. 149. Curve of pulse height vs energy, plotted on an exaggerated scale to emphasize possible deviations from linearity. The solid dots are the centroids of the pulser calibration peaks. The dashed lines show schematically how the curve is used to determine the energies of the peaks shown.

peaks. From the computer-fitted centroids of the sample gamma-ray peaks and the pulser peaks, one may then utilize this curve together with the linear relationship between digital voltmeter readings and energy to obtain the energies of the spectral gamma rays to within approximately 1 keV in favorable cases.

Then by utilizing a predetermined efficiency curve for the particular Ge(Li) detector employed, one can obtain the relative intensities of the various gamma rays present in the spectrum from the areas of the lines derived from the computer fits to the gamma-ray peaks.

* * *

E. B. SHERA, Los Alamos Scientific Laboratory: Have you considered the possibility that the linearity of the electronic system as measured with a pulser might not be equivalent to the linearity for

gamma rays? A lack of equivalence might arise from such things as a slight difference between the pulse shapes from the pulser and from your detector.

BOLOTIN: Yes, we have seriously considered this possibility. A few people at Argonne have investigated several well-known cascades by this technique, and have obtained excellent agreement between the sum of the energies of the cascade γ rays and the energy of the crossover transition. I think this is good evidence that this method works quite well.

R. T. CARPENTER, University of Iowa, Iowa City: I certainly agree that the width of a peak does not depend upon statistics, but it is a very slowly varying function of energy. Does your program constrain the widths to have a constant value over reasonably small energy intervals?

BOLOTIN: The procedure is to start with peaks believed to be single and to plot their widths as a function of energy. This gives an idea of the width a peak can be expected to have in a given energy region. The next step is to inspect the widths of some obvious doublets. The decision to invoke a smaller or larger number of gamma rays in that region is then based on the widths the fitting program obtains for these doublets. As a general rule, there is no need to fix the widths. The energy finally assigned to a peak comes from its centroid. In some test cases, the widths have been varied (locking them to a series of slightly different values) and the resulting centroids have been found to remain virtually unchanged. If the line widths are consistent (within the error) with the observed widths of nearby single lines, this is accepted as one criterion of a good fit.

L. M. BOLLINGER, Argonne National Laboratory: How much do the widths scatter around your curve of width vs energy?

BOLOTIN: In my experience, the widths of most lines are within approximately 10—15% of the average in that region.

M. G. STRAUSS, Argonne National Laboratory: The nonlinearity you showed for your system indicates inequality of the channel widths.

BOLOTIN: The curve I drew was just to illustrate the method described; it greatly exaggerated the nonlinearity actually found in practice. There certainly are differential nonlinearities, but it is not clear that they are great enough to cause concern. They are not disturbing in intensity measurements since the detector efficiencies introduce larger uncertainties. When there are five or six points straddling a peak, the pulse-height region fitted is narrow and any such nonlinearity would have to be drastic to affect the accuracy by more than our quoted error.

O. W. B. SCHULT, Technical University, Munich and Brookhaven National Laboratory: Could you get an idea of the nonlinearity of your multichannel analyzer by looking for nonuniformity in the spacing of the centroids of your pulser peaks?

BOLOTIN: We have done this, and within the quoted accuracy of the centroids, the pulser centroid spacing is constant over fairly broad regions.

SESSION E

3 NOVEMBER 1966

**DETERMINATION OF DECAY SCHEMES,
SPINS, AND PARITIES**

R. E. CHRIEN, CHAIRMAN

E-1. INVESTIGATION OF CONVERSION-ELECTRON SPECTRA FOLLOWING NEUTRON CAPTURE

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As a result of slow-neutron capture, a nucleus emits not only gamma rays but also internal-conversion electrons. The investigation of these gives information about transitions in the radiating nucleus which supplements the study of the gamma rays. In addition to energy and intensity measurements, you may be able to obtain conversion coefficients which provide, in some cases, the multipolarity of the radiation in question. This, of course, is very important for the assignment of spins and parities to levels and for the construction of level schemes in general.

Two main principles have been applied for the study of prompt internal-conversion electrons: the external-target and the internal-target techniques.

As an example of the external-target arrangement, Fig. 150 shows the experimental setup of Pelekhov and Malov¹ in Russia.

Fig. 150. Diagram of an external-target arrangement for the investigation of internal-conversion electrons [Ref. 1].

¹V. I. Pelekhov and A. F. Malov, *Izv. Akad. Nauk SSSR, Ser. Fiz.* 25, 1069 (1961).

Fig. 151. Internal-target arrangement at the Munich reactor [Ref. 3].

The reactor core is to the left. The neutrons travel through a collimating system and hit the target outside the reactor. The target is placed inside the beta-ray spectrometer. Actually these are two spectrometers with an intermediate focus.

This gives the possibility of coincidence measurements by using two counters. The coincidence measurement turns out to be necessary because of a rather high background caused by gamma radiation which comes from the reactor core and is scattered at the target and at the wall of the spectrometer. A similar apparatus is used by Bäckström and Bäcklin² in Sweden. They have a slightly different spectrometer, but the principle is the same.

An example of the internal-target technique is the internal-conversion spectrometer (Fig. 151) used by the group in Munich.³ The people working with it are T. v. Egidy who actually built the spectrometer, Thomas Elze, and (until 1965) myself. The target is placed in the beam tube next to the reactor. The neutron capture occurs at the target and the electrons travel out to a system of lead collimators and into a double-focusing sector-type magnetic spectrometer which focuses them onto the entrance slit of the detector.

²G. Bäckström, A. Bäcklin, N. E. Holmberg, and K. E. Bergkvist, Nucl. Instr. Methods 16, 199 (1962).

³E. Bieber, Z. Physik 189, 217 (1966).

Another internal-target arrangement is used by Balodis⁴ in Riga, Russia. He uses a homogeneous-field magnetic spectrograph and records his spectra on film. His apparatus does not have as good a resolution as the Munich spectrometer but, of course, he is able to get a spectrum in a much shorter time.

Now, what is the difference between the external- and the internal-target techniques? In the first case, you had a small angle for the neutrons to come out from the reactor and in the second you have a small range of angles for the electrons. But the advantage of the latter is that you can use a much bigger target area because the image, which is produced by the spectrometer, is smaller by a factor of 10 than the target itself. This gives you a much higher intensity and, of course, a higher background too. Now if we take the background into account by defining the sensitivity as the number of conversion electrons divided by the square root of the number of background counts, then it turns out that the internal-target arrangement is about 20 times as sensitive as the external. The best resolution width achieved with this instrument so far has been 0.08% in momentum, but the so-called "weekday resolution," if you really measure a complete spectrum, is about 0.2% in momentum. The neutron flux at the target position is about 2×10^{12} neutrons/cm²-sec, but this changes a little with the reactor fuel arrangement. I think the power of the Munich reactor has been raised to 2.5 MW, so it might be better now.

As I mentioned earlier, the trouble starts with the background. There are many components of the background. For example, in the Munich spectrometer electrons are scattered from a graphite plate at the far end of the beam tube (lower left in Fig. 151). In addition, the gamma radiation from the reactor core produces Compton electrons,

⁴M. K. Balodis, W. A. Bondarenko, and P. T. Prokofiev, *Izv. Akad. Nauk SSSR, Ser. Fiz.* 28, 262 (1964).

Fig. 152. Positioning of the target at the reactor core [Ref. 3].

pair electrons, and photoelectrons at the collimating lead plugs here in the beam tube. Figure 152 is a close-up view of the reactor core and the target position. The gamma radiation from the core produces photoelectrons, Compton electrons, and pair electrons in the target itself and also in the wall of the beam tube. The target scatters these electrons into the spectrometer. Then there are electrons from the radioactive decay of aluminum in the wall of the beam tube and electrons from the radioactive decay in the target itself. The most important component of the background is the Compton electrons produced by the gamma radiation in the target

itself. To avoid this, special bismuth elements were placed at appropriate positions in the reactor core in order to shield the target from the reactor gamma radiation.

Superimposed on the background continuum, we find a few background lines produced by external conversion. A rather strong silicon line at 1778.7 ± 0.7 keV is produced by the reaction $\text{Al}^{27}(n, \gamma)\text{Al}^{28}$ which beta decays to Si^{28} . The line from $\text{H}^1(n, \gamma)\text{H}^2$ gives the neutron binding energy of the deuteron; from measurements with different targets, in this case converters, we get a line energy of 2225.5 ± 0.8 keV — which agrees well with the measurements of other groups.

A typical background plot may be seen in Fig. 153. The maximum is found around 600 keV. The drop towards higher energy is due to the shape of the reactor gamma-ray spectrum, and the drop toward lower energies may be explained by the angular dependence of the photoemission taking place at the entrance of the spectrometer. The background at higher energies has been reduced by using a coincidence

counter tube which registers only beta particles that come in the desired direction.

The sensitivity of the spectrometer is determined by this background. From this background plot we can derive a curve for the sensitivity of the spectrometer. If we assume that a conversion line can be seen if at least three points are well above the statistical fluctuations, then we end up with the plot shown in Fig. 154, which shows the results for Sm^{150} , with a measuring time of 1.3 min per point. For example, at ~ 200 keV you would be able to see a conversion line if you have an intensity of 10^{-4} per 100 neutron captures. The sensitivity for the higher energies is much better because of the lower background, and one can use a rather thick target because the resolution is not impaired by energy losses in the target substance itself.

To obtain the intensity a γ -ray transition must have if it is to be detected (Fig. 155), these values (electron intensities per capture) are divided by the conversion coefficient. Since each point is a gamma

Fig. 153. Typical background, measured with the single counters and with the coincidence counter tube shown in cross section above [Th. W. Elze, Z. Physik 194, 280 (1966)].

Fig. 154. Detection limit for Sm^{150} conversion lines. The measuring time was 1.3 min per point. [From Th. W. Elze, Z. Physik 194, 280 (1966).]

line, this is really a compressed spectrum. Around 1 MeV, if you would like to detect a K-conversion line of an E1 transition, the gamma ray must have at least the intensity 0.1 per 100 neutron captures. The sensitivity is poorest here at ~ 1 MeV but gets better toward the lower energies and higher energies because of the reasons already mentioned. We are able to do a little better here toward the lower energies if we accelerate the low-energy electrons. We apply up to 15 kV high voltage to the target, and so have been able to measure electrons down to 0 keV. However, it is not very useful, because in this low region there are many Auger electron lines and they mask all our conversion lines.

At the high-energy end, because of the decreasing background, and because we can use rather thick targets, the conditions are more favorable. Hence we have been able to detect conversion lines up to 7 MeV, as seen in Fig. 156, which shows the conversion lines in samarium. The highest line is at 7.2 MeV. At the right is an enlarged plot of the portion enclosed by the dashed line. It consists of several overlapping K lines. The half-width is a little bigger than I quoted at first because of the peculiar technique used to prepare the target substance in this case. High-energy lines such as this have been measured in samarium and in gold because we have had either rather

high capture cross sections or a high Z which gives a high conversion coefficient.

The usual evaluation method is now to compare the experimental conversion coefficients with the theoretical predictions, in the hope of deducing the multipolarities of the transitions. But often it is rather ambiguous as shown in Fig. 157. This is a measurement in cadmium combining the work of Bäcklin² in Sweden and Smither⁵ at Argonne. In this plot of the K conversion coefficients, the curves for E2 and M1 are seen to be rather close together—and may even intersect. If you find an

experimental conversion coefficient at the intersection, you do not know what kind of transition it is. It may be a mixture, or either one of the two possibilities. Then there is another problem. Here obviously you have a lot of E3 transitions and this does not seem very probable either, especially if you look at the level scheme. So you try to get some

Fig. 155. Distribution of measured γ transitions and detection limits for the corresponding conversion lines [Th. W. Elze, Z. Physik 194, 280 (1966)].

⁵R. K. Smither (private communication).

Fig. 156. Measured conversion-electron spectrum in samarium.

Above: The spectrum up to 7.2 MeV [Th. W. Elze, T. v. Egidy, and E. Bieber, *Z. Physik* **184**, 229 (1965)]. Below: An enlarged plot of the region enclosed by the dashed rectangle in the spectrum at the left [Th. W. Elze, *Z. Physik* **194**, 280 (1966)].

further information by looking, for example, at the K/L ratio if you are able to measure the L lines.

Figure 158 illustrates this. In this case M1 and E2 are very well separated, and the value for E3 conversion is rather low. This is why one tries to get a higher sensitivity with the spectrometer; when one gets above 1 MeV, however, it is hard to make any decisions from the K/L ratios.

As Fig. 159 indicates, once the gamma energy goes above 2.5 MeV, you would hardly get any information because all of these conversion coefficients seem to converge. The calculations have been done by Sliv and Band⁶ up to 2.5 MeV, and we extrapolated carefully in order to obtain the conversion coefficients at these higher energies. We checked the E1 extrapolation with the 7.2-MeV transition in samarium (which has to be of the type E1), and this fits very well with our extrapolation.

The sensitivity limit at the moment seems to be around a capture cross section of 1–10 b. In samarium (which has an extremely high capture cross section), 400 conversion lines have been measured; but in terbium (with a 30-barn capture cross section) we found only

⁶ L. A. Sliv and I. M. Band, *Coefficients of Internal Conversion*, University of Illinois Report 57-ICC-K1.

Fig. 157. Plot of the K conversion coefficients for the low-energy portion of the $\text{Cd}^{113}(n, \gamma)\text{Cd}^{114}$ spectrum.

Fig. 158. Ratio of the intensities of K and L conversion lines for different pure multipole transitions in Au ($Z = 79$) [A. H. Wapstra, in *Methods of Experimental Physics*, Vol. 5: *Nuclear Physics*, edited by L. C. L. Yuan and C.-S. Wu (Academic Press Inc., New York, 1963), Part B, p. 154].

Fig. 159. Energy dependence of the K conversion coefficients for Sm ($Z = 62$) [Th. W. Elze, T. v. Egidy, and E. Bieber, *Z. Physik* **184**, 229 (1965)].

20 lines. Now, what could we do to get higher sensitivity? There are three plans at the moment in Munich. In one plan, the single counter at the end of the spectrometer would be replaced by an array of 10 small counters about 3 mm in diameter, so you can take a big portion of the spectrum at the same time. The next step is a completely new spectrometer design (actually the combination of two spectrometers similar to that in Fig. 150) just to produce an intermediate focus, and then looking at this focus with another 270° spectrometer with a rather high resolution. With this, people expect to double the transmission and to improve the resolution. In addition, going to a high-flux reactor might also gain something. We hope to arrive at capture cross sections maybe a little below 100 mb within a few years.

* * *

R. K. SMITHER, Argonne National Laboratory: With regard to the few cases where rather large conversion coefficients were observed in the energy region below 2.5 MeV, which you mentioned in connection with your Figs. 157 and 158, these coefficients have been assigned to transitions between pairs of states with the same spin and parity and thus the large value of the K conversion coefficient can be explained by assuming the presence of some E0 conversion-electron strength, as everyone suspected; there is no need to invoke the presence of higher multipoles (E3, etc.).

H. H. BOLOTIN, Argonne National Laboratory: At the higher energies, the resolution in your conversion-electron experiment is worse than is achieved in using germanium detectors to look at gamma rays. Since the conversion coefficient is low, what is the advantage of looking at conversion electrons at the higher energies?

BIEBER: Initially, after discussions with R. K. Smither, we were just curious whether we could find some. Then we looked at the conversion coefficients and found that they converge. Better resolution would be helpful, but we had trouble in preparing the target—a rather thick source.

BOLOTIN: Then you probably would not be able to determine any multipolarities because all of the theoretical internal-conversion coefficients are really extrapolations and may be wrong. And besides, as you say, they converge.

BIEBER: In gold, for example, we found that all of the high-energy transitions are E1, as should be expected.

SMITHER: Note added in proof: There is now some evidence that although the M1 and E1 conversion coefficients do converge at high energies, they still do not overlap at 9 MeV and that, if the errors on the electron and γ -ray intensities are of the order of 10% or less, it will be possible to distinguish between E1 and M1 transitions on the basis of their conversion coefficients. This is shown in Fig. 160.

O. W. B. SCHULT, Technical University, Munich and Brookhaven National Laboratory: I would like to say a few words with regard to the figures of merit of different existing magnetic spectrometers for (n, e^-) studies. If the power of the reactor used by Malov is assumed to be the same as that of the reactor in Munich, then we can compare the Rh^{104} results obtained by the two groups. Such a comparison shows that Bieber's data are clearly better. Furthermore, I do not regard the ability to measure a conversion-electron spectrum in a very short

Fig. 160. Experimental values for K conversion coefficients of the 1—9-MeV gamma rays from $\text{Cd}^{113}(n, \gamma)\text{Cd}^{114}$. The crosses indicate known E1 transitions while the open circles indicate known M1 and E2 transitions. The solid lines through the data points depend on energy as $E_\gamma^{-1.96}$ and $E_\gamma^{-2.18}$ for the E1 and M1 radiations, respectively. The dashed lines are the theoretical predictions of Sliv and Band [Ref. 6]. [From R. K. Smither, Phys. Letters 25B, 128 (1967).]

time to be a major advantage because it will ordinarily take several months to analyze the data and to prepare the results for publication.

There is much less bias in a comparison between the measurements at Riga, Studsvik, and Munich. All three groups have studied the conversion-electron spectrum of Ho^{166} . I believe that the neutron flux at the target position is considerably larger at the 5-MW reactor in Riga than it is at the 1-MW Munich reactor. Still the Munich data on Ho^{166} are better than the Riga data. The Studsvik data are comparable to the Munich data, although the Studsvik reactor has a power of 20—30 MW. Thus when the experimental data are compared on the basis of equal reactor power, the experimental arrangement chosen

by the Munich group is seen to be better than those in the other existing facilities.

W. R. KANE, Brookhaven National Laboratory: In comparing the relative figures of merit of the different experimental arrangements, you said that the in-pile arrangement gives about 20 times the sensitivity of an external-beam arrangement. On the other hand, the external-beam experiments (such as that of Bäcklin at Studsvik) afford the possibility of using a multiple-source arrangement. Wouldn't this be rather difficult in your experiment? What does this do to the relative figures of merit of the two types of experiments?

SCHULT: The comparison I made for Ho^{166} is a realistic one. If Bäcklin had not used the multiple-strip source to measure the Ho^{166} spectrum, his counting rate would have been a factor of 20 lower. A multiple-strip source seems to be more difficult if the in-pile geometry is used.

BIEBER: To obtain a figure of merit for use in comparing the two techniques, one has to take account of (1) the solid angle accepted by the beta-ray spectrometer, (2) the area of the source, and (3) the usable fraction of the reactor flux, i. e., the flux at the target divided by the maximum flux available. The combination of these gives a factor of about 1000 in favor of the internal-target arrangement. But the background is higher for the internal-target arrangement, and taking this into account gives the factor of about 20—30.

KANE: Do you have a numerical value for the ratio of the figures of merit of the Munich and Studsvik arrangements on the basis of the same flux?

BIEBER: The ratio of the figure of merit for Munich to that for Studsvik is exactly 1140. This takes account of the multiple-source arrangement but not the background.

H. T. MOTZ, Los Alamos Scientific Laboratory: If one ignores the difference in reactor power and the fact that the source used in the Studsvik experiments is somewhat thinner than the one used in Munich and considers just the data obtained, then the ratio of actual conversion counts for Ho^{166} betas to the square root of the background counts gives a factor of 4 in favor of Munich. Hence I would expect that if a multiple-source arrangement were used under the conditions of these two experiments, the ratios of beta counts to square root of background would agree within something like a factor of two at 149 keV.

BIEBER: This might be due to our trouble in preparing the source for the Ho^{166} measurements and to being limited to a smaller amount of source material than we would have liked.

K. G. PORGES, Argonne National Laboratory: You indicated that the gamma background is the limit to your sensitivity. Can't this be subtracted out reasonably well—perhaps by putting in a different target with a low cross section, e. g., one whose Z would give about the same Compton effect? Then the limit would be determined mainly by patience and perseverance.

BIEBER: The subtraction would still leave the statistical fluctuation of the background. But by spending 10—20 min measuring every point, the sensitivity could indeed be pushed to lower values.

E-Z. SUPERCONDUCTING INTERNAL-CONVERSION-ELECTRON SPECTROMETER*

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Intensive research has focused upon the spectrum of gamma rays emitted by the nucleus as a result of thermal neutron capture. High-precision Compton and diffraction gamma-ray spectrometers and, more recently, germanium-diode detectors have yielded a wealth of information concerning the energies of transitions and of many of the excited states of the product nucleus. However, these data rarely yield unambiguous evidence about the spins and parities of the levels. In an effort to reduce the extent of these ambiguities, there have been a number of attempts to measure the internal-conversion coefficients of some of the transitions—but most of the successful experiments have been on nuclides with extremely high capture cross sections. The new conversion-electron spectrometer being constructed at Argonne will use an external beam from the reactor CP-5. The beam experiment (in contrast to a target-in-pile experiment) has the advantage that gamma-ray and conversion-electron spectra can be measured simultaneously and with the same sample. Moreover, with suitable instrumentation, γ - e^- , γ - γ , and other coincidence experiments are possible.

The design of the system is shown schematically in Fig. 161. A collimated beam of thermal neutrons from the reactor enters an evacuated target chamber (8 in. in diameter and 3 in. high) and impinges upon a thin target located at the center of the chamber. The target is mounted on a carrier by which it is moved along a path intersecting the beam at right angles. The carrier passes through a vacuum lock which allows the insertion or removal of samples from the chamber without disturbing the vacuum. The detectors are mounted on a vertical line through the intersection of the beam and the path of the target.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

Fig. 161. Target chamber and Dewar of the conversion-electron spectrometer. The horizontal tube of the target changer (lower photograph) is a vacuum lock to permit changing the target without breaking the vacuum. The neutron beam traverses the chamber via the channel (capped off in the photograph) perpendicular to this tube. Conversion electrons from the target are guided by the field of the superconducting magnet (diagram) to a Si(Li) detector mounted on a cold finger inside the Dewar (upper photograph). These electrons are counted in coincidence with γ rays detected in a Ge(Li) detector mounted ~2 in. below the target. The reservoir at the top of the upper photograph maintains the liquid nitrogen at a constant level.

The gamma-ray detector, a 7-cm³ Ge(Li) diode, is housed in an independent vacuum system. It is inserted into the target chamber through a sleeve sealed with O rings so that its distance below the target can be adjusted. From a hole through the center of the top cover of the target chamber, an evacuated tube (1.5 in. in diameter) extends upward a distance of 50 in., passing completely through the liquid helium cryostat in which the superconducting magnet is housed. The electron detector, a Si(Li) diode 0.75 in. in diameter and 2 mm thick, is mounted on the end of a cold finger suspended from the top of the through tube. The distance from target to detector can be adjusted by moving the cold finger up or down in the tube.

The magnet measures 2 in. inside diameter by 10 in. long and is situated immediately above the target chamber. Its central field is about 2×10^4 G. Conversion electrons having a velocity component upward along this field as they leave the target describe helical paths up the tube until they strike the detector approximately 10 in. above the target. This focusing action in effect enhances the solid angle of the electron detector approximately 50 fold, but the inverse-square law still reduces the gamma-ray flux at the detector. The electron spectrum obtained is thus virtually free of gamma-ray background.

The electron detector currently in use has a resolution width of 6 keV at the 975-keV line of Bi²⁰⁷, a value competitive with that of beta-ray spectrometers of conventional design. In addition, the Si(Li) detector has the advantage of making integral rather than differential measurements—i. e., all electrons striking the detector are analyzed for energy. The magnetic lens not only enhances the electron intensity relative to the gamma background but also affords an acceptance angle comparable to that of the best conventional spectrometers.

The new spectrometer has not yet been installed in the reactor building, but preliminary performance data have been taken

Fig. 162. Internal-conversion spectrum of Os^{181} , observed 30 min after chemical separation from the W^{182} target. For simplicity, the lines of only eight of the transitions have been indicated.

with radioactive samples. For example,¹ one source was prepared by chemically extracting 105-min Os^{181} produced by the $(\text{He}^3, 4n)$ reaction on a tungsten target enriched in W^{182} . The source undergoes orbital-electron capture to Re^{181} , which in turn decays to W^{181} with a 20-hour period. Successive electron spectra were observed at 30-min intervals in order to distinguish the Os^{181} spectrum from that of the daughter

¹ S. B. Burson, P. J. Daly, and P. F. A. Goudsmit, Bull. Am. Phys. Soc. 13, 673 (April 1968).

as the latter grew into the source. No internal-conversion coefficients for the transitions in Re^{181} were previously available. The spectrum shown in Fig. 162 is representative of the data obtained with the new spectrometer. More than 60 gamma transitions are observed, and of these we have already determined conversion coefficients for 20. The data are still being analyzed.

* * *

O. W. B. SCHULT, Technical University, Munich and Brookhaven National Laboratory: What was the solid angle at your apparatus?

BURSON: For a target of normal size (say, a few square centimeters in area), it is approximately $\frac{1}{2}\pi$ sr. The geometric calculation of this would be very complicated, and we have done it only very qualitatively. As seen in Fig. 161, the target is placed in the center of a target chamber 3 in. thick; so it is $1\frac{1}{2}$ in. below the aperture at the bottom of the magnet. The hole through the magnet has a diameter of $1\frac{1}{2}$ in. The detector (about 0.75 in. in diameter) is centered on the axis, about 10 in. above the target. Since the diameter of the detector is half that of the entrance aperture, and since the magnetic field at the detector is twice that at the aperture, a field line that clears the edge of the aperture will pass through the detector. The electrons move in tight helices about the field lines, so virtually all the electrons that pass the aperture will be detected (except for a modest fraction excluded by the magnetic-mirror effect).

The difficult part of the analysis is to determine what fraction of the electrons emitted from a particular target point will pass through the aperture. Since they are guided by the field lines, one can assume as a first approximation that if the field line through the point of emission passes through the aperture, the electron will be

detected if its velocity component along the field line is directed toward the detector. For a point on the axis of the solenoid, the field is normal to the target and all electrons emitted into the hemisphere above the target would be collected. Off the axis, the field lines are increasingly oblique to the target and the collection efficiency drops off. Hence the effective solid angle of the instrument depends on the size of the target. A more reliable estimate would have to take account of such complicating factors as the diameter of the electron helices and the magnetic-mirror effect, but an experiment performed since the meeting indicates that the estimate of $\frac{1}{2}\pi$ sr is reasonable for a target of normal size.

Thus the transmission of the instrument is around 20%, comparable to that of very large spectrometers. It is of the order of 50 times the 0.5% transmission of a typical sector spectrometer.

SCHULT: You need not consider a sector spectrometer for this type of experiment; you could, for instance, take an "orange" spectrometer. The iron-free "orange" spectrometer at Munich can be used for measurements up to something like 300 keV at the present time, but a better power supply would make it useful up to 1 MeV. In a typical application, it accepts 20% of the 4π solid angle and has a resolution a little better than 1%. I think that it would be best to first measure the detailed (n, e^-) spectrum with a high-resolution spectrometer. With this as a starting point, the computer could be used to analyze another (n, e^-) spectrum—which has been obtained with a detector having a poorer resolution, in particular at low energies.

BURSON: I don't think there is any argument. Each instrument has its own advantages and disadvantages, so one instrument is better for one job and another is better for some other job. I believe that our device will be useful and very convenient in coincidence experiments because almost any desired type of detector can in effect be placed very close to the target.

I believe we have licked the question of analysis, although we have not yet tried it with this instrument. I feel that if one can peel NaI(Tl) spectra, then one can certainly peel spectra as simple as these since the background is constant and the response of the system is uniform.

In coincidence experiments, for which I believe our instrument is adaptable, high resolution at the lower energies is less important than when doing only singles measurements.

J. R. TATARCZUK, Rensselaer Polytechnic Institute: Did I correctly understand that your field-effect transistor is mounted in with your detector, but that the rest of the preamplifier is well outside the magnet?

BURSON: Yes. I should acknowledge here that this system was built by Irvin S. Sherman and Harry M. Mann and his group. They had serious misgivings about this arrangement, since this was the first Argonne instrument in which such a preamplifier was built with the FET removed this far from the remainder of the amplifier. The FET is mounted with the detector so it is kept cold, and the amplifier is about 5 ft away. Of course the wires are strung so as to minimize the capacitance to the tank, from which they emerge near the top of the cold finger. The rest of the preamplifier is bolted to the gooseneck in the cold finger. The system showed an intrinsic jitter of about 1.5 keV; but since the detector is not a particularly good one, we do not know how much of this is due to the circuit. One can't just pull the detector out and put in another; it takes a couple of days to pull the cold finger out and make the replacement.

(N)
E-3. GAMMA-GAMMA ANGULAR CORRELATIONS IN THE
 $\underline{V}^{51}(n, \gamma)\underline{V}^{52}$ REACTION

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The apparatus described earlier^{1,2} has been used to study gamma-gamma angular correlations in the $\underline{V}^{51}(n, \gamma)\underline{V}^{52}$ reaction. A neutron beam from the Saclay EL3 reactor is diffracted by a Pb crystal, resulting in a flux of 10^6 neutrons/cm² per sec at the target position. The capture γ rays are detected in a 4×4-in. NaI(Tl) rotating crystal and a 3×5-in. stationary crystal; the latter is surrounded by a 10×12-in. NaI(Tl) annulus, working in the anticoincidence mode. High-energy capture γ rays are detected in the stationary crystal, the low-energy ones in the rotating crystal. The following² information is stored on magnetic tape for each coincidence event between pulses in the two counters: the energy deposited in the two detectors, their analogous sum, and the separation time between the two pulses. The information on the magnetic tape is then sorted out for various conditions imposed on one or several of the four numbers stored for each coincidence event. For instance, the Hoogenboom sum-coincidence technique can be used by selecting a window in the sum channel, whereas the real and chance coincidences can be separated by a suitable choice of the time-channel window. The measurements are performed at 90° and 180°, and the asymmetries deduced are used to compute the coefficient a_2/a_0 of the $P_2(\cos \theta)$ term in the angular-correlation function, on the assumption that the high-energy primary transition is E1.

¹ P. Carlos, H. Nifenecker, R. Samama, and J. Fagot, J. Phys. 25, 203A (1964).

² R. Samama et al., Rapport C.E.A. — R. 3034 (1966).

Fig. 163. Sum spectrum for $E_{\text{total}} = 7.300 \pm 0.175$ MeV. The angle between the two detectors is 90° .

An example of a Hoogenboom sum-coincidence spectrum is shown in Fig. 163. The sum window has been set at the ground-state transition energy (7.300 MeV), and the angle between the two detectors is 90° . Some of the peaks shown are probably doublets—for instance those corresponding to the levels around 0.800 MeV. Some also correspond to cascade transitions between the capturing state and an excited level in V^{52} , since the window width on the sum pulses was 0.350 keV; this is the case for the peaks around 0.400 and 0.800 MeV. Several spectra of this kind have been registered, for different sum window settings and various angles between the counters. The γ - γ cascades which have been seen are shown in Table XIV; and in Table XV their relative intensities are compared with previous results.^{3,4} The agreement is satisfactory.

The asymmetries which have been obtained are given in Table XVI and are compared with theoretical expectations⁵ on the

³O. A. Wasson, K. J. Wetzell, and C. K. Bockelman, Phys. Rev. 136, B1640 (1964).

⁴P. Van Assche, U. Gruber, B. P. Maier, H. R. Koch, O. W. B. Schult, and J. Vervier, Nucl. Phys. 79, 565 (1966).

⁵J. Vervier, Nucl. Phys. 78, 497 (1966).

TABLE XIV. The observed transitions and the γ - γ cascades in which they occur. All γ -ray energies are in MeV.

Energies of observed transitions	Corresponding γ - γ cascades
0.125	7.150 - 0.125
0.295	6.87 - 0.295
0.428	6.87 - $\begin{cases} 0.419 \\ 0.436 \end{cases}$
0.645	6.51 - 0.645
0.820	$\begin{cases} 6.51 - 0.793 \\ 6.46 - \begin{cases} 0.823 \\ 0.846 \end{cases} \end{cases}$
1.4	5.9 - 1.4
1.55	5.75 - 1.55
1.78	5.52 - 1.78
2.05	$\begin{cases} 5.22 - 1.96 \\ 5.15 - 2.15 \end{cases}$

TABLE XV. Relative intensities of the observed γ - γ cascades. Gamma-ray energies are in MeV.

γ - γ cascade	Relative intensity ^a	
	Our results	Refs. 3 and 4
6.87 - 0.295	27	27
6.87 - $\begin{cases} 0.419 \\ 0.436 \end{cases}$	100	100
6.51 - 0.645	170	187
$\begin{cases} 6.51 - 0.793 \\ 6.46 - \begin{cases} 0.824 \\ 0.846 \end{cases} \end{cases}$	120	150
5.9 - 1.4	19	
5.75 - 1.55	47	
5.52 - 1.78	20	
$\begin{cases} 5.22 - 1.96 \\ 5.15 - 2.15 \end{cases}$	19	

^aThe intensity of the 0.428-MeV transition has arbitrarily been normalized to 100.

assumption of pure E1 primary transitions and pure M1 secondary transitions; the two possible capturing-state spin values, 3^- and 4^- , are considered.

The asymmetries obtained are rather small and the analysis is complicated by the probable occurrence of the spin values of both capturing states (since no resonance dominates the thermal capture) and of E2 admixtures in the secondary transitions. The details of the analysis will be given in a forthcoming paper. If the hypothesis is made that the E2 admixtures are small in predominantly M1 radiations, the following main conclusions can be reached. (1) The ground-state spin is 3^+ , as suggested by Eckert.⁶ (2) Most of the low-energy transitions have non-negligible E2 admixtures; i. e., the observed anisotropies cannot often be accounted for by assuming pure M1 transitions. (3) A large part of the primary capture γ -ray transitions

⁶H. G. Eckert, Z. Physik 181, 401 (1964).

TABLE XVI. Comparison between the measured asymmetries a_2/a_0 and the theoretical values calculated according to Ref. 5.

	Cascade (E_γ in MeV)	Corrected value of a_2/a_0	
		Our result	Ref. 5
1.	7.150 - 0.125	$-0.06 < a_2/a_0 < 0.01$	$\begin{cases} 3^- - 4^+ - 5^+ & 0.05 \\ 4^- - 4^+ - 5^+ & -0.07 \end{cases}$
2.	6.87 - 0.295	$-0.03 < a_2/a_0 < 0.03$	$3^- - 2^+ - 1^+ \quad 0.05$
3.	$6.87 - \begin{cases} 0.419 \\ 0.436 \end{cases}$	$-0.07 < a_2/a_0 < 0$	$\begin{cases} 3^- - 2^+ - 2^+ & -0.05 \\ 3^- - 2^+ - 3^+ & 0.014 \end{cases}$
4.	6.51 - 0.645	$-0.17 < a_2/a_0 < -0.10$	$\begin{cases} 3^- - 3^+ - 4^+ & -0.06 \\ 4^- - 3^+ - 4^+ & 0.02 \end{cases}$
5.	$\begin{cases} 6.51 - 0.793 \\ 6.46 - \begin{cases} 0.824 \\ 0.846 \end{cases} \end{cases}$	$-0.07 < a_2/a_0 < 0.01$	$\begin{cases} 3^- - 3^+ - 3^+ & 0.187 \\ 4^- - 3^+ - 3^+ & -0.062 \end{cases}$
			$\begin{cases} 3^- - 4^+ - 5^+ & 0.05 \\ 4^- - 4^+ - 5^+ & -0.07 \end{cases}$
			$\begin{cases} 3^- - 4^+ - 3^+ & 0.098 \\ 4^- - 4^+ - 3^+ & -0.137 \end{cases}$
6.	5.9 - 1.4	$-0.11 < a_2/a_0 < 0.03$	$\begin{cases} 3^- - 3^+ - 3^+ & 0.187 \\ 4^- - 3^+ - 3^+ & -0.06 \end{cases}$
7.	5.75 - 1.55	$-0.12 < a_2/a_0 < 0.03$	$\begin{cases} 3^- - 4^+ - 3^+ & 0.098 \\ 4^- - 4^+ - 3^+ & -0.137 \end{cases}$
8.	5.52 - 1.78	$-0.15 < a_2/a_0 < 0$	
9.	$\begin{cases} 5.22 - 1.96 \\ 5.15 - 2.15 \end{cases}$	$-0.15 < a_2/a_0 < 0$	

issue from a 3^- capturing state. This is the case for the 7.15- and 6.51-MeV gamma rays leading to the 4^+ level at 0.140 MeV and to the $4^+ - 3^+$ doublet around 0.800 MeV, respectively.

E-4. ANGULAR DISTRIBUTION MEASUREMENTS OF GAMMA RAYS FROM RESONANCE NEUTRON CAPTURE*

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Historically, this work began with the acquisition, several years ago, of samples of separated tin isotopes. Intensive total-cross-section measurements, which will figure later in this paper, were made with these samples. Then followed a series of neutron-capture gamma-ray-spectra measurements from thermal neutron capture and capture in individual resonances, made by the then largest NaI crystal in the world. Strong high-energy transitions observed from capture in individual resonances indicated that the transitions were anomalously strong M1 gamma rays (if s-wave capture was occurring) and/or E1 transitions were made possible by capture in anomalously strong p-wave neutron

Fig. 164. Level diagram for $^{118}\text{Sn} + n$, showing gamma-ray transitions observed for thermal and resonance neutron capture.

resonances. These questions motivated further measurements using Ge(Li) crystals. While this bettered the gamma-ray resolution width from 6% to about 0.1%, intensity requirements dictated a worsening of neutron energy resolution to that obtainable with an open dc neutron beam using filters and the like. The Ge(Li) spectrometer enabled the primary transitions from capture in the even-even targets to the $\frac{3}{2}^+$ and $\frac{1}{2}^+$ low-lying levels to be resolved—for example, as shown in Fig. 164

* Research sponsored by the U. S. Atomic Energy Commission under contract with the Union Carbide Corporation.

for neutron capture by ^{118}Sn . The 6492-keV and 6469-keV primary transitions proceed to states separated by only 23 keV. The high-energy transitions, prominent in resonance capture, are seen only weakly in thermal capture, indicating that the two compound states involved differ in nature.

Neutron capture by even-even nuclei leading to a $J=\frac{1}{2}$

compound state will exhibit isotropy of the emitted de-excitation gamma rays. Compound states

with $J = \frac{3}{2}$, formed by p- and

d-wave capture in even-even nuclei, will usually lead to anisotropy of the emitted gamma rays with respect to the incident neutron beam.

This is shown for pure dipole transitions from $\frac{3}{2}$ to $\frac{3}{2}$ and from $\frac{3}{2}$ to $\frac{1}{2}$ in Fig. 165. The $\frac{3}{2} \rightarrow \frac{3}{2}$ transition has a minimum at 90° , and the $\frac{3}{2} \rightarrow \frac{1}{2}$ transition has a maximum at 90° . The ratio of the intensities of these two transitions changes by a factor of 1.964 from 90° to 135° .

The effect of multipole mixtures can be to render the distributions more isotropic. For p-wave capture leading to $\frac{3}{2}^-$ compound states, an E1/M2 mixture is possible. However, the single-particle estimate for the E1/M2 ratio is 10^5 , so little admixture is expected.

Gamma-ray spectra following neutron capture in ^{118}Sn were measured at angles of 90° and 135° to the incident resonance-neutron beam. Resonance neutron capture occurs predominantly in the 45.8-eV and 359-eV resonances. Capture was restricted mainly to the 45.8-eV resonance by the use of a Mn filter (to take out the 359-eV resonance

Fig. 165. Relative angular distributions of pure dipole gamma-ray transitions for $\frac{3}{2} \rightarrow \frac{3}{2}$ and $\frac{3}{2} \rightarrow \frac{1}{2}$.

Fig. 166. The $\frac{3}{2} \rightarrow \frac{3}{2}$ (lower energy) and $\frac{3}{2} \rightarrow \frac{1}{2}$ (higher energy) transitions from neutron capture in the 45.8-eV resonance of ^{118}Sn , as observed at 90° to the incident neutron beam.

Fig. 167. The $\frac{3}{2} \rightarrow \frac{3}{2}$ (lower energy) and $\frac{3}{2} \rightarrow \frac{1}{2}$ (higher energy) transitions from neutron capture in the 45.8-eV resonance of ^{118}Sn , as observed at 135° to the incident neutron beam.

capture, according to a suggestion by Lowell Bollinger) and boron filters. Of interest is the change in the ratio of the intensities of the gamma rays from 90° to 135° . Figure 166 shows the two gamma-ray lines for 90° capture, fitted by a least-squares program obtained from H. T. Motz. The $\frac{3}{2} \rightarrow \frac{3}{2}$ transition has the lower energy. It is easy to see that the ratio of intensities is about unity. Figure 167 shows the capture at

135^0 ; the $\frac{3}{2} \rightarrow \frac{3}{2}$ transition has increased relative to the $\frac{3}{2} \rightarrow \frac{1}{2}$ transition by a factor of 1.63 ± 0.13 , definitely indicating anisotropy. Since relative angular distributions for gamma rays so close in energy are subject to much less systematic error than absolute angular distributions, the failure of the measurement to yield the full factor of 1.96 can be attributed to residual systematic

error, statistical error, multipole admixture, and capture in other than the 45.8-eV resonance. All these effects are expected to be small. The 45.8-eV resonance in ^{118}Sn , now identified as $p_{3/2}$, has a reduced neutron width which is 17 times the average p-wave reduced neutron width expected for this region.

The spectrum from the 359-eV resonance in ^{118}Sn , known to be s-wave from the previously mentioned total-cross-section measurements, was obtained by subtraction of the Mn-filter-in run from the Mn-filter-out run. It shows different partial radiation widths than the 45.8-eV resonance; but the ratio of intensities changed by 1.38 ± 0.38 , which is in agreement with an isotropic distribution. The reduced transition strengths for these two M1 gamma rays are about 53 times (for $\frac{3}{2} \rightarrow \frac{3}{2}$) and 27 times (for $\frac{3}{2} \rightarrow \frac{1}{2}$) the average of experimental M1 reduced transition strengths.¹

The low-lying $\frac{3}{2}^+$ and $\frac{1}{2}^+$ states are still apparent in the compound nucleus formed by resonant neutron capture in ^{122}Sn , except that the $\frac{3}{2}^+$ state is now the lower. Figure 168, which shows the measured $d_{3/2} - s_{1/2}$ energy separation for five of the even-odd Sn nuclei, tends to

Fig. 168. Difference in energy between $d_{3/2}$ and $s_{1/2}$ states in Sn isotopes.

¹ G. A. Bartholomew, Ann. Rev. Nucl. Sci. 11, 259 (1961).

reinforce the postulate that the observed high-energy primary transitions do proceed to the $d_{3/2}$ and $s_{1/2}$ levels. ^{122}Sn has prominent resonances at 107 eV and 260 eV, which are not separable by the crude neutron energy resolution available using ^{10}B filters. The ratio of intensities changes by a factor of 1.5 ± 0.24 from 90° to 135° for all neutrons captured above 3 eV. This implies that either or both of these resonances corresponds to a $p_{3/2}$ capturing state. For the 107-eV resonance, either the reduced neutron width is 2.4 times the expected average or the reduced transition strengths are 59 times ($\frac{3}{2} \rightarrow \frac{1}{2}$ transition) and 65 times ($\frac{3}{2} \rightarrow \frac{3}{2}$ transition) the experimental average; the corresponding figures for the 260-eV resonance are 1.4 times the width and 18 and 21 times the strengths.

The dominant 62-eV resonance in ^{124}Sn is known to be p-wave from the total-cross-section measurements. The relative angular distribution changed by a factor of 0.94 ± 0.07 for all neutron capture above 3 eV, and changed by a factor of 0.88 ± 0.10 for all neutron capture between 3 eV and 400 eV. This indicated isotropy agrees with the work of McNeill, McConnell, and Firk² (in which the two gamma rays were not resolved), implying that the resonance is associated with a $p_{1/2}$ capturing state. The reduced neutron width for this resonance is 76 times the average expected.

The measurement of relative neutron-capture gamma-ray angular distributions can, in fortuitous circumstances, be a quick, easy way to determine the angular momenta of capturing states.

²K. G. McNeill, D. B. McConnell, and F. W. K. Firk, Can. J. Phys. 43, 2156 (1965).

* * *

R. E. CHRIEN, Brookhaven National Laboratory: I have some reservations about one aspect of this technique. When you use a crude filtering technique to investigate resonance capture, is it not possible that you sometimes get a large contribution from off-resonance capture? This would be difficult to estimate.

SLAUGHTER: I suspect you may be thinking of our work on the 1148-eV resonance in iron. For this case you are probably right. But in the tin isotopes, resonant capture exceeds off-resonance capture by quite a large factor; so such contributions are not too important for these cases.

CHRIEN: Even though off-resonance capture has a small total cross section in a particular isotope, interference effects may produce one or two dominant off-resonance lines which might have relatively large partial widths. Until these lines have been measured, I don't see how you can correct for their presence.

SLAUGHTER: I agree.

L. M. BOLLINGER, Argonne National Laboratory: Will you explain how you determine the ratio of the neutron widths to their expected values? The ratios you quote are extremely large. I know of no other case in which such large ratios are encountered.

SLAUGHTER: The widths are obtained from the measured total cross sections, as usual. Then Jack Harvey estimates the expected p-wave neutron widths in this region.

BOLLINGER: How does he do that?

J. A. HARVEY, Oak Ridge National Laboratory: I assumed that the p-wave strength function would be 4×10^{-4} in this region. For this assumption, the neutron widths for the 45.8-eV resonance in Sn^{118} and the 62-eV resonance in Sn^{124} are ~ 20 and ~ 80 times the expected widths.

2
E-5. ON THE CONSTRUCTION OF NUCLEAR LEVEL SCHEMES
USING PRECISE RELATIVE (n, γ) ENERGIES

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and

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Conventional decay-scheme spectroscopy permits the "unambiguous" construction of the level diagram of the daughter nucleus, if the data are obtained with sufficient precision. A beautiful example is the W^{183} scheme proposed by Murray et al.¹ These authors have measured the multiplicities and very accurate γ energies of the transitions between low-lying states in W^{183} and used the energy combination principle for the construction of the level scheme. This procedure leads to a correct result if the probability for the occurrence of accidental combinations is negligible. This probability was certainly small in the case mentioned, although it was not negligibly small. This follows from the fact that one of the lines identified as a single transition by Murray et al. and used for the construction of the W^{183} level diagram is a very-close-lying doublet.² Evidently, the construction of a level scheme is never "unambiguous," but it is a more or less probable result. This is the emphasis of the present considerations.

The chance to obtain a level "by accident" is usually very small, if few transitions have been found—as is usually the case in decay-scheme spectroscopy. However, the low-energy ($E \lesssim 1$ MeV) (n, γ) spectrum is so complex that the chance to find accidental levels

¹J. J. Murray, F. Boehm, P. Marmier, and J. W. M. DuMond, Phys. Rev. 97, 1007 (1955).

²U. Gruber, R. Koch, B. P. Maier, and O. W. B. Schult, Z. Naturforsch. 20a, 929 (1965).

contains only this one line ($n_0 = 1$). Because of its intensity, this line can only feed the ground state of Rh^{104} , the 51.4-keV level, or the 97.0-keV state. Thus there are $\mu_0 = 3$ possible locations for the 180-keV transition.

Considering now the possibility that the 180.8-keV line leads into the ground state, the chance for an accidental fit of a second transition of the "strength" (see Ref. 3) of the 129.418-keV line is calculated as follows. The line under consideration must lead to a level between 51.4 and 129 keV. The energy range ΔE_1 for possible transitions is from ~ 129.5 keV to ~ 51.8 keV. Besides the 51.422- and 97.099-keV lines which already have been assigned, there are $n_1 = 13$ more transitions in this region as strong or stronger than the 129.418-keV transition. They form another subset and yield a total error δE_1 given by

$$\delta E_1 \approx 2 \sum_{i=1}^{n_1=13} dE_i \approx 100 \text{ eV}.$$

The chance w_1 that one of these thirteen lines fits by accident between the 180.8-keV state and one of the $\mu_1 = 3$ levels (51.4, 97.0, and 128.9 keV) is approximately given through

$$w_1 \approx \delta E_1 / \Delta E_1 \approx 1.3 \times 10^{-3}.$$

(A more sophisticated calculation would have to consider not only the errors dE_i of the relative γ -ray energies E_i but also the errors de_λ in the relative energies e_λ of the levels. However, these are neglected in the present calculations since we usually have $de_\lambda < dE_i$ so that the probability w_1 would change only very little.)

The total chance for a second line (as strong or stronger than the 129.4-keV line) that fits by accident between the 180.8-keV state and the three remaining levels is then

$$W_1 = \mu_1 \times w_1 \approx 3.9 \times 10^{-3}.$$

For the computation of the chance of an accidental fit of a line as strong as or stronger than the 83.740-keV transition, we find that the energy range ΔE_2 for the possible candidates is

$$\Delta E_2 \approx 83.7 \text{ keV} - 51.8 \text{ keV} = 31.9 \text{ keV}.$$

Furthermore, for this subset we obtain

$$\delta E_2 \approx 8 \text{ eV}.$$

Thus, w_2 becomes

$$w_2 \approx 2.5 \times 10^{-4}.$$

And since $\mu_2 = 2$ (only two more levels remain as "targets"), we find

$$W_2 = \mu_2 \times w_2 \approx 5 \times 10^{-4}.$$

The chance to obtain the 180.8-keV level by accident is therefore

$$W_{180} = n_0 \times \mu_0 \times W_1 \times W_2 \approx 6 \times 10^{-6}.$$

This means that the 180.8-keV level can be considered to be well established.

The chance W_{186} that the 186.040-keV state is found through accidental energy combinations is calculated in the same way as that for the 180.8-keV level. However, now we have to consider five "safe" levels, the first four states plus the 180.8-keV level. The result is

$$W_{186} \approx 6 \times 10^{-5},$$

and, for this reason, we add also the 186.040-keV state to the set of "safe" levels.

Proceeding in this manner and considering all levels k as "safe" if $W_k < 3 \times 10^{-2}$, we arrive at the 220.777-keV level. Since the 220.798-keV line (Fig. 169) fits into the level scheme only within 1.6 times the quoted error, there is some doubt whether the assignment is correct, i. e., whether this line proceeds from the 220.7-keV level

to the ground state or not. Consequently, we disregard the 220.798-keV line in our calculation of W_{220} and find

$$W_{220} \approx 0.26.$$

This result indicates that the 220.77-keV level is probable, but its existence is still doubtful.

In contrast to this level, the 266.767-keV state is very well established. The calculated value $W_{266} \approx 8 \times 10^{-9}$ is, of course, due to the fact that five transitions (including three intense lines) de-excite the 266-keV state.

When one continues applying the energy combination principle, the possibility that W_s for higher lying states s is small decreases because (1) the number of "safe" levels and thus $\mu_0, \mu_1, \mu_2, \dots$ increases; (2) the most intense transitions have been assigned and the numbers $n_0, n_1, n_2, \dots$ increase with decreasing transition intensity; and (3) transitions of higher γ energy must be considered and thus the relative energy errors dE_i increase.

The chance $W_s(N)$ that a level s which is depopulated through N transitions is found by accident is given through

$$W_s(N) \propto \epsilon^{N-1},$$

where ϵ is proportional to the energy errors. An improvement in determining accurate relative energies will, therefore, strongly reduce the chance that levels for which N is large are found by accident. If the multipolarities of m of these N transitions have been determined, $W_s(N, m)$ becomes

$$W_s(N, m) = W_s(N) / 2^{m-1}$$

for obvious reasons. Thus, the determination of the multipolarities⁷ of the 169.3- and 123.6-keV transitions de-exciting the possible 220-keV

⁷E. Bieber, Z. Physik 189, 217 (1966).

level in Rh^{104} (Fig. 169) reduces W_{220} by a factor of 2. Such reduction factors (2) are also found for the probabilities W_{180} , W_{186} , and W_{266} which have been mentioned before.

SESSION F

3 NOVEMBER 1966

PRECISE GAMMA-RAY ENERGY DETERMINATIONS

H. T. MOTZ, CHAIRMAN

(7)

F-1. PRECISE MEASUREMENTS OF PRIMARY CAPTURE GAMMA-RAY
ENERGIES USING A "BOOTSTRAP" METHOD*

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Analogue-to-digital converters with 4096 channels and good integral and differential linearities have recently become available. A good-resolution lithium-drifted germanium detector system employing one of these ADC's is capable, in principle, of providing measurements of gamma-ray energies with a precision of about 1 part in 10^4 over a wide range of energies. It has not, however, been possible to fully utilize this capability in capture gamma-ray spectroscopy because precise gamma-ray energy standards were not available above 3 MeV. To help remove this limitation, the measurements reported in this paper were made to obtain precise values for the energies of selected primary capture gamma-ray lines. A "bootstrap" approach was used to make these measurements; and for comparison some measurements were also made using a "pulser" method. Parenthetically, it might be noted that the bootstrap method is the more rigorous approach to determining higher energy gamma-ray standards since it does not make the a priori assumption that the detector has a linear energy response.

Briefly, in the bootstrap approach the neutron binding energy of the compound nucleus formed in the neutron capture process is obtained as a sum of the transition energies in a two- or three-step gamma-ray cascade from the capturing state to the ground state. In order to achieve the greatest precision, cascades were used where all of the transitions have double-escape peak energies less than 3 MeV. Once a value for the neutron binding energy is established, it is then

*Work performed under the auspices of the U. S. Atomic Energy Commission.

Fig. 170. The integral linearity of the detector system used in these experiments.

possible to obtain equally precise values for the energy of a primary capture gamma ray emitted in direct transitions from the capturing state to low-energy levels.

In order to measure gamma-ray line energies, calibration sources were recorded simultaneously with the capture gamma-ray spectra. The capture gamma-ray line energies (below 3 MeV) were obtained by making a least-squares straight-line fit to the peak positions of the calibration lines after making a correction for the nonlinearity of the detector system. The integral linearity curve for the detector system used in the present measurements is shown in Fig. 170. The maximum deviation from linearity from channel 300 to channel 3800 is 0.2 channels. A more complete discussion of this technique for measuring gamma-ray energies has been given in a number of references¹⁻³ by Heath, Black, and Cline.

Beryllium and sodium were selected as samples for the first series of experiments because of the relative simplicity of the decay schemes of the Be^{10} and Na^{24} compound nuclei and because each has a strong primary capture gamma-ray transition to a low-lying state.

The target samples were irradiated using an external neutron beam from the Materials Testing Reactor (MTR) and prompt gamma rays were detected in a $2.5 \text{ cm}^2 \times 4 \text{ mm}$ Ge(Li) detector.

¹R. L. Heath, W. W. Black, and J. E. Cline, IEEE Trans. Nucl. Sci. NS-13(3), 445 (1966).

²W. W. Black, U. S. AEC Report No. IDO-17140 (1965).

³W. W. Black and R. L. Heath, Nucl. Phys. (to be published).

Fig. 171. A beryllium thermal-neutron-capture gamma-ray spectrum measured with a $2.5 \text{ cm}^2 \times 4 \text{ mm}$ Ge(Li) detector.

A typical beryllium capture gamma-ray spectrum, using the annihilation radiation⁴ and the hydrogen capture gamma-ray lines⁵ as internal energy standards, is shown in Fig. 171. Lines not identified in this figure result from background. A total of seven separate beryllium capture gamma-ray spectra were measured. In four of these measurements, the 15-hr Na^{24} lines were used as energy standards⁴ instead of the hydrogen capture gamma-ray lines. The beryllium capture gamma-ray line energies shown in Table XVII are an average of these seven runs. The decay scheme of the Be^{10} compound nuclear state formed by thermal-neutron capture in beryllium has been determined by Motz *et al.*⁶

⁴G. Murray, R. L. Graham, and J. S. Geiger, Nucl. Phys. **63**, 353 (1965).

⁵R. C. Greenwood and W. W. Black, Phys. Letters **21**, 702 (1966).

⁶H. T. Motz, R. E. Carter, and W. D. Barfield, Symposium on Pile Neutron Physics, Vienna, 1960 (IAEA, Vienna, 1962), p. 225.

TABLE XVII. The transition energies of prompt gamma rays from the $\text{Be}^9(n, \gamma)$ reaction, and the neutron-binding-energy values determined for Be^{10} by summing transition energies of two- and three-step cascades occurring between the capturing state and the ground state in Be^{10} .

Average line energy ^a (keV)	Gamma-ray energy (keV)	Nuclear recoil energy correction (keV)	Transition energy (keV)
853.5 ± 0.3	853.5 ± 0.3	0.04	853.5 ± 0.3
$1567.9 \pm 0.2_5$	$2589.9 \pm 0.2_5$	0.36	$2590.3 \pm 0.2_5$
2345.4 ± 0.2	3367.4 ± 0.2	0.61	3368.0 ± 0.2
2421.3 ± 0.3	3443.3 ± 0.3	0.64	3443.9 ± 0.3
<hr/>			
Be^{10} cascade sums			
$3443.9 + 3368.0 = 6811.9 \pm 0.4$			
$853.5 + 2590.3 + 3368.0 = 6811.8 \pm 0.5$			

^aThe error values shown here include an allowance for the uncertainties in the energies of the calibration lines.

Based on their decay scheme, the sums of the transition energies of each of the two cascades that are suitable for use in determining the neutron binding energy of Be^{10} are also shown in Table XVII. Since both of these cascades go directly to the ground state, we obtain

$$\text{Be}^{10} \text{ neutron binding energy} = 6811.9 \pm 0.4 \text{ keV.}$$

Thus the energy of the primary thermal-neutron-capture gamma ray emitted in the strong transition to the ground state of Be^{10} is

$$6809.4 \pm 0.4 \text{ keV.}$$

The annihilation radiation and the 15-hr Na^{24} activity, which is built up through the neutron irradiation of the target, were used as standards for the measurements of sodium capture gamma-ray energies. In making these energy measurements it was necessary to make a small correction (about 0.2 keV) to the energy of the calibration lines resulting from the 2753.92-keV Na^{24} decay gamma rays because of the presence of the weaker 2752.3-keV sodium capture gamma rays. The decay scheme which was obtained during the course of the present

Fig. 172. The decay scheme of the compound-nucleus state of Na^{24} produced as a result of thermal-neutron capture in sodium.

work for the Na^{24} compound nuclear state formed by thermal neutron capture in sodium is shown in Fig. 172. This level scheme will not be discussed further here since it will be published separately in the near future.⁷ Based on this decay scheme, eleven well defined two-step cascades were identified as occurring between the capturing state of Na^{24} and levels at either 472.32 keV, 563.31 keV, or 1341.36 keV. These cascades are shown in Table XVIII. For each of these cascades, the values obtained for the Na^{24} neutron binding energy are shown in the final column of this table. There is a very small spread, a total of 0.7 keV, in these individual binding-energy values. From these data, we obtain

$$\text{Na}^{24} \text{ neutron binding energy} = 6959.3 \pm 0.4 \text{ keV.}$$

⁷R. C. Greenwood (to be published).

TABLE XVIII. Values for the neutron binding energy of Na^{24} , obtained by summing transition energies of two-step prompt gamma-ray cascades occurring between the capturing state and low-lying levels at 472.32, 563.31, and 1341.36 keV.

Two-step cascades in Na^{24} ^a (keV)	Na^{24} neutron binding energies (keV)
Transitions to the 472.32-keV level	
$3981.64 + 2505.4 = 6487.0 \pm 0.3$	6959.4 ± 0.3
$2981.9 + 3504.6 = 6486.5 \pm 0.4$	6958.8 ± 0.4
$2517.70 + 3969.4 = 6487.1 \pm 0.4$	6959.4 ± 0.4
Transitions to the 563.31-keV level	
$3981.64 + 2414.4 = 6396.0 \pm 0.3$	6959.4 ± 0.3
$3587.53 + 2808.4 = 6395.9 \pm 0.3$	6959.2 ± 0.3
$2517.70 + 3878.23 = 6395.9 \pm 0.3$	6959.2 ± 0.3
$2208.5 + 4187.69 = 6396.2 \pm 0.3$	6959.5 ± 0.3
$3370.2 + 3025.8 = 6396.0 \pm 0.4$	6959.3 ± 0.4
$2981.9 + 3414.1 = 6396.0 \pm 0.6$	6959.3 ± 0.6
Transitions to the 1341.36-keV level	
$3587.53 + 2030.2 = 5617.7 \pm 0.4$	6959.1 ± 0.4
$2208.5 + 3409.5 = 5618.0 \pm 0.5$	6959.4 ± 0.5

^aThe error values shown here include an allowance for the uncertainties in the energies of the calibration lines.

calibration data are still achieved. This indicates that this Ge(Li) detector had a linear response over this energy range. From these data the energy of the principal gamma ray emitted in the decay of 7.35-sec N^{16} was measured as

$$6128.9 \pm 0.4 \text{ keV.}$$

(This line was present in many of our spectra as a contaminant.) The energies measured separately for this O^{16} line from the beryllium and sodium capture gamma-ray spectra provide a check on the internal consistency of the present Be^{10} and Na^{24} data; these values are 6128.8 keV and 6128.9 keV, respectively.

Finally, I would like to present the results of a series of measurements I have just recently completed with the nitrogen capture

(This error assignment contains an allowance for the errors assigned to the standards and to the low-energy Na^{24} levels.⁷) Thus, based on this Na^{24} binding energy value, the energy of the primary capture gamma ray emitted in the strong transition to the second excited state of Na^{24} is

$$6395.1 \pm 0.4 \text{ keV.}$$

When these Be^{10} and Na^{24} primary capture gamma-ray lines are themselves used as energy standards, excellent linear fits to the energy

TABLE XIX. Transition energies of prompt gamma rays from the $N^{14}(n, \gamma)$ reaction, and the neutron-binding-energy values determined for N^{15} by summing transition energies of two- and three-step cascades occurring between the capturing state and the ground state.

Average line energy ^a (keV)	Gamma-ray energy (keV)	Nuclear recoil energy correction (keV)	Transition energy (keV)
$1884.9 \pm 0.2_5$	$1884.9 \pm 0.2_5$	0.12	$1885.0 \pm 0.2_5$
$2518.0 \pm 0.2_5$	$2518.0 \pm 0.2_5$	0.23	$2518.2 \pm 0.2_5$
$2510.3 \pm 0.2_5$	$3532.3 \pm 0.2_5$	0.44	$3532.7 \pm 0.2_5$
$2656.1 \pm 0.2_5$	$3678.1 \pm 0.2_5$	0.48	$3678.6 \pm 0.2_5$
3487.2 ± 0.3	4509.2 ± 0.3	0.73	4509.9 ± 0.3
$4247.6 \pm 0.3_5$	$5269.6 \pm 0.3_5$	0.99	$5270.6 \pm 0.3_5$
$4276.3 \pm 0.3_5$	$5298.3 \pm 0.3_5$	1.00	$5299.3 \pm 0.3_5$
4511.5 ± 0.4	5533.5 ± 0.4	1.09	5534.6 ± 0.4
4540.6 ± 0.4	5562.6 ± 0.4	1.11	5563.7 ± 0.4
$5300.0 \pm 0.4_5$	$6322.0 \pm 0.4_5$	1.43	$6323.4 \pm 0.4_5$
N^{15} cascade sums			
$3678.6 + 1885.0 + 5270.6 = 10834.2 \pm 0.7$			
$5563.7 + 5270.6 = 10834.3 \pm 0.7$			
$5534.6 + 5299.3 = 10833.9 \pm 0.7$			
$4509.9 + 6323.4 = 10833.3 \pm 0.7$			

^aThe error values shown here contain an allowance for the uncertainties in the energies of the calibration lines.

gamma-ray spectrum. A mixed sample of sodium oxalate and melamine was used for these measurements. The nitrogen capture gamma-ray line energies shown in Table XIX were obtained by use of the annihilation radiation, Co^{60} , the hydrogen capture gamma ray, and the 6395.1-keV sodium capture gamma ray as internal energy standards. Based on the decay scheme proposed by Motz et al.⁶ for the compound-nucleus state in N^{15} , the sums of the transition energies of the cascades which were found suitable for use in determining the neutron binding energy of N^{15} are also shown in this table. Since each of these cascades goes directly to the ground state, we obtain

$$N^{15} \text{ neutron binding energy} = 10833.9 \pm 0.7 \text{ keV.}$$

Thus the energy of the primary thermal-neutron-capture gamma ray emitted in the strong transition to the ground state of N^{15} is

$$10829.7 \pm 0.7 \text{ keV.}$$

It is a pleasure to acknowledge the helpful discussions with Dr. W. W. Black on gamma-ray energy measurement techniques.

* * *

L. M. BOLLINGER, Argonne National Laboratory: How does this value for the high-energy gamma ray in nitrogen compare with the value Jackson⁸ assumed in his work?

GREENWOOD: Jackson assumed the older mass-adjusted value, which I believe was 10 834.2 keV. Our value is in very good agreement with this—within 0.3 keV. However, the most recent mass-adjusted value is $10\,834.8 \pm 0.8$ keV. Our value is consistent with this newer figure, although a little bit low.

E. D. EARLE, Chalk River Nuclear Laboratories: Our measurement of the neutron binding energy of N^{15} is in excellent agreement with that; it is within about 1 keV. However, our estimated error was about twice yours.

R. E. COTÉ, Argonne National Laboratory: I may add that the measurement of the nitrogen line at 6128.9 keV is in excellent agreement with the value we adopted when we used this line as the calibration line for our work on muonic x rays. The satisfactory agreement between our muonic results and the expected values can be taken as confirmation of this value.

⁸H. E. Jackson, A. I. Namenson, and G. E. Thomas, *Phys. Letters* 17, 324 (1965).

G. T. EMERY, Indiana University: Isn't the 511-keV annihilation radiation line broader than the gamma-ray lines? And if so, does this cause any difficulty in its use as a calibration line?

GREENWOOD: Yes. The 511-keV line is very noticeably broader.

EMERY: Then presumably you have to unfold the Doppler broadening in order to get the centroid.

GREENWOOD: The line shape is still Gaussian, so one can still make a Gaussian fit.

EMERY: Some have found that a detector with a slightly asymmetric response in the low-energy region may shift the peak of the 511-keV line relative to the apparent peak.

GREENWOOD: Fortunately none of the detectors we used had an asymmetric response. The peaks were all fitted very nicely with Gaussians.

F12. GAMMA RAYS FROM THE $\text{Cr}^{53}(n, \gamma)\text{Cr}^{54}$ REACTION*

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With the adoption of Ge(Li) detectors for neutron-capture gamma-ray studies, a new set of problems has arisen in the employment of these devices for the measurement of gamma-ray energies and intensities. These new problems are primarily a consequence of the resolution and precision attainable with Ge(Li) detectors.

For energy determinations, the basic problem is one of correcting for the nonlinearities in a system—preamplifier, one or more amplifiers, and analog-to-digital converter—which measures the charge collected following the interaction of a gamma ray in the sensitive region of a detector. This is usually done with the use of a highly stable and linear precision pulser. However, owing to the fact that the widths, and often the shapes, of gamma-ray peaks are energy dependent—and, in particular, that they may be asymmetric—the intercomparison of gamma-ray energies by this method over an extended energy range is generally regarded as subject to possible error. Because of this difficulty, most high-precision measurements have been made by the "bootstrap" method, in which energy determinations are made over an extended range by the intercomparison of closely spaced full-energy, single-escape, and double-escape peaks. The bootstrap method, however, depends on the accidental proximity of spectrum peaks, and usually, because of the number of steps required, involves considerable effort. A more feasible

*Work performed under the auspices of the U. S. Atomic Energy Commission.

method for many purposes is the intercomparison of gamma-ray peaks from composite targets in which the isotope being studied is combined with others whose capture-gamma-ray energies have been carefully determined. In certain cases, background peaks suffice for this purpose. Ordinarily, gamma rays from neutron capture in a few light elements—usually H^1 , C^{12} , N^{14} , and Al^{27} —are employed as intercomparison standards.¹ These all have small capture cross sections, so that while they are suitable for work with in-pile targets, they may provide insufficient intensity for some external-beam experiments. The gamma rays from the decay of N^{16} produced by fast neutrons via the $\text{O}^{16}(\text{n}, \text{p})\text{N}^{16}$ reaction have also been utilized.²

The determination of gamma-ray intensities with Ge(Li) detectors is complicated by several factors. Efficiency calculations feasible for NaI are complicated in the case of Ge(Li) detectors by edge effects involving not only gamma rays but electrons as well. Moreover, while NaI detectors are available with a few standard dimensions, Ge(Li) detectors are as yet "tailor made" in a great variety of sizes and shapes, with sensitive regions which have complicated and often undetermined shapes. Accordingly, a straightforward empirical method for determining the efficiency of a Ge(Li) detector as a function of energy would be desirable. So far, for high-energy capture gamma rays this has usually been done by utilizing the intensities measured with a magnetic pair spectrometer at Chalk River³ and with a Compton spectrometer in the

¹G. A. Bartholomew, E. D. Earle, and M. R. Gunye, *Can. J. Phys.* **44**, 2111 (1966).

²K. T. Faler and R. R. Spencer, *Bull. Am. Phys. Soc.* **11**, 336 (1968).

³G. A. Bartholomew and L. A. Higgs, *Compilation of Thermal Neutron Capture Gamma Rays* (Atomic Energy of Canada Ltd., Chalk River, Ontario, July 1958), Report No. CRGP-784.

Soviet Union.⁴ The errors in the efficiency curves of these devices are estimated to range from $\sim 10\%$ at 2.75 MeV to $\sim 30\%$ at 10 MeV for the pair spectrometer³ and to be $\sim 15\%$ for the Compton spectrometer.⁵

We have chosen the gamma rays from the $\text{Cr}^{53}(\text{n}, \gamma)\text{Cr}^{54}$ reaction to serve as a standard for the measurement of both the energies and intensities of capture gamma rays in our work. Cr^{53} has a number of properties which are advantageous in this application. The thermal capture cross section is reasonably large (18 barn). Moreover, the cross sections of the neighboring isotopes are small (0.76 barn for Cr^{52} and < 0.3 barn for Cr^{54}), so that for a target moderately enriched in Cr^{53} , only the gamma rays from capture in Cr^{53} will have appreciable intensities. The gamma-ray spectrum has strong peaks which are numerous enough to provide a number of energy calibration points but not so numerous as to obscure many features of the spectrum of another isotope. Owing to the simplicity of the spectrum, the decay scheme is almost completely understood.

Several fortuitous features of the Cr^{54} decay scheme are important in the determination of the energies of the high-energy transitions. First, there is a strong gamma ray at 3.72 MeV whose double-escape peak at 2.70 MeV is closely bracketed by the full-energy peaks of the gamma rays of radiothorium (2614.47 ± 0.10 keV) and Na^{24} (2753.92 ± 0.12 keV). Second, the 3.72-MeV full-energy peak is closely adjacent to a doublet of double-escape peaks from gamma rays with energies of 4.84 and 4.87 MeV. The latter constitute a two-step cascade from the capture state to the ground state. This is illustrated in Fig. 173.

⁴ L. V. Groshev, A. M. Demidov, V. N. Lutsenko, and V. I. Pelekhov, Atlas of γ -Ray Spectra from Radiative Capture of Thermal Neutrons (Pergamon Press, New York, 1959).

⁵ L. V. Groshev, B. P. Adyasevich, and A. M. Demidov, in Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955 (Columbia University Press, New York, 1956), Vol. 2, p. 39.

Fig. 173. Partial capture-gamma-ray spectrum and level scheme of Cr^{54} illustrating the method used to determine the neutron separation energy of Cr^{54} . The 3.72-MeV double-escape peak was first compared with the full-energy peaks of gamma rays of RdTh and Na^{24} , and then the 4.85- and 4.87-MeV double-escape peaks were compared with the 3.72-MeV full-energy peak. The 4.85- and 4.87-MeV transitions constitute a two-step cascade from the capture state to the ground state of Cr^{54} .

Thus, these two intercomparisons of closely-spaced peaks provide a determination of the neutron separation energy. These measurements have been carried out, along with determinations of the energies of several lower-energy lines by intercomparison with gamma rays from radioactive isotopes. In addition, the energies of the 6.00- and 7.10-MeV gamma rays were determined by extrapolation with a pulser from the 3.72- and 4.84-MeV lines. Some preliminary results of these measurements are summarized in Table XX. The neutron separation energy is given by several combinations of the measured transition energies, providing a check on the consistency of the measurements.

TABLE XX. Energies of gamma rays from the $\text{Cr}^{53}(\text{n}, \gamma)\text{Cr}^{54}$ reaction.

Energy (keV)	Comparison source	
	Isotope	Energy (keV)
<hr/>		
834.96 ± 0.2 ^a		
1784.1 ± 0.5	Bi ²⁰⁷	1769.71 ± 0.13
2238.8 ± 0.5	Co ⁶⁰	1173.226 ± 0.040, 1332.483 ± 0.046
3719.7 ± 0.5	RdTh	2614.47 ± 0.10, Na ²⁴ - 2753.92 ± 0.12
4846.9 ± 1.0	Cr ⁵⁴	3719.7 ± 0.5
4872.0 ± 1.0	Cr ⁵⁴	3719.7 ± 0.5
5999.3 ± 2.0	Cr ⁵⁴	3719.7 ± 0.5
7099.9 ± 2.0	Cr ⁵⁴	3719.7 ± 0.5, 4846.9 ± 1.0

^aC. Chasman and R. Ristinen (private communication). This energy was measured in the decay of Mn⁵⁴.

TABLE XXI. Neutron separation energy of Cr⁵⁴ from several combinations of gamma-ray energies.

Gamma-ray and recoil energies (keV)		Separation energy S _n (keV)
<hr/>		
4846.9 + 4872.0 + 0.46	=	9719.4
5999.3 + 3719.7 + 0.50	=	9719.5
834.96 + 1784.1 + 7099.9 + 0.55	=	9719.5

These are shown in Table XXI. If the capture state is provisionally assigned an energy of 9719.4 ± 2.0 keV, then the two highest energy gamma rays have energies of 9718.4 ± 2.0 and 8883.6 ± 2.0 keV, respectively.

The relative intensities of the capture gamma rays of Cr⁵⁴ were determined in the following way. First an efficiency curve was constructed for the Ge(Li) detector (a coaxial device with ~10 cm³ volume) in the range between 0.2 and 2.75 MeV. This was done with the use of radioactive isotopes for which the intensity ratios of two or more gamma rays are known, either from the decay scheme or from other measurements. The isotopes Na²², Na²⁴, Co⁶⁰, Ag^{108m}, Hf^{180m}, Bi²⁰⁷, and Th²²⁸ were used for this purpose. With the efficiency of the detector established up to 2.75 MeV, the relative intensities of the gamma rays of Cr⁵⁴ in this energy region were then determined. Finally,

with the intensities of the lower energy transitions known, and the details of the decay scheme established, it was possible to relate the intensities of the high-energy transitions populating these levels with the measured intensities of the low-energy transitions depopulating them. As an example of this, we consider the 2.619-MeV level of Cr^{54} .

This is populated, apparently,

only by the 7.100-MeV

transition from the capture

state and a weak 1240-keV

transition from a state at

3.862 MeV. Similarly, it decays almost entirely via the 1.783-MeV

transition to the first excited state; the upper limit on the intensity of

the crossover transition to the ground state is 2%.⁶ Thus the intensities of the 1.783- and 7.100-MeV transitions stand in a nearly 1:1

correspondence, with a small, known correction. In this way the

intensities of the 8.884-, 7.100-, and 6.642-MeV transitions were

established and, correspondingly, the relative efficiency of the Ge(Li)

detector established at these energies. The known intensity relationship

of the 6.000- and 3.720-MeV transitions was also used to establish points

on the efficiency curve at these energies, although this involved

extrapolation of the high- and low-energy parts of the efficiency curve.

The measured intensities of the stronger transitions of Cr^{54} are shown in Table XXII along with the corresponding values determined by Kinsey and Bartholomew⁷ and Groshev *et al.*⁴

⁶D. H. White, Phys. Rev. 131, 777 (1963).

⁷B. B. Kinsey and G. A. Bartholomew, Phys. Rev. 89, 375 (1953).

TABLE XXII. Intensities of strong gamma rays from the $\text{Cr}^{53}(n, \gamma)\text{Cr}^{54}$ reaction.

E_{γ} (keV)	I_{γ}		
	Present work ^a	Kinsey and Bartholomew ^b	Groshev <i>et al.</i> ^c
8884	34	34	36
7100	5.6	4.6	6.1
6642	6.8	5.4	7.5
5999	2.9	1.8	2.9
4872	0.5	1.1	1.1
4847	1.0		
3720	2.1	0.9	2.4
2239	6.8		3.5
1783	6.3		3.5
835	53		36

^aNormalized to 8884-keV line of Kinsey and Bartholomew, Ref. 7.

^bReference 7.

^cReference 4.

The intensities of the transitions below 2.75 MeV and the corresponding high-energy transitions depend only on the low-energy efficiency curve and the correctness of the decay scheme. The intensities of the remaining transitions should be regarded as preliminary. Known intensity relationships of high-energy gamma rays from several other isotopes will be utilized to fix additional points on the efficiency curve. The feasibility of the method for the measurement of the intensities of high-energy capture gamma rays is evident.

* * *

E. B. SHERA, Los Alamos Scientific Laboratory: I noticed that the errors you have assigned at any given energy are about three times those given in the previous talk. What is the reason for the difference?

KANE: The errors we quote reflect the fact that these are only preliminary values. We intend to take more measurements.

R. T. CARPENTER, University of Iowa, Iowa City: With what precision do you know the efficiency curve?

KANE: I would say that the error in the low-energy efficiency curve, which is determined directly by ratios of gamma-ray intensities, certainly is no worse than 10% over the entire range—and perhaps is closer to 5%.

CARPENTER: Do you normally measure the efficiency with the sources placed the same as in the later measurements?

KANE: That is correct. Since we have an external beam, it is easy to keep the geometry and hence the absorption the same for both measurements.

F-3. A STUDY OF THE $^{28}\text{Si}(n, \gamma)^{29}\text{Si}$ AND $^{35}\text{Cl}(n, \gamma)^{36}\text{Cl}$ REACTIONS

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The use of lithium-drifted germanium detectors in the capture- γ -ray field requires the determination of precise energy standards from 0 to 10 MeV. To date, precise energies are available only in the range from 0 to 3 MeV. As a result we have attempted to establish accurate energies for the γ rays emitted in the thermal neutron capture of some light nuclei. The results presented here are for the $^{28}\text{Si}(n, \gamma)^{29}\text{Si}$ and the $^{35}\text{Cl}(n, \gamma)^{36}\text{Cl}$ reactions.

The method used to obtain accurate high-energy measurements is applicable to reactions where many cascades to the ground state are known. The low-energy region of the spectra from zero to 3 MeV can be calibrated using the usual mixed-source techniques with the accurately known energy standards available in this region.

Above 3 MeV, only relative energies can be found. These can be obtained as follows. The energy difference between two high-energy γ rays is the energy difference between the two levels that they populate provided corrections are made for recoil losses. The level energies are obtainable from the low-energy data since we have assumed that the γ rays depopulating these levels can be identified. The

Fig. 174. Schematic of the channel-number-to-energy calibration curves, showing the two sets of data. E_1 is the curve associated with the low-energy gamma rays whose energies are known absolutely and E_2 is the curve associated with the high-energy γ rays whose energies are only known relatively.

Fig. 175. Plot of χ^2 as a function of the assumed $^{28}\text{Si}(n, \gamma)^{29}\text{Si}$ Q value, showing a minimum at 8476.2 keV.

identification of photopeaks and of single-escape and double-escape peaks associated with the same γ ray also provide accurate energy differences in the high-energy region.

We have then two groups of data, the low-energy data for which the peak energies are known exactly and the high-energy data for which the accurate energy differences are known. These ideas are presented in Fig. 174. Assuming that the channel-

to-energy transformation is quadratic, the data can be fitted by four parameters A_1 , A_2 , B, and C. These can be determined by least-squares techniques.

In this application the value of A_2 was found graphically. An estimate of the Q value was used to provide a basis for absolute energies in the high-energy region. A least-squares analysis was then performed over the entire energy range and a value for χ^2 obtained. By varying the Q value, the minimum in $\chi^2(Q)$ was obtained; and this then gives the least-squares estimate of Q. Figure 175 shows the results of such an analysis.

This procedure has been used to obtain energies for the γ rays emitted in the $^{28}\text{Si}(n, \gamma)^{29}\text{Si}$ reaction. The relevant part of the decay scheme is shown in Fig. 176. The 1273-, 2427-, 2092-, and 3540-keV γ rays have been calibrated using the precise energies of the γ rays emitted in the β decay of ^{60}Co , ^{208}Tl , and ^{24}Na published by Murray et al.¹ The decay scheme is in essence the same as that published by Adayasevich et al.² The results of a two-dimensional

¹ G. Murray, R. L. Graham, and J. S. Geiger, Nucl. Phys. 63, 353 (1965).

² B. P. Adayasevich, L. V. Groshev, and A. M. Demidov, J. Nucl. Energy 3, 258 (1956).

coincidence experiment using a Ge(Li) and a NaI(Tl) detector were in agreement with these decay modes. The high-energy γ rays were then calibrated using the technique discussed earlier. The results obtained are shown in Table XXIII. The errors in the low-energy data (E_1) are felt to be of the order of 0.5 keV while the high-energy results have an error of approximately 1.0 keV. The average Q value of the reaction to the 8476.2-keV state is felt to be accurate to approximately ± 0.8 keV.

The same procedure has been used to calibrate the γ rays emitted in thermal neutron capture in natural chlorine. The relevant part of the decay scheme is shown in Fig. 177. Eight cascades and the ground-state transition were included in the analysis. The 6627—1957-keV cascade was not included because of the strong interference from the single-escape peak of the 6115-keV gamma ray.

Fig. 176. Partial γ -ray decay scheme of ^{29}Si produced in thermal-neutron capture in ^{28}Si . The cascades used in this analysis are shown.

TABLE XXIII. Estimates of the $^{28}\text{Si}(n, \gamma)^{29}\text{Si}$ Q value.

E_2 (keV)	R_2 (keV)	E_1 (keV)	R_1 (keV)	Q (keV)	Deviations (keV)
8474.8	1.3			8476.1	- 0.1
7202.5	1.0	1273.0	0.0	8476.5	+ 0.3
6383.4	0.8	2092.0	0.1	8476.3	+ 0.1
6049.1	0.7	2427.0	0.1	8476.9	+ 0.7
5110.4	0.5	{ 2092.0 1273.0 }	{ 0.1 0.0 }	8476.0	- 0.2
4936.0	0.4	3539.7	0.2	8476.3	+ 0.1
3956.0	0.3	{ 2427.0 2092.0 }	{ 0.1 0.1 }	8475.5	- 0.7
		$\bar{Q}$	-	8476.2	± 0.4

Fig. 177. Partial γ -ray decay scheme of ^{36}Cl produced in thermal-neutron capture in ^{35}Cl . Those cascades relevant to this work are shown.

This more complicated decay scheme was checked using coincidence techniques. For these experiments, the two-dimensional surface obtained using a NaI(Tl) detector was recorded in a 1024 $\times$ 256-channel array using delay-time analysis. For the system uses, each magnetic tape could store up to 1.5×10^6 pairs of addresses. In all, 22 such tapes were used and about 3×10^7 events were analyzed. Figure 178 shows part of the projection of the coincidence surface $P(f)$ on the axis associated with the germanium counter and the same region of the projected chance events $S(f)$. The spectra obtained by summing

Fig. 178. A two-dimensional NaI-Ge(Li) coincidence experiment on the $^{35}\text{Cl}(n, \gamma)^{36}\text{Cl}$ reaction. Shown here is a portion of the projections of the coincidence surface $P(f)$ and the chance events $S(f)$ onto the axis associated with the germanium counter. The channels labeled ℓ and u indicate the digital restrictions used to find the spectrum in coincidence with the 5718-keV γ ray.

Fig. 179. Spectra associated with the digital window shown in Fig. 178. Curve $T(m)$ is the total spectrum associated with the 5718-keV γ ray and the underlying Compton background and $B(m)$ is an estimate of this Compton background. The curve $B(m)$ is the spectrum associated with the 5718-keV γ ray after the removal of the Compton background, and $C(m)$ is the estimated chance contribution in $\beta(m)$.

between the channels designated by ℓ and u are shown in Fig. 179. Here $T(m)$ is the spectrum resulting from summing between ℓ and u , and $B(m)$ is an estimate of the spectrum associated with the underlying continuum between ℓ and u . The spectrum $\beta(m)$ is then the difference

$$\beta(m) = T(m) - B(m),$$

TABLE XXIV Estimates of the Q value of the $^{35}\text{Cl}(n,\gamma)^{36}\text{Cl}$ reaction The strong 6627-keV transition was not included in the calibration because of the interference from the single-escape peak of the 6115-keV gamma ray.

E_2 (keV)	R_2 (keV)	E_1 (keV)	R_1 (keV)	Q (keV)	Deviations (keV)
8581.8	1 1			8582.9	- 0 1
7794 1	0.9	788 0	0 0	8583 0	0 0
7419.2	0.8	1163 3	0 0	8583 3	+ 0.3
6981.9	0.7	1600 7	0 0	8583 3	+ 0 3
6114 6	0 6	$\left\{ \begin{array}{l} 517.4 \\ 1950 4 \end{array} \right.$	$\left\{ \begin{array}{l} 0.0 \\ 0 0 \end{array} \right.$	8583 0	0 0
5906 0	0.5	2675.4	0 1	8582.0	- 1 0
5719 7	0 5	2863 7	0.1	8584.0	+ 1 0
5520.9	0 4	3061 2	0 1	8582.6	- 0.4
4982 7	0.4	$\left\{ \begin{array}{l} 1131.9 \\ 517.4 \\ 1950.9 \end{array} \right.$	$\left\{ \begin{array}{l} 0 0 \\ 0 0 \\ 0.0 \end{array} \right.$	8582 8	- 0.2
$\overline{Q} =$				8583.0	± 0.5

and $C(m)$ is an estimate of the chance contribution in $\beta(m)$. Since the Compton interference has been removed, the spectrum $\beta(m)$ is that associated with the γ rays in coincidence with the 5718-keV gamma ray. The spectra associated with similar digital gates have been analyzed and used to determine the decay scheme for $^{35}\text{Cl}(n,\gamma)^{36}\text{Cl}$ shown in Fig. 177.

The constraints imposed by these cascades and the low-energy data were then used to calibrate the high-energy region. The results are shown in Table XXIV. The low-energy data (E_1) have been calibrated relative to the γ rays emitted in the β decay of ^{60}Co and ^{24}Na and the annihilation γ ray. Their errors are of the order of 1 keV. The high-energy data have an error of approximately ± 2 keV. The resulting Q value of 8583 keV has an estimated error of ± 1 keV.

* * *

R. C. GREENWOOD, Idaho Nuclear Corporation: You said that it was assumed in your work that the nonlinearity of your detector system could be described by a quadratic term. Presumably this is the case only within restricted limits—i. e., if you ignore the first and last few hundred channels.

HUGHES: Yes, I should have mentioned this. We are doing experiments now to check this out; but with our system it looks fairly reasonable above channel 700 or 800.

GREENWOOD: What is the maximum deviation from linearity?

HUGHES: I think it was linear to about 0.3%.

GREENWOOD: I mention this because the nonlinearity curve I showed earlier (paper F-1) could not have been fitted with a quadratic.

HUGHES: No. Your curve is completely different from the ones we have seen.

GREENWOOD: The nonlinearity correction was, of course, very small; and it was rather irregular.

HUGHES: If we could find a functional form for the nonlinearity, we would have no problem in using this same technique.

GREENWOOD: I would also like to comment about chlorine. There is probably another reason why you cannot use that strong 6626.5-keV line for an energy calibration: it is a doublet.

HUGHES: It looks as if it might be; but our coincidence work does not show a second decay.

GREENWOOD: We have resolved the doublet. The higher energy line is almost as strong as the lower energy line.

HUGHES: We noticed that it was broad and that there is another level in this region. In the low-energy spectrum we can see the decays of both levels. One of the levels is populated indirectly by the 6615-keV transition. The coincidence results indicated that this level was also weakly populated by a direct transition.

GREENWOOD: It turns out that they are both populated directly.

G. G. SLAUGHTER, Oak Ridge National Laboratory: One bit of information some of you may find useful is that Saran Wrap, made by the Dow Chemical Corporation, is approximately 65% chlorine by weight. This might be useful as a calibration target.

F-4. PRECISION MEASUREMENTS OF STANDARD GAMMA-RAY ENERGIES

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I believe it is recognized that the precision (reproducibility) available with a Ge(Li) detector is generally much better than the accuracy obtained. That is, one is usually limited by calibration standards.

A typical Ge(Li) spectrum must contain one or more reference peaks of known energy—for example, a standard radioactive source or the hydrogen capture gamma. The linearity of the system can then be calibrated (in the presence of the same standards) with a high-precision pulser. However, at present the number of well measured calibration sources is inadequate.

The need for high precision is mainly due to the application of the Ritz combination principle to the analysis of nuclear structure problems. Even with the best precision available today, the use of the combination-principle method alone is marginal. Moreover, with complex spectra, there are still many unresolved peaks even with the best Ge(Li) resolution. High accuracy is desirable because it allows consideration of other data, such as those from (d,p) measurements. For these reasons, it is desirable to have a useful and consistent set of primary and secondary standard energies available.

The specific work reported here consists of a series of measurements of gamma-ray energies greater than 1 MeV, by comparing escape-peak energies with well-measured secondary standard gamma rays.

There are two primary standards (Table XXV) to which I will refer. The first is Bearden's x-ray standard, viz. the K_{α_1} tungsten

TABLE XXV Primary standards.

 Bearden x-ray standard^a (the tungsten x ray)

$$W_{a_1} = 59318.2 \pm 0.6 \text{ eV}$$

 1963 least-squares adjusted constants^b (annihilation radiation)

$$m_0 = 511006 \pm 5 \text{ eV}$$

$$E_\gamma = 511003 \pm 5 \text{ eV}$$

 Comparison^c

$$1) \text{ Knowles}^d \frac{9 \lambda (\text{ann. rad.})}{\lambda (W_{a_1})} = 1.044811$$

$$511003 \pm 5 \text{ eV (ann. rad.)} \rightarrow 59322.4 \pm 0.7 \text{ eV } (W_{a_1})$$

$$2) \text{ Murray et al.}^b$$

$$511003 \pm 5 \text{ eV (ann. rad.)} \rightarrow 411795 \pm 9 \text{ eV } (^{198}\text{Au})$$

 Riedy and Wiedenbeck^e

$$411800 \text{ eV } (^{198}\text{Au}) \rightarrow 59319.0 \pm 2.5 \text{ eV } (W_{a_1})$$

^aReference 1

^bReference 2.

^cThe consistency of the two primary standards is tested by combining the value of the annihilation radiation with other data to deduce a value for the W_{a_1} x ray

^dReported in Ref 2

^eReference 3

x ray, based on many careful spectroscopic measurements,¹ and on the 1963 adjusted constants. The other is the annihilation gamma energy, based on the electron mass as fixed by the 1963 constants.² Comparison between these has been made in two different ways as shown. The latter comparison, based mainly on the curved-crystal measurements of Riedy and Wiedenbeck,³ agrees within 2 eV with the Bearden value. We have therefore tentatively accepted both primary standards.

¹J. A. Bearden, USAEC Division of Technical Information Extension, Oak Ridge, Tennessee, Report NYO-10586 (1964).

²G. Murray, R. L. Graham, and J. S. Geiger, Nucl. Phys. 63, 353 (1965).

³J. J. Reidy and M. L. Wiedenbeck, Nucl. Phys. 79, 193 (1966).

TABLE XXVI.
Secondary standards used in
calibration.

Isotope	γ -ray energy (keV)
^{182}Ta	152.429 ± 0.003
	156.389 ± 0.004
	179.392 ± 0.005
	222.104 ± 0.005
	229.317 ± 0.008
^{192}Ir	264.068 ± 0.009
	295.953 ± 0.010
	308.448 ± 0.010
^{198}Au	316.502 ± 0.010
	411.795 ± 0.007
^{137}Cs	661.632 ± 0.069

Workers in this field have tended to focus upon certain sets of secondary energy standards, which are both convenient and relatively easy to measure. Those which we found useful are shown in Table XXVI. The ^{182}W gammas resulting from beta decay of 105-day ^{182}Ta have been extensively studied by the Cal Tech group,⁴ using a curved-crystal spectrometer. The recent work of the Risö group⁵ on ^{182}Ta , using the Bearden x-ray standard, has reduced the energy error to about 3 eV for the ^{182}Ta gammas. The ^{192}Pt gamma energies resulting from the beta decay of 74-day ^{192}Ir have been measured by several groups.⁶⁻⁸ The ^{198}Au decay to ^{198}Hg has also been well measured, principally by the Chalk River group.²

Let me now quickly survey the methods of precision gamma measurement (Fig. 180). Below 300 keV, the bent-crystal spectrometer has produced the majority of high-resolution gamma-energy data. Above 300 keV, the resolution of the Ge(Li) detector becomes rapidly more promising.

⁴E. J. Seppi, H. Henrikson, F. Boehm, and J. W. M. DuMond, Nucl. Instr. Methods 16, 17 (1962).

⁵V. Gruber, R. Koch, B. P. Maier, and O. W. B. Schult, Z. Naturforsch. 20, 929 (1965).

⁶B. Lindstrom and I. Marklund, Nucl. Phys. 49, 609 (1963).

⁷D. E. Muller, H. C. Hoyt, D. J. Klein, and J. W. M. DuMond, Phys. Rev. 88, 775 (1952).

⁸P. Bergvall, Ark. Fys. 17, 125 (1960).

Comparable precision has been reported from an iron-free conversion spectrometer² and diffraction methods such as a double flat crystal.⁹ However, the Ge(Li) detector allows for simultaneous accumulation of large amounts of data covering a wide spectral region with much higher efficiency.

The precision of a Ge(Li) measurement is generally found to be about 1% of the full width at half maximum (fwhm) of a well-formed peak. The peak width is roughly 1 keV fwhm at the 122-keV line of ⁵⁷Co, a result obtainable with a low-capacity germanium detector and a good low-noise preamplifier with a liquid-nitrogen-cooled field-effect transistor in the input loop.

We find accuracies of the order of 0.1 keV are reproducibly obtained using a multichannel pulse-height analyzer, calibrated by a precision pulser, with absolute scaling based on two or more gamma peaks bracketing the measured peak. When the measured peak occurs very close to a known peak, the system calibration error is reduced and the accuracy is based almost entirely on the precision of peak-fitting techniques. This is generally much better than 0.1 keV.

When the measured peak is so close to the known peak that they cannot be resolved, alternate runs are taken, exchanging the known and measured sources while keeping two or more other gamma peaks in the spectrum as markers to guard against shifts in gain and

Fig. 180. Relative resolution of precision energy instruments.

⁹J. W. Knowles, in α -, β -, and γ -Ray Spectroscopy, 2nd ed. (North-Holland Publishing Co., Amsterdam, 1965), Vol. I.

Fig. 181. Spectrum of several radioactive sources in the 1.0–1.4 MeV region.

Fig. 182. Spectrum of ^{124}Sb and ^{137}Cs in the 700-keV region.

base line. Under these conditions, the system calibration ceases to be a major source of error, but measurement of the positions of marker peaks from run to run will add to the error. We consider digital feedback gain stabilization to be essential.

For gamma rays with energies above 1 MeV, the spectrum typically contains a full-energy peak and two subsidiary peaks corresponding to one or two positron annihilation gammas escaping the detector. These energy peaks can often be measured with respect to full-energy peaks of known gammas. This allows 0.1 keV measurements in the 1–2-MeV region. We take the escape peaks to differ from the full-energy peak by exactly 1 and 2 times the energy of the annihilation gamma.

In Fig. 181 we see a comparison of the ^{60}Co peak with the ^{88}Y single-escape peak. In Fig. 182 the ^{124}Sb double-escape peak is compared with the ^{137}Cs peak.

The peaks are usually not symmetric, but are often characterized by a low-energy tail, especially at higher energies. In a given energy region, however, the shapes of full-energy peaks and escape peaks appear to be identical.

The results of the difference measurements are listed in Table XXVII. Doublets differing by less than 3 keV were calibrated in two steps as described. Additional gammas, incidental to the calibration program, were also measured when it was convenient. The series of measurements was carried out at the Livermore Pool Type Reactor.

This allowed for the extensive use of short-lifetime, neutron-activated sources such as ^{28}Al , ^{41}Ar , and ^{52}V . These intermediate results are presented in such a way that final results may be re-evaluated if further refinements are made in the input calibration gamma energies.

Final results are presented in Table XXVIII. The success of the calibration technique relies partially on the assumption that the energy of the escape peaks is lower than the full-energy peak by amounts equal to 1 and 2 times the annihilation gamma energy. Although such an assumption may seem obvious, subtleties in the interaction process between the γ rays and the Ge(Li) detector could conceivably lead to a small systematic error. For example, pair escape processes are more likely near the edges of the detector, where ion collection rates may be slightly different from that in the interior. We must ultimately rest the assumption on experiment, and note that our ^{60}Co results compare extremely well with the results of Murray *et al.*,² who use a completely different method.

Moreover, various measurements of the hydrogen capture gamma, some involving escape-peak calibration, appear to be in agreement to within 0.1 keV.¹⁰⁻¹² With care and patience, somewhat

TABLE XXVII. Measured differences between gamma-ray energies.

^{60}Co (2 escape) - ^{182}Ta	$= -1.19 \pm 0.07 \text{ keV}$
^{60}Co (2 escape) - ^{192}Ir	$= 2.11 \pm 0.04 \text{ keV}$
^{51}Cr - ^{192}Ir	$= 3.61 \pm 0.02 \text{ keV}$
^{51}V (2 escape) - ^{198}Au	$= 0.39 \pm 0.05 \text{ keV}$
^{88}Y (1 escape) - ^{60}Co	$= -7.39 \pm 0.10 \text{ keV}$
^{124}Sb (2 escape) - ^{137}Cs	$= 7.38 \pm 0.02 \text{ keV}$
^{28}Al (1 escape) - ^{22}Na	$= -6.88 \pm 0.14 \text{ keV}$

¹⁰ J. W. Knowles, Can. J. Phys. 40, 257 (1962).

¹¹ W. V. Prestwich, T. J. Kennett, L. B. Hughes, and J. Fiedler, Can. J. Phys. 43, 2086 (1965).

¹² R. C. Greenwood and W. W. Black, Phys. Letters 21, 702 (1966).

TABLE XXVIII.
Final measured gamma-ray
energies.

Isotope	Energy (keV)
^{141}Ce	145.41 ± 0.03
^{51}Cr	320.11 ± 0.03
$^{69}\text{Zn}^{\text{m}}$	438.70 ± 0.10
^{22}Na	1274.58 ± 0.10
^{41}Ar	1293.76 ± 0.14
^{60}Co	1173.25 ± 0.08
^{60}Co	1332.56 ± 0.05
^{52}V	1434.19 ± 0.05
^{124}Sb	1691.02 ± 0.08
^{28}Al	1778.70 ± 0.17
^{88}Y	1836.17 ± 0.12

lower error could be obtained with the escape-peak method. With recent improvement of system resolution, the ^{60}Co double-escape peaks could be resolved from the corresponding standards, thus obviating the present two-step measurement and thereby reducing the estimated error.

The general success of the method shows that by proper choice of gammas precise energies can be calibrated by "bootstrap" comparisons up to 10 MeV by using neutron-capture gamma rays.

* * *

R. C. GREENWOOD, Idaho Nuclear Corporation: This question of whether the energy of the double-escape peak is $2m_0c^2$ less than that of the full-energy peak came up at our laboratory 6 months ago. When we checked by looking at Na^{24} and Y^{88} , the difference seemed to be $2m_0c^2$ within the accuracy of our measurement, i.e., within perhaps 0.05 keV. If you think about it, there is no clear reason why it should not be $2m_0c^2$ but there are good reasons why it should be. The fact that you see an annihilation peak at all is reasonable evidence for it; if the annihilation occurred in flight, the annihilation peak would be spread all over the place so you just would not see it.

WHITE: Yes, but such arguments are easier to make from hindsight than from foresight.

GREENWOOD: I did not understand what effect the edge of the crystal could have on the energy difference between the double-escape peak and the full-energy peak.

WHITE: I just threw that possibility in as an example. One could argue that pairs could get out more easily if the interaction occurs near the corner of the detector; and this would affect the two-pair escape peak more than the full-energy peak. However, the corners are also likely to be regions of weak fields so that ion collection occurs at a slower rate; and this slower collection affects the peak shape. The shapes of the full-energy peaks may thus be different from those of the double-escape peaks. How much this affects the peak shape (and hence the energy) depends on the electronics. Admittedly, the effect may be small—perhaps negligible—but such effects may exist.

L. M. BOLLINGER, Argonne National Laboratory: I want to make sure I understand what Greenwood is saying. Are you saying that there is no difference whatever between the line shapes of the full-energy peak and the escape peaks? Have you looked carefully for such a difference?

GREENWOOD: We have not found any difference between the line shapes, but we have not looked very carefully. They both seem to be represented by Gaussians.

BOLLINGER: The reason I ask is that we believe there is a difference in line shape, though we do not understand it. The double-escape peak appears to have a very definite tail; but within the accuracy of our determination of it, the full-energy peak seems to be symmetrical.

GREENWOOD: As you have indicated, those deviations occur low down on the peaks.

BOLLINGER: Yes. They are at about the 3% level.

GREENWOOD: I do not make any fit in that region. My point was that with normal, reasonable fitting procedures, the difference between the full-energy and the double-escape peaks was not found to deviate from $2m_0 c^2$.

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~~F~~5. ABSOLUTE OR RELATIVE (n, γ) DATA?

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The determination of absolute (n, γ) energies and intensities with the highest possible precision is without any doubt the ultimate goal. The primary result of almost every experiment is a set of relative numbers $F_{i \text{ rel}}$ from which the absolute data $F_{i \text{ abs}}$ are obtained through a calibration. Evidently, the calibration is associated with a percent error e_{cal} . If this error and the percent errors $e_{i \text{ exp}}$ of the relative numbers $F_{i \text{ rel}}$ are uncorrelated, the final absolute percent error of the measured quantity $F_{i \text{ abs}}$ is given through

$$e_{i \text{ abs}} = \sqrt{e_{\text{cal}}^2 + e_{i \text{ exp}}^2}.$$

Rather precise relative energies of low-energy (n, γ) transitions can be obtained with curved-crystal spectrometers. If effort is made,¹ a relative energy error $dE_{\text{rel}}/E_{\text{rel}} \approx 4 \times 10^{-6} \times E$ (100 keV) can be achieved. It seems reasonable to quote an error with a 10% precision. A typical result might then be

$$E_{\text{rel}} = 246.0607 \pm 0.0020.$$

For the determination of absolute energies at crystal spectrometers a number of facts must be considered.

The most precisely determined reference lines which can be used for calibration are the $K\alpha$ x rays of the rare earths² and

¹U. Gruber, R. Koch, B. P. Maier, and O. W. B. Schult, Z. Naturforsch. 20a, 929 (1965).

²P. Bergvall, Ark. Fysik 16, 57 (1959).

the tungsten $K\alpha_1$ line.³ However, these lines are given in x units. It is noteworthy that the "x unit" has been defined at least four times in different ways (as explained in more detail in Ref. 1) so that the use of the x unit is quite confusing unless one always says exactly which x unit has been chosen. The x unit must be converted into centimeters and then the conversion factor relating absolute energies (in keV) and γ -ray wavelengths (in cm) can be applied to obtain absolute energies of the reference lines (as explained in Ref. 1). Thus the absolute energy calibration involves (1) the error of the conversion factor (keV $\div$ cm), (2) the error of the conversion factor (x unit $\div$ cm), (3) the error of the reference line, and (4) the error of the measurement of the wavelength of the reference line using the spectrometer which serves to measure the (n, γ) data. In total, the error associated with the absolute energy calibration is about 2×10^{-5} . A typical absolute energy might then be¹

$$246.061 \pm 0.005 \text{ keV}$$

—which is less precise than the relative number, unless the error is given in an academic fashion as

$$246.0607 \pm 0.0053 \text{ keV.}$$

Since there does not seem to exist a direct need for absolute energies in the low-energy (n, γ) data, it would certainly seem advisable for the experimenter to retain the maximum precision in his data by quoting only relative energies, which, of course, have been measured with a well calibrated apparatus so that they will not differ from absolute energies (in keV) by more than say a factor 1.00000 ± 0.00005 . Then people uninterested in precisions better than 5×10^{-5} might simply consider his relative numbers as absolute energies in keV. On the other hand, the same set of relative energies obtained with another equipment

³J. A. Bearden, A. Henins, J. G. Marzolf, W. C. Sauder, and J. S. Thomsen, Phys. Rev. 135A, 899 (1964).

with similar relative accuracy could easily be compared with the first set when a least-squares fit is performed. Here the agreement will definitely be better than if every experimentalist impairs the precision of his data by introducing a systematic error connected with the measurement of the calibration line.

The advantage of the use of relative instead of absolute energies is most obvious if a level scheme is constructed out of relative energies. Then a relative precision around 10^{-5} is common for the level energies, even for routinely measured data.⁴ Lithium-drifted germanium detectors allow very good resolution at higher energies ($\gtrsim 500$ keV). For this reason they should also be capable of yielding very precise relative energies for (n, γ) transitions. However, at the present time this precision is limited by the electronics. If these difficulties are overcome, it should (in principle) be possible to measure the peak positions with an accuracy of $0.01 \times \text{FWHM}$. Then a relative precision $dE_{\text{rel}}/E_{\text{rel}} < 10^{-5}$ for $E > 1$ MeV could be achieved with these spectrometers.

The knowledge of absolute transition energies to an accuracy better than 2×10^{-5} would not be necessary for the determination of the (n, γ) Q values unless there is interest in such a precision. Relative energies would be sufficient for the combination of high-energy and low-energy (n, γ) data. For convenience, the relative γ energies should agree with absolute energies within a factor 1.0000 ± 0.0001 .

The use of relative energies would not require particular lines as standards, nor would it make necessary the introduction of new energy units. Still it is of major importance to know the absolute energy of the 511-keV annihilation radiation with maximum possible precision since this energy appears regularly as the spacing of the single- and double-escape peaks in the high-energy γ spectra which are measured

⁴O. W. B. Schult, M. E. Bunker, D. W. Hafemeister, E. B. Shera, E. T. Journey, J. W. Starner, A. Bäcklin, B. Fogelberg, U. Gruber, B. P. K. Maier, H. R. Koch, W. N. Shelton, M. Minor, and R. K. Sheline, Phys. Rev. 154, 1146 (1967).

with Ge(Li) detectors. Unfortunately, the 511-keV peak observed in curved-crystal spectrometers is usually fairly weak and broad so that a measurement with a relative energy precision better than 2×10^{-5} seems very difficult.

Precise intensity measurements at curved-crystal spectrometers are quite difficult. Extended sources are used in order to achieve a high sensitivity. Under these circumstances, the source geometry at a DuMond-type spectrometer is not well defined. Source absorption corrections amounting to factors up to 30 slightly above the K absorption edge of the source material are frequent and the uncertainty can here be as large as a factor of 2. In a single-run experiment, the average precision of relative (n, γ) intensities is normally 10–30% with the exception of very weak lines and low-energy transitions (< 100 keV).

The relative (n, γ) intensities can be improved when the large-source run is taken only for the determination of intensity ratios of close-lying lines. An additional small-source run could then yield relative intensities for the strongest lines in the whole spectrum. The combination of these two measurements should permit the determination of relative intensities with a precision around 4–8% except for very weak transitions.

A further reduction of the errors of the relative intensities might be possible through the application of the Hatch-Brown technique⁵: the γ spectrum of a radioactive source is measured with a scintillation counter. The pulse-height spectrum obtained in this way is computer analyzed utilizing the response functions of the scintillation detector for the individual monochromatic γ rays present in the spectrum. These response functions are measured with a curved-crystal spectrometer.

⁵ E. N. Hatch, Department of Physics, Iowa State University, Ames, Iowa (private communication); J. E. Brown and E. N. Hatch, *Bull. Am. Phys. Soc.* 10, 53 (1965).

Of course, a computer treatment of the very complex (n, γ) spectra detected with a NaI(Tl) counter would require extremely good stability of the electronics and a very high number of counts if the intensity accuracy should be better than 10% for lines with an intensity range of 1:100. However, the use of a lithium-drifted germanium detector with its much better resolution seems a promising possibility.

In order to obtain absolute (n, γ) intensities, one can perform an absolute intensity calibration of the spectrometer, measure and monitor the neutron flux at the source position, and determine the capture rate per unit neutron flux in the source. Another very attractive possibility is, according to a proposal by Maier-Leibnitz,⁶ the use of mixed sources. Here one can apply two methods:

- (1) If the relative intensities have been measured in a large-source run and in a small-source run, it would be sufficient to have a single reference line. The 478-keV transition in Li^7 , emitted after the neutron capture in B^{10} , seems ideal for this purpose because B^{10} is a v^{-1} absorber, its cross section is known with a precision better than 1%, and the intensity of the 478-keV line per neutron capture in B^{10} is also known to better than 1%. Thus the absolute intensity errors would be given mainly through the errors in the relative intensity and the error in the cross section of the target material.
- (2) If the admixed isotope emits a spectrum of many γ lines covering the whole energy region of interest and if the absolute intensities of the stronger of these lines were known with high precision ($\approx 2-4\%$), it would be possible (for evident reasons) to omit the small-source run. This advantage must be balanced against the disadvantage that reflexes of the transitions due to the admixed

⁶H. Maier-Leibnitz, Physik-Department, Technical University, Munich (private communication).

isotope cause narrow regions where the spectrometer is fairly insensitive to lines from the target substance. In fact, those transitions in the target which are too close in energy to the transitions from the admixed isotope would affect the heights of the corresponding reflexes and might therefore lead to incorrect results. To avoid this error, one might make a separate measurement with a source whose mixing ratio is sufficiently different from the one in the first source.

* * *

H. T. MOTZ, Los Alamos Scientific Laboratory: Are you suggesting that the 478-keV line should be used for energy measurements or only for intensity?

SCHULT: For intensity.

MOTZ: The limitation to intensity measurements is presumably due to the broadness of the line. It is several percent broad in most chemical compounds.

SCHULT: Yes, but it is a single line.

MOTZ: Boron is especially good for an external-beam measurement. You can get the beam intensity very accurately by putting up a black absorber and measuring the neutron flux.

SESSION G

3 NOVEMBER 1966

CORRELATIONS; COMPARISON WITH (d,p) RESULTS

J. A. HARVEY, CHAIRMAN

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G-^(H)f. THERMAL-NEUTRON CAPTURE GAMMA-RAY STUDIES OF THE
EXCITED STATES OF ODD-A HAFNIUM ISOTOPES*†^(H)

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The wave function of a purely compound capture state, whether at thermal energies or at a resonance, is expected to be a conglomerate, statistically-constituted admixture of many parts. The neutron resonances close to the binding energy are only a few eV apart, and each of the resonances is expected to have a wave function built up of fairly similar components which are distributed in a statistical manner over the many closely spaced states. The strength of a particular primary transition will vary from resonance to resonance with respect to the average value for all resonances, and should follow a χ^2 distribution with one degree of freedom—that is, a Porter-Thomas distribution.¹ This variation can be distributed over many orders of magnitude. In this context, when we speak of a particular transition we are referring to a transition from one of the various capture states to the same final state.

Whether we are dealing with thermal- or resonance-capture states, these capture states are only electron-volts apart and we do not have to consider the E^3 energy dependence for these dipole transitions to a particular final state. If we examine the transition strength of a particular transition from resonance-to-resonance to a particular final state and plot these strengths with respect to the average strength, we

* Work performed under the auspices of the U. S. Atomic Energy Commission.

† This work has now been published: A. I. Namenson and H. H. Bolotin, Phys. Rev. 158, 1206 (1967).

¹ C. E. Porter and R. G. Thomas, Phys. Rev. 104, 483 (1956).

Fig. 183. Gamma-ray pulse-height spectrum from the thermal-neutron-capture reaction in a sample of natural Hf. All labeled lines are double-escape peaks unless prefixed by SE (single-escape peak) or FE (full-energy peak). The γ -ray energies are given in keV. The isotopic identification denotes the nuclide in which the transition takes place. Background lines are identified by the chemical symbol of the relevant contaminant.

obtain a broad distribution. This distribution predicts a great many weak transitions with respect to the average, and relatively few strong transitions, but this variation is the type expected and has been shown to be in agreement with the experimental distributions obtained for the cases of several nuclei which have been studied.

I would like to describe some recent investigations of the thermal capture gamma-ray spectrum of Hf¹⁷⁹ and Hf¹⁸¹, and then combine these results with similar work on three odd-A tungsten isotopes

Fig. 184. Gamma-ray pulse-height spectrum from the thermal-neutron-capture reaction $\text{Hf}^{178}(n, \gamma)\text{Hf}^{179}$ in an enriched Hf^{178} target. All labeled lines are double-escape peaks unless prefixed by SE (single-escape peak) or FE (full-energy peak). The γ -ray energies are given in keV. The isotopic identification denotes the nuclide in which the transition takes place. Background lines are identified by the chemical symbol of the relevant contaminant.

which was reported² by the Oak Ridge group using thermal neutrons. There is a strong suggestion that the behavior of the decay of the capture states of these nuclides may not be consistent with a wholly statistical capture model. We have used four enriched Hf isotopes and one natural Hf sample as targets in order to investigate the capture gamma-ray spectra of these nuclides and to try to assign the observed lines to the various isotopes in an unambiguous manner.

²M. J. Martin, J. A. Harvey, and G. G. Slaughter, Bull. Am. Phys. Soc. 11, 336 (1966).

Fig. 185. Gamma-ray pulse-height spectrum from the thermal-neutron-capture reaction $\text{Hf}^{180}(n, \gamma)\text{Hf}^{181}$ in an enriched Hf^{180} target. All labeled lines are double-escape peaks unless prefixed by SE (single-escape peak) or FE (full-energy peak). The γ -ray energies are given in keV. The isotopic identification denotes the nuclide in which the transition takes place. Background lines are identified by the chemical symbol of the relevant contaminant.

The product nuclei to which I will devote my attention are Hf^{179} and Hf^{181} . Figures 183—185 show some representative pulse-height spectra that had been obtained with these targets. The first is that of the natural Hf sample, the second that seen with an enriched Hf^{178} target, and the third the spectrum obtained with an enriched Hf^{180} target. Many of the transitions in these figures are labeled in terms of the isotopic assignments we had made, which we feel in virtually every case has been assigned unambiguously.

Fig. 186. Level scheme of Hf^{179} . Only states to which primary transitions were observed to proceed are shown. All energies are in keV. The intensities of all lines are expressed as the percent per neutron capture in the capturing isotope. The level shown dashed is uncertain.

Figure 186 illustrates the decay scheme represented only by the high-energy primary capture gamma rays which we have observed to populate the low-lying levels. This is the level scheme for Hf^{179} . The energies of the states determined in this experiment agree within a few keV with the excitation energies reported by the Florida State group³ in their (d,p) studies. I would like to call attention to two particular states which the Florida State group had identified as two members of the $\frac{1}{2}^- [510]$ Nilsson band. These states have spins of $\frac{1}{2}^-$ and $\frac{3}{2}^-$. Since in this case we are dealing with capture in an even-even target nucleus, the capture state has the unique spin and parity $\frac{1}{2}^+$; and since most of the transitions we see here are of some moderate strength, we assume that all the levels that we have seen have spins of either $\frac{1}{2}^-$ or $\frac{3}{2}^-$. I do not intend to spend any time on the other levels present in this diagram. They are themselves of some interest and several of these have also been seen in (d,p) studies, but not many definitive Nilsson orbital assignments have made for them, except for one state at 721 keV to which no primary transition has been observed. This level has been identified as the band head of the $\frac{3}{2}^- [512]$ band. Notice that the two transitions to the $\frac{1}{2}^- [510]$ band members account for effectively 10% of all the transition strength from the capture state.

³M. N. Vergnes and R. K. Sheline, Phys. Rev. **132**, 1736 (1963); F. A. Rickey and R. K. Sheline (private communication).

Fig. 187. Level scheme of Hf^{181} . Only states to which primary transitions were observed to proceed are shown. All energies are in keV. The intensities of all lines are expressed as the percent per neutron capture in the capturing isotope. The level shown dashed is uncertain.

In Fig. 187 we see a similar level scheme for Hf^{181} showing only those states which we have observed to be populated by means of high-energy primary gamma-ray transitions. I wish to confine my remarks to those states that are labeled with Nilsson assignments. In this case we do see the [512] band head at 252 keV populated by a primary transition and, again, also see strong transitions to the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ members of the [510] band. Again those transitions to the [510] band account for more than 10% of the transition strength from the capture state. The transition strength to the $\frac{3}{2}^-$ member of the [512] state is only 0.6% of the decay of the capture state, which is somewhat weaker than the 4.2% transition proceeding to the $\frac{3}{2}^-$ member of the [510] band.

Table XXIX summarizes, in addition to some of the results I have presented, the intensity of gamma rays to upper levels. If we confine our attention for a moment to the [510] band members in both nuclei, we see that approximately 10% of the primary decay strength in Hf^{179} goes to these levels and approximately 18% of the primary decay strength proceeds to these levels in Hf^{181} . The [512] band is not populated in Hf^{179} , but is populated in Hf^{181} . But even in the latter case it is considerably weaker in intensity than the transitions to the [510] band levels.

These data taken by themselves are somewhat suggestive, but yet they apply to only two nuclides. In this mass region we feel we know something about the low-lying rotational levels and their asymptotic quantum numbers. If we combine these data with fairly similar

TABLE XXIX. Summary of the transitions identified in odd-A Hf isotopes.

Gamma-ray energy ^a (keV)	Intensity ^b of transition (% per neutron capture)	Excitation energy of terminal level (keV)		Spin and parity (if known)	Nilsson band assignment (if known)	References
		Present work	(d, p)			
A. Hf ¹⁷⁸ (n, γ)Hf ¹⁷⁹						
5720	8.8	378	373	$\frac{1}{2}^-$	$\frac{1}{2}^-$ [510]	1, 9, 10
5675	1.1	423	421	$\frac{3}{2}^-$	$\frac{1}{2}^-$ [510]	1, 9, 10
5418	0.78	680	679			9, 10
4391	0.73	1707	1706			9, 10
4372 ^c	1.4	1726	. . .			
4341	2.3	1757	1759			9, 10
4334	1.3	1764				
4287	0.55	1881	1815			9, 10
B. Hf ¹⁸⁰ (n, γ)Hf ¹⁸¹						
5693	14.4	0	0	$\frac{1}{2}^-$	$\frac{1}{2}^-$ [510]	1, 10
5648	4.2	45	48	$\frac{3}{2}^-$	$\frac{1}{2}^-$ [510]	1, 10
5441	0.76	252	255	$\frac{3}{2}^-$	$\frac{3}{2}^-$ [512]	10
4607	0.78	1086				
4371 ^c	1.7	1322				
3977 ^c	2.2	1716				

^aAn uncertainty of ± 3 keV is associated with the quoted transition energies.

^bNormalization of the intensity of the 5720-keV transition in the present work to the value of 8.8% per neutron capture found for this transition by L. V. Groshev, A. M. Demidov, V. A. Ivanov, V. N. Lutzenko, and V. I. Pelekhov [Izv. Akad. Nauk SSSR, Ser. Fiz. 28, 1244 (1964)] allowed all transitions listed in this table to be expressed in terms of percent per neutron capture, when coupled with the relative intensities per capture determined in the present work. An uncertainty of $\pm 30\%$ is to be associated with the quoted intensity values.

^cIsotopic identification is uncertain.

Oak Ridge data² for W¹⁸³, W¹⁸⁵, and W¹⁸⁷, the combination of the results in these five nuclides are highly suggestive of some particular pattern. In Table XXX, the reduced transition probabilities for the transitions to the $\frac{3}{2}$ level of the [510] band are compared with the population of the $\frac{1}{2}$ member of the [510] band, and we see that in all cases (excluding W¹⁸⁷, which is on the borderline of the rotational region), the transitions to the $\frac{1}{2}^-$ member of the [510] band are considerably stronger. In fact, only in the case of W¹⁸⁷ do these

TABLE XXX. Admixtures in and reduced transition probabilities to some $\frac{3}{2}^-$ levels of odd-A isotopes of hafnium and tungsten. The admixtures a_K of $|512\rangle$ and $|510\rangle$ states in the wave functions Ψ of the $\frac{3}{2}^-$ levels are defined implicitly by the expression $\Psi = a_{3/2} |512\rangle + a_{1/2} |510\rangle$. The reduced transition probabilities are expressed as ratios to that of the transition to the $\frac{1}{2}^-$ level in the $\frac{1}{2}^- [510]$ band.

Nucleus	Admixture in $\frac{3}{2}^-$ level				Relative reduced transition probability for transition to the $\frac{3}{2}^-$ level		
	In $\frac{1}{2}^- [510]$ band		In $\frac{3}{2}^- [510]$ band		In $\frac{1}{2}^- [510]$ band	In $\frac{3}{2}^- [512]$ band	Sum
	$a_{1/2}$	$a_{3/2}$	$a_{1/2}$	$a_{3/2}$			
Hf ¹⁷⁹	..	...	...	...	0.128	0.00	0.13
Hf ¹⁸¹	...	...	...	...	0.299	0.061	0.36
W ¹⁸³	0.971	0.239	0.239	-0.971	0.34	<0.01	0.34
W ¹⁸⁵	0.891	-0.454	0.454	0.891	0.155	0.099	0.25
W ¹⁸⁷	0.994	-0.110	0.110	0.994	1.39	0.05	1.44

transitions become at all comparable. In all of these cases the population of the $[512]$ band is quite weak. Only in the case of W¹⁸³ do the two transitions to the $\frac{3}{2}^-$ states become comparable. From the results of Erskine,⁴ who investigated the low-lying states of some of the tungsten nuclides in (d,p) studies, W¹⁸³ is the only case in which there is any indication of the $[510]$ band admixing into the $[512]$ band. Moreover, this is the only case in which the $\frac{3}{2}^-$ members of these bands are populated with a strength comparable to that from the capture state.

The combined results of these five nuclides seem to indicate that a wholly statistical picture for the capture state may not be adequate to explain these experimental results. A statistical sampling of the Porter-Thomas distribution, or possibly several Porter-Thomas distributions, would have a rather small chance of displaying these systematic regularities. These regularities may be evidence for the operation of some selection rules acting between the capture states and low-lying levels; that is, if we do not have a purely statistical pattern, then some selection rules involved in the transition rates may cause these systematic regularities to appear. One might speculate as to the

⁴J. R. Erskine, Phys. Rev. 138, B66 (1965).

invocation of some particular selection rules that may be operative. The selection rule that I will discuss is only one of several possible selection rules that could be invoked. The operation of such a selection rule could explain these regularities; however, it is possible that this particular selection rule may play absolutely no role at all in what is going on. What is significant is that it does seem highly suggestive that some selection rule or rules are operative.

Let us speculate in the following way. We start from an even-even deformed-core target nucleus of 0 spin and have incident upon it an s-wave neutron. We can conceive the s-wave neutron coupling to this even-even spin-0 deformed core to form the $K=\frac{1}{2}$ band with $\Lambda = 0$ (since the s-wave neutron carries no orbital angular momentum). There is an asymptotic selection rule which involves the quantity Λ , namely $\Delta\Lambda$ must be 0, or ± 1 . Referring back to the Nilsson assignments, the capture takes place in a $\Lambda=0$ state; so that the transition probabilities are not hindered by the $\Delta\Lambda$ selection rule in going from the capture state to the [510] band which has $\Lambda = 0$. However, the [512] band has $\Lambda = 2$, and the Λ selection rule states that a transition from the capture to this state is forbidden. By invoking this selection rule, one concludes that the transitions to the $\frac{3}{2}^-$ [512] band should be relatively weak because of the hindrance caused by this selection rule. We have seen evidence that these particular transitions are hindered. This selection rule does not hinder transitions to the [510] band and we do observe that these transitions are strong. Only in the case of W^{183} , for which we have some admixture of the [510] band in the [512] band, do we see a comparable strength for the transitions to the two $\frac{3}{2}^-$ states of the two bands. Following along with this selection rule, in this nucleus a stronger transition to the $\frac{3}{2}^-$ [512] band head may arise from the admixed part of the [510] band in the [512] band. Again, let me say that this is only one possible selection rule that could account for these observed regularities.

Hopefully, some resonance data on some of these nuclides will be presented tomorrow. In these cases, pertinent information may be forthcoming from similar studies of several resonances, and we might see whether or not these regularities persist. At least in the first few resonances studied by several groups, including the Idaho Nuclear Corporation and the Brookhaven groups, strong transitions are seen to the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ members of the [510] band and either very weak or absent branches are observed to the $\frac{3}{2}^-$ [512] band.

* * *

R. E. CHRIEN, Brookhaven National Laboratory: As will be discussed more fully in three of our papers tomorrow (papers I-4, I-5, and I-6), I agree that the problem has to be studied by looking at the spectra from capture in resonances. In fact, W^{183} ($W^{182} + \text{neutron}$) has a level at 114 eV which shows a very strong transition to the [512] state. I think thermal capture does not represent a good average over the resonances.

BOLOTIN: I do not think it does either. However, if that transition is considered, would the results for all the resonances at lower energies fit a Porter-Thomas distribution?

CHRIEN: The results are not inconsistent with the Porter-Thomas distribution, within the limited number of resonances we have examined.

C. F. CLEMENT, Florida State University, Tallahassee: I don't want to anticipate what I am going to say later this afternoon (paper H-3), but there are strong reasons for saying the situation is not entirely statistical. Transitions from different resonances to a given low-lying state might be expected to follow a Porter-Thomas distribution, but the distribution of partial widths from a given resonance to a set of low-lying states is not expected to be entirely random. There may be correlations with corresponding (d, p) spectroscopic factors.

BOLOTIN: I am not sure we are all applying the Porter-Thomas distribution to the same problem. Although the examples I gave you might really be averages only over the contributions of the low resonances, they are taken from experiments on different nuclei. It would be expected that the resonances in the tungsten isotopes are independent of the resonances in hafnium, and that the partial radiation widths in the two cases are not derived from the same Porter-Thomas distribution. Yet in each nucleus one part of the Porter-Thomas distribution is being selected out. It seems remarkable that only the strong parts, or at least the same parts, are selected out in all five cases.

M. BEER, State University of New York at Stony Brook and Brookhaven National Laboratory: I would like to add to what Chrien has said. The [512] transition shows up strongly not only in the 114-eV resonance but also in the 21-eV resonance; and it might very well follow a Porter-Thomas distribution.

BOLOTIN: What are the characteristics of the transitions to the [510] states? Are they still very strong? Do they ever disappear?

BEER: The ground-state transition is strong in all three resonances. The first excited state is very weak in the 114-eV resonance but is strong in the 21-eV resonance.

R. E. SEGEL, Argonne National Laboratory: I had not thought that the Porter-Thomas distribution required the same average strength for all gamma rays of the same multipolarity. I thought it only required that the gamma-ray widths should follow a certain distribution. Therefore, there is no reason why the average strength to the $\frac{1}{2}^-$ level could not be much greater than the average to the $\frac{3}{2}^-$ level; but the ratio of strengths should change a good bit from resonance to resonance, as I believe it did. For example, one might measure the partial radiation width of the ground-state transition from different resonances. This distribution of

widths would not, as I understand it, need to have the same average as the distribution to the $\frac{3}{2}^-$ level.

L. M. BOLLINGER, Argonne National Laboratory: I want to amplify what Segel has said because he raises a question that is fundamental to much of the discussion in the next few sessions. I agree with Segel's comment in the sense that in the abstract there seems to be no reason why a Porter-Thomas distribution should not be associated with transitions from a series of initial states to a single final state, and that at the same time the average widths of transitions to different final states would be different. However, if one takes the next step and tries to explain the origin of these differences in the average transition intensities, does he not necessarily talk himself into models that are inconsistent with the required complexity of the initial state? In other words, does this explanation necessarily mean abandoning the Porter-Thomas distribution?

SEGEL: I would think not. I would expect that both the strong E1 gamma ray and the neutron width arise from single-nucleon transitions. Thus, for example, the neutron width could be variable since it depends on the overlap between the complicated compound-nucleus state and the inert core plus the escaping neutron. Similarly, if the $\frac{1}{2}^-$ ground state is a core plus a p nucleon, then there is a strong E1 transition when the single nucleon goes from s to p. The width for this transition will therefore be very similar to the neutron width, since the neutron transition also requires the single nucleon plus the core.

R. R. SPENCER, Idaho Nuclear Corporation: I have one comment and one question. The comment is that the thermal capture in W^{183} includes fairly significant contributions from three resonances, so the results reflect what is happening in three different initial states.

The question is this. I believe a significant portion of the thermal spectrum comes from a negative-energy resonance. The usual way of thinking about a compound nucleus is that a neutron is pretty

well mixed up before anything happens. In what sort of a system do you expect this $\Delta\Lambda$ selection rule to be good? Under what conditions do you expect Λ to be a good quantum number at 6, 7, or 8 MeV in the compound system? Or can you propose some model other than pure compound-nucleus capture?

BOLOTIN: I am only raising the possibility that selection rules may be operating. I am not prepared to argue that capture does not proceed primarily by a pure compound-nucleus process and follow the statistical prescription. I am not sure under what conditions Λ is a good quantum number; that is one of the reasons Clement is here.

On the other hand, one can ask why it shouldn't be a good quantum number. I wouldn't expect Λ to be a good quantum number at such high excitations; but at these high excitation energies there could just be a small admixture of a configuration in which Λ is a good quantum number, and this might be enough to account for the observed behavior. Even if there is such an admixture, I do not know how much it contributes to the state. It may be only a small admixture.

SPENCER: Do you have a clear idea of a model that might account for this?

BOLOTIN: On the contrary, I am not even proposing a particular model; I only suggest that some unknown selection rule may be operating. This Λ selection rule just happens to be one that might be dreamed up to explain the characteristics we have observed. However, it need not be the one that is operating. The point is that the experimental evidence appears to suggest that some selection rule is operative.

G. T. EMERY, Indiana University, Bloomington: The quantum number Λ is, after all, the quantum number that applies to a one-particle state. It is no longer a good quantum number for more complicated states such as three-quasiparticle states, two-particle one-hole states, or five-particle four-hole states. One simple model that would give such a selection rule is direct capture; but there may be other models.

BEER: Even if one invokes a resonance single-particle capture mechanism, as Lane and Lynn have done, a Porter-Thomas distribution would still be followed. The partial radiation widths would be proportional to the resonance reduced neutron widths, and one would not expect such a selection rule to be operative.

BOLOTIN: It certainly would not be direct capture in the sense that the transition strengths would be expected to follow the (d,p) strengths; if I remember correctly, the people at Idaho Nuclear Corporation looked into this and did not find any correlation between the (n,γ) and (d,p) strengths.

G-2. RECENT COLLABORATIVE RESULTS ON NEUTRON CAPTURE IN Ho^{165}

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The summary I would like to present has to be very superficial in comparison to the effort that has gone into the problem. I am reporting on work done at four reactors and the Florida State University Van de Graaff, and the author list includes 14 names as submitted to the Physical Review.¹

I should point out that Ho^{165} is an odd-proton nucleus. This target nucleus has a Nilsson configuration $[523\frac{1}{2}^+]$ from Gallagher's assignment,² which, of course, is spin $\frac{7}{2}^+$. When a thermal neutron is captured, compound states are formed with spin parity of 3^- and 4^- . We would expect the E1 transitions from the 3^- compound state to go to 2^+ , 3^+ , and 4^+ states; and similarly E1 transitions from the 4^- compound state would go to 3^+ , 4^+ , and 5^+ states. States of opposite parity would be populated by M1 transitions. It is known from the Brookhaven work³ on polarized neutrons that the thermal-capture population gives 60% 3^- states and 40% 4^- states.

The odd neutron, which is $\frac{7}{2}^+$ in the case of Ho^{166} , combines with the odd proton. The odd proton and odd neutron combine to give the ground state a spin-parity of either 0^- or 7^- . We can measure the

¹H. T. Motz, E. T. Journey, O. W. B. Schult, H. R. Koch, U. Gruber, B. P. Maier, H. Baader, Gordon L. Struble, Jean Kern, R. K. Sheline, T. von Egidy, Th. Elze, E. Bieber, and A. Bäcklin, Phys. Rev. 155, 1265 (1967).

²C. J. Gallagher, Jr., and V. G. Soloviev, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Skrifter 2, No. 2 (1962).

³R. I. Schermer, Bull. Am. Phys. Soc. 8, 334 (1963); Phys. Rev. 136, B1285 (1964).

Fig. 188. High-energy (n, γ) spectrum of Ho^{166} , determined with Los Alamos magnetic Compton spectrometer. (B. E. $\equiv$ binding energy.)

population of the 7^- isomeric state in this particular experiment since we know the half-life is 1200 years. This population is about 5.5% of the population of the 0^- state. This result came from an auxiliary measurement that we had to make; it showed that the predominant cascade goes to the 0^- ground state.

Figure 188 shows one of the last runs made with the magnetic spectrometer at Los Alamos before it was shut down, and I merely want to point out for comparison the peaks at the higher energies. You notice that there is a doublet at the highest energy and three lines at about 200 keV less energy. We will ignore the lower part of the spectrum. Our germanium spectrometer has about $\frac{1}{3}$ as great a line width as the Compton spectrometer. Figure 189 shows these data; the upper doublet is well-resolved and the lower doublet has now become a triplet. The lower pair is separated by 9.8 keV. We have taken data on holmium with several detectors, and we have observed a spread in these values. You will see that the data do not claim to be quite as accurate as some described today, but I think our errors are very realistic for this reaction considering all the data.

The (d, p) work has been published separately by Struble, Kern, and Sheline⁴ and is shown in Fig. 190. I want to point out that there

⁴G. L. Struble, J. Kern, and R. K. Sheline, Phys. Rev. 137, B772 (1965).

Fig. 189. High-energy neutron-capture γ spectrum of Ho^{166} measured with the Ge(Li) detector at Los Alamos operated as a double-escape pair spectrometer. The radiation from a 1.5-g holmium target penetrated a 1.0-cm lead absorber. A resolution of 8.0 keV (FWHM) was obtained during the 63.5-h run.

is a very close comparison of the (n, γ) excitation; the length of the bar is proportional to the observed intensity and the error is proportional to the width of the line. The (d, p) reaction excites neutron excited states; i. e., the proton orbital is identical to the target nucleus, $[523\uparrow]$, so that we see immediately a correlation between the states excited from (n, γ) and these neutron excited states. The hollow bars refer to dubiously excited states.

Figure 191 (top) was shown by Otto Schult yesterday (paper C-1, Fig. 53). I want to point out the following comparison to you. In the upper part, you see a strong line at 136.6 keV, a relatively strong line at 126.2 keV, and another at 116.8 keV; these are the three strongest lines. At lower energies, there is more detail showing

Fig. 190. Bar plot of high-energy (n, γ) and (d, p) lines feeding Ho^{166} states. The lengths of the bars are proportional to the intensities of the corresponding (n, γ) lines or proton groups.

lower-intensity lines. In the region extending slightly beyond this, there is an observed intensity ratio of 1600/1. I would also like to point out (center graph) the line at 543 keV. If you look carefully, you can see it is a little wide; it has been resolved as shown in the inset.

Intensity problems with the diffraction spectrometer occur because one does not correct for the variable geometrical position of the target. Hence we took the low-energy data using a $\text{Ge}(\text{Li})$ detector in a $\text{NaI}(\text{Tl})$ annulus. In Fig. 191 (bottom) are the three lines that I pointed out before: the 116-, 126-, and 136-keV lines.

These are the only three lines that you can see in this energy range. All the other small lines, about a dozen of them, are buried in the valleys and in the background. There is far less detail. We can use the intensity observations from the $\text{Ge}(\text{Li})$ data after having seen the high-resolution work. We can determine the intensities of the three gamma rays after correcting for the unresolved components. We certainly could not arrive at very much of a conclusion about the spectrum using only the details from this $\text{Ge}(\text{Li})$ work.

Figure 192 (left) shows the Studsvik internal-conversion work done by bringing a neutron beam out of the reactor and using a multiple-source technique to increase the intensity. It was a reasonably thin source. Bäcklin, who did this work, only looked at the stronger

Fig. 191. Left: Small sections of the low-energy (n, γ) spectrum obtained with the diffraction spectrometer. The line at 120.8 keV has not been assigned as a transition in Ho^{166} because its intensity increases during the irradiation of the target with slow neutrons. The upper part of the figure shows the improvement of the resolution when going from the first- to the second-order reflection. The actual measurements are usually performed in the third- or fifth-order reflections. The insert in the lower graph clearly shows that the group at 543 keV is complex. The decomposition into a doublet is indicated. Right: Low-energy (n, γ) spectrum of Ho^{166} measured with the Los Alamos Ge(Li) detector inside a NaI annulus in anticoincidence.

Fig. 192. Left: Part of the conversion-electron spectrum of Ho^{166} measured with the double-focusing spectrometer at Studsvik using an external beam of neutrons from the R-2 reactor. The resolution width (FWHM) was better than 0.3%. Right: Part of the conversion-electron spectrum of Ho^{166} , measured with the "Elephant spectrometer" at the FRM reactor near Munich.

lines such as the 116-keV K- and ($L_1 + L_2$)-conversion lines. By looking in the proper part of the spectrum for the L_3 , one can give an upper limit which is very important here. Other K lines are also shown in this figure.

The internal-conversion work was extended by the Munich data with a somewhat greater line width. This is shown in the right-hand graph of Fig. 192. One can see immediately that there is difficulty in getting the intensities of these lines because the background is so high. In the Studsvik data, I should point out that instead of 100 counts per minute, it was really one count per minute—but the signal-to-noise ratio was 1:1. But here you can see that the signal-to-noise ratio is only 1:6 for the Munich data.

Figure 193 shows the observed gamma rays from the diffraction instrument; gamma-ray intensity is plotted versus energy and the lines for which internal-conversion measurements have been made are indicated by triangles. The curves are drawn so that if a point is above the E2-K curve, its K line should be observable if it were

E2. The position of a dot enables one to draw a conclusion concerning the multipolarity of its associated transition. You can see that those transitions for which conversion is measured are above these lines. The lower curve is the sensitivity curve that allows us to pick certain subsets for random calculations that Schult (paper C-1) referred to earlier.

Table XXXI is a section of one of the six pages of Table III in Ref. 1. I picked this one because it shows the 116.835-keV line as measured by Schult. The relative energies from Ge(Li) are also given. The intensity measured by Schult is 15.8%, a strong line. With the germanium detector (and, as I said, we used this only to measure intensities), we determined 117.4 keV energy for this, equal to Schult's value within our error. I show this for comparison to indicate that there is a tremendous gap in detail for the Ge(Li) data. The next line that we feel we can identify from Ge(Li) as a single line is a line at 99.5 keV. The L_3

Fig. 193. Log-log plot of the low-energy neutron capture γ transitions of Ho^{166} . The curve S corresponds to the sensitivity limit of the Risø curved-crystal spectrometer. The other curves indicate sensitivity limits of the "Elephant spectrometer" for the detection of electron lines from internal conversion in different atomic shells. Triangles correspond to transitions for which the conversion-electron-line intensities have been measured. Points correspond to all other measured low-energy γ rays.

TABLE XXXI Low-energy γ -ray and electron data from $\text{Ho}^{165}(n, \gamma)\text{Ho}^{166}$ In the diffraction-spectrometer data, E_γ and I_γ are the relative γ -ray energy (keV) and intensity (γ rays per 100 neutrons captured) and dE_γ and dI_γ are their relative errors (%) A check in the "Used?" column indicates that the γ ray was used in the decay scheme, a question mark that the γ ray is questionable The γ -ray energies E and their intensities I and errors dI (%) are corresponding values from the germanium-spectrometer data The next columns give the energies E_e (keV), relative intensities I_e (keV), relative errors dI_e (%), and internal-conversion coefficients a_{exp} for conversion electrons from the indicated atomic shells The columns labeled $\alpha(E1)$, $\alpha(E2)$, and $\alpha(M1)$ are the theoretical conversion coefficients of Rose The column labeled "Multipolarity" summarizes the conclusions from the electron conversion coefficients. For further details, see Ref. 1.

[illegible]

^a Underlined value is from a measurement in an external neutron beam at the Studsvik reactor

^b Data from the Elephant β -ray spectrometer at the FRM reactor in Munich (target close to the core) and (underlined) from the Studsvik β -ray spectrometer (target in spectrometer irradiated by an external beam from the R2 reactor).

^c M. E. Rose, Internal Conversion Coefficients (North-Holland Publishing Company, Amsterdam, 1958)

^d Normalization value.

TABLE XXXII. Comparison of level energies of Ho¹⁶⁶.

(n,γ) Low energy		(n,γ) High energy ^a		(d,p) ^b		(n,γ) Low energy		(n,γ) High energy ^a		(d,p) ^b	
E (keV)	IπK	E (keV)	dE (keV)	E (keV)	IπK	E (keV)	IπK	E (keV)	dE (keV)	E (keV)	IπK
0	0-0	...		5±2	7-7	598 462	4+1	602.3	2	599±2	
54 239	2-0	...		53±2	2-0					(610±2)	
82 470	1-0	...		82±3	1-0			637.3	1 2	632±1	
				136±2	8-7					653±1	
171 074	3-0	170 8	0 8	(168±2)	(3-0)			659 7	1 5		
180 467	4-0			181±1	4-0			666 6	2	668±2	
190 901	3+3	190 9 ^c		191±1	3+3			686.6	2		
		197 9	2			693 652	5+1	693 7	1 5	691±1	
260 661	4+3							719 1	0 7	721±2	
263 787	(5+5)	263 2	1	260±2	4+3			741 8	2 5	739±1	
		...		294±2	6+6			767 8	4	767±1	
		...		308±3	(9-7)			783 7	3		
329 775	5-0	330 7	3	330±2	5-0	(807 296)	(6+1)	...			
		338 8	2 5					816.2	0 5	814±1	
348 257	5+3			348±2	5+3			829 8	1		
371 984	4+4	372.5	0 5	373±2	4+4			881 6	1		
373 13	(0, 1-)	...						890 6	1	891±1	
377 806	6-0	...						905 2	1	907±3	
				(386±2)						925±2	
				(401±2)						(942±3)	
		...		421±2	7+6			961 6	3	961±1	
425 990	1+1	...								982±1	
430 041	(2+2)	430 1	0 5					1006 0	1 5	1007±1	
453 772	6+3	...		457±2	6+3			1030 3	0 7		
464.480	2+1									1035±1	
470 839	5+4	471 8	0 8	469±2	5+4					1057±1	
				476±1				1062 1	0 7		
481.845	(3+2)	481 6	0 7					1089 3	1 5	1080±2	
				514±1				1099 3	2		
521 996	3+1	522 1	2	524±2						1105±1	
		544 7	1 5	546±2				1117 9	2	1122±2	
547 956	(4+2)							1137 0	1 5	1137±2	
557 688	(7-0)	...								1154±3	
				557±2				1160 4	1 5		
558 562	(5, 4+)	558 9	1	(566±2)						1173±1	
				(578±3)				1191 7	1	1188±1	
577 210	(7+3)	...		589±2				1204 0	2	(1205±2)	
588 103	(6+4)	...						1216 0	2	(1221±2)	
		594 7	0 8					1231 6	0 8	(1245±2)	

^a Three dots for the high energy (n,γ) entry indicates that quadrupole or higher multipole would be expected from the assigned spins.
^b Alignment of (d,p) and (n,γ) states in those cases where a spin assignment has not been made from the (d,p) cross section suggests only energy agreement. The excited states may not be identical.
^c Reference line used to establish the excitation energy scale.

internal conversion of the 116-keV line has an upper limit given; this is nearly a pure M1 transition. Bäcklin checked the intensities carefully and normalized his data at the K line from this transition using 15.8% as the gamma intensity. You can see that on this entire page we have one, two, three gammas from Ge(Li) that we thought we could fit with least squares as compared with 38 lines from the diffraction results. The check mark means we have assigned the transition in our decay scheme. If you refer to the Physical Review article (Ref. 1), you can see where these transitions are assigned.

Table XXXII gives the low-energy (n,γ) levels and the levels excited by the high-energy (n,γ) transitions if one assumes that

the high-energy gamma rays directly populate these states. For example, the 190.9-keV 3^+ state should be excited by (n, γ) . It is the normalization value for the excitation scale. On the right is the (d, p) work. Now, in working on the decay scheme, we tried to take the philosophy that we would not use the (d, p) work to develop the decay scheme. We do have some initial knowledge about the low-lying states. On the left are the spins derived from the capture work. On the right are the previously published spins using the (d, p) population coefficients from the Nilsson quantum numbers. From (d, p) the 7-7 state is seen, but we do not claim to have any assigned population of this or to see it directly in our work because it is very weakly populated (5.5% total). Similarly, the 8-7 state does not have any firm information from neutron capture. To point out some of the agreement and disagreement here, we claim a 3-keV error for the 330.7-keV excited state, which certainly agrees with the (d, p) value within that error. We have not found how it decays; perhaps it is a chemical impurity which we haven't been able to identify. It is a low-lying state, but we have no information about the spin. Similarly, there seems to be a level at 197.9 keV that has not been further identified.

Figure 194 shows that part of the decay scheme in which we have firm evidence and interpretation. The development of the scheme was begun by taking beta-decay population information on the 54-keV and 82-keV levels from the ground-state rotational band as studied here at Argonne,⁵ at Chalk River,⁶ and by a Swedish group.⁷ Also known

⁵R. G. Helmer and S. B. Burson, Phys. Rev. 119, 788 (1960).

⁶J. S. Geiger, R. L. Graham, and G. T. Ewan, Bull. Am. Phys. Soc. 5, 255 (1960); Proceedings of the International Conference on Nuclear Structure, Kingston, Canada, 1960 (University of Toronto Press, Toronto, 1960), p. 610.

⁷V. Brabec, O. Bergman, Y. Grunditz, E. Aasa, and S. E. Karlsson, Arkiv Fysik 26, 511 (1964).

Fig. 194. Nuclear level scheme of Ho^{166} . The experimental evidence for the dashed levels is not sufficient for an unambiguous assignment of these states. The energies and energy errors given in this scheme are absolute values (keV). Conversion-electron transitions are given as white areas of arrows limited at both sides by dark lines, the total width of which is proportional to the γ intensity. A short thick vertical arrow leading into a level indicates feeding of this state through a high-energy γ transition directly from the compound state. An open arrow indicates that the high-energy population through a primary transition is uncertain. The intensity of the transition (γ 's per 1000 neutrons captured) is written beside the arrow. A triangle directed downwards at the right end of a level indicates that the state has been observed in the (d,p) reaction.

is a weak population of the state at 426 keV from Dy^{166} . It is an unusual case of radioactive decay to be able to study the odd-odd nucleus Ho^{166} , and is brought about because double neutron capture on Dy^{164} to form Dy^{166} is strong. Now, to give you an idea about errors, I want to point

out that you can form several loops using transitions between these states. You find that for one loop there is a 9-eV closure discrepancy when adding two gamma rays to compare with the crossover; a 25-eV error results. If you go around a loop using another pair at stopovers, you have a 1-eV error. This is a known case of coincidence where the gamma rays are intense but the gamma-ray energies alone strongly suggest coincidence by themselves. Further, the intense 116-keV gamma ray is almost a pure M1, there is just no other place for it to go in the decay scheme. It cannot be in parallel with the 54-keV transition; it has to be in series.

Using similar arguments to build up these loops, one can go up to the 6^- level and show that the most logical spins are in this order. Then assuming a rotational formula, one can predict a higher level and show that within the errors of 60 and 70 eV for these two lines, they do fit in very closely to where the upper level is expected to be. We dashed in this higher level; we have to admit there is probably a 10%, perhaps a 15% probability of this particular combination being random and that some other level might in fact be the 7^- level belonging to this rotational band.

Knowing the decay of the isomeric state at 190 keV, one can build up the 3^+ rotational band. You notice that the 3^+ and 4^+ bands correspond to opposite alignment of the odd neutron and proton. By using the rotational formula, one can similarly extend these to include the 7^+ and 6^+ states. We feel we have a fairly model-independent assignment of the lower (solid) levels. One basic assumption always is that we should have reasonable transition rates (i. e., from a level to the ground state; and for a 3^- state, we would not expect to have such a transition), and this interpretation is used in judging the most probable spin. It is a most basic assumption used throughout.

An extension of this level scheme (Fig. 195), in which the levels in Fig. 194 have been shown in very bold lines, has been constructed by taking the levels populated by the high-energy gamma rays. These high-energy transitions are shown by the arrows. The most strongly populated is the 430-keV state. We feel certain this is a positive-parity level, although we cannot say where the spin lies in the range between 2 and 5. By looking as closely as we could for intense gamma rays which could depopulate this level, we arrived at several loops which put it at 430.03 keV. You can build up a rotational band, assuming in this case reasonable rotational parameters.

We do not see gamma rays going to the 7^- level. We do see a strong low-energy line consistent with the expected $8^- \rightarrow 7^-$ decay. Similarly, we see two low-energy lines which we believe are related to the 6^+ state. You will notice that the proton configuration for all these assignments is in fact the same as the proton configuration of the Ho^{165} target nucleus. The only indication we have of an excited proton state is the 373-keV state. This state is seen also in coincidence studies of the decay of Ho^{166} . It had not been seen in a singles spectrum until this capture work was done. But it has been seen in a singles spectrum with a diffraction spectrometer now, as well as in the dysprosium decay.

Now, in trying to be honest about it, we put down the levels we could not assign in this decay scheme. These may in part be other proton-excited states. They are so weak that we do not understand how they decay. This is still quite a collection; there is a lot more work to do.

I also want to give one example of combinations, namely the loop formed by the 181-, 111-, and 69-keV lines at the right in Fig. 194. If you take the complete set of gamma rays and ask "How many random combinations can you get from the 69.76-keV gamma ray

Fig. 195. Tentative extension of the firm part (Fig. 194) of the Ho^{166} level scheme. The level energies and the errors are absolute (keV). Unassigned levels from both the (d, p) and high-energy (n, γ) reactions are shown on the right. All levels from Fig. 194 are shown, in general, without the transitions. Bold levels are those believed most certain. See caption of Fig. 194 for symbol conventions.

and any two others?" (let's say it is equal to the difference between two other gamma rays), you find from the complete set of over 300 gamma rays in the scheme there would be 42 such random combinations predicted on the average, knowing the errors and the energy range.

Obviously, for any one such combination, you have no way of telling whether it is real or whether it is accidental. A particular combination involving this gamma ray is $111.324 + 69.7604 = 181.0844$ keV, where the individual relative errors are 1.4 and 2 eV, versus the observed gamma-ray energy of 181.086 ± 0.005 keV. These are all very strong transitions. If, instead of considering the entire set of more than 300 gamma rays, we restrict ourselves to that subset of gamma rays having intensities comparable to the 69.7604- and 111.234-keV transitions, then the number of gamma rays to be considered is reduced to 15, and the random probability of getting the combination drops from 14% to 0.6%. It is no longer one of 42 combinations.

I think the statement made earlier about the dubious reliability of forming loops of this sort is not generally true. One has to be very careful as to what loops he does believe and uses in building up the decay scheme, but some combinations are very reliable.

I like to refer to this as the "energy coincidence" method. In the normal coincidence method, you see two gamma rays which are time correlated. Usually you don't have high energy accuracy. In the "energy coincidence" method, you have high accuracy on the energy correlation, and you have no real observation about their time relationship.

Figure 196 shows the "trueness" of rotation, that is, fitting the simple rotational equation without the B term; an illustration that Ho^{166} gives very pure rotational states. The errors on the B terms that one gets from these very accurate data, in this decay scheme, are really surprisingly small; and furthermore, in order to confirm the fact that we do assign these to rotational bands, not referring to the

rotational formula, the inner band transitions have very constant transition strengths. And these show that the character of these states is probably related and that they do come from the same rotational band.

Figure 197 shows the results of Gordon Struble's calculations.¹ The experimental results are at the right. This case is a known violation⁸ of the Gallagher-Moszkowski coupling rule. That rule predicts that the 7^- state should be the ground state and not the isomeric state. Because of the configuration mixing in this case, it is believed that there is an inversion or a violation of this simple rule. Column I gives the prediction from the zero-order model. Column II gives the results of the first-order correction when interaction effects are included, and column III shows the results of the configuration mixing. There is an unusual splitting of a $K=0$ band where the even and odd members are displaced. The C value is one-half of the displacement of the odd members relative to their predicted position. So this shows how well the theory predicts level positions. We have only picked out the band heads here that we have assigned.

Fig. 196. Dependence of the experimental moment-of-inertia parameter on the spin I of the rotational levels. $A_I = E(I \rightarrow I - 2)/(4I - 2)$ for $K = 0$ and $A_I = E(I \rightarrow I - 1)/2I$ for $K \neq 0$.

⁸C. J. Gallagher and S. A. Moszkowski, Phys. Rev. 111, 1282 (1958).

Fig. 197. Comparison of the experimentally observed states and the theoretically predicted energies. Column I gives the predictions for the zeroth-order model. Column II displays the results when the first-order effects of H_{INT} are included. Column III shows the results when configuration interactions and the Coriolis effects are taken into account. The quantity C is one-half of the energy shift between the even and odd members of the $K=0$ rotational band.

* * *

J. A. HARVEY, Oak Ridge National Laboratory: Will you make a few comments about the correlation with (d,p) studies?

MOTZ: I think the simple fact that we excite the same states shows that we are exciting the neutron states. Frankly, we are quite dubious about believing all the spin assignments from the (d,p) work; there was a strong admixture in all of these states, so it is extremely

complicated. To use the Nilsson wave functions and the predicted amplitudes to deduce a complete set of spins and parities from (d,p) experiments alone is a process that requires checking. This checking is what we try to do; we did not want to assume that the (d,p) assignments were correct and merely try to confirm them. Obviously one has to follow the argument in our rather lengthy paper (Ref. 1) to see if he can be convinced. I hope I have tempted you to do this.

H. H. BOLOTIN, Argonne National Laboratory: Near the end of the Tm paper⁹ by your United Nations group, there is the statement that you did not see any excited proton states populated directly from the capture state. Since one would expect roughly the same number of neutron states as proton states, it is somewhat of a surprise that you saw no proton states.

MOTZ: You expect a lot of proton states, but they may not be as numerous as neutron states.

BOLOTIN: Below about 700 keV excitation in thulium you seem to see only the neutron states. The states you observed to be populated directly from the capture state were only those seen also in the (d,p) spectra. Is this as true in holmium?

MOTZ: I think it is more true in holmium. We feel that the spin and parity assignments and the Nilsson assignments in Ho are far more reliable than in Tm.

BOLOTIN: This is a surprising result. The capture state should play no favorites.

MOTZ: I agree with you. One would expect to see lots of excited proton states; yet neither in Ho nor Tm—both odd-odd nuclides—do we see this. The residual nucleus very definitely seems to remember

⁹R. K. Sheline, C. E. Watson, B. P. Maier, U. Gruber, H. R. Koch, O. W. B. Schult, H. T. Motz, E. R. Journey, G. L. Struble, T. v. Egidy, Th. Elze, and E. Bieber, Phys. Rev. 143, 857 (1966).

where the proton was. As mentioned earlier, it is possible that a good fraction of the capture is by way of a true compound nucleus. Perhaps the bulk of the gamma rays at 2—3 MeV are controlled completely by this, but these high-energy transitions that go directly to the low-lying states certainly seem to remember the initial proton character. Note that although this seems to be the case for an odd-odd nucleus, it is not necessarily true for an even-even nucleus. It may be that the odd proton is polarizing the nucleus (i. e. , providing a reference axis in the target nucleus) and somehow affecting it.

G-3. ELECTROMAGNETIC TRANSITIONS IN $\text{Mg}^{26\dagger}$

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We have obtained precision gamma-ray spectra in separated isotopes of magnesium by use of the CP-5 through-hole facility described yesterday (paper B-1) by George Thomas. I will not show the spectra, which look very much like ones you have already seen, and will restrict myself in this report to results obtained for $\text{Mg}^{25}(n, \gamma)\text{Mg}^{26}$.

The levels in Mg^{26} have been previously investigated^{1, 2} in great detail by $\text{Mg}^{25}(d, p)$, $\text{Mg}^{24}(t, p)$, and $\text{Al}^{27}(t, \alpha)$ by use of a broad-range magnetic spectrograph with a resolution width of approximately 10 keV. Levels were observed up to excitations well in excess of the neutron binding energy, with 95 levels below the neutron binding energy. The extent of this existing knowledge has led us to hope for a complete analysis of the $\text{Mg}^{25}(n, \gamma)$ spectrum. Accordingly we have made a serious effort to obtain energies and intensities of all observed lines in the energy range from 400 keV to 11 100 keV. The analysis technique employed consisted of first subtracting a base line obtained by a visual inspection of the data, then plotting these results on log paper, and finally unpeeling the spectra by hand with the aid of standard line shapes obtained from the strongest isolated lines in the spectrum.

In this way the heights and positions were determined for 533 lines in the energy range considered. The peak positions were

[†] Work performed in part under the auspices of the U. S. Atomic Energy Commission.

¹ S. Hinds, H. Marchant, and R. Middleton, Nucl. Phys. 67, 257 (1965).

² B. Cujec, Phys. Rev. 136, B1305 (1964).

Fig. 198. Ratios R_{21} of the height of the double-escape peak to that of the single-escape peak and R_{20} of the double-escape to the full-energy peak. Also shown are the relative efficiencies ϵ_0 for the full-energy peak and ϵ_2 for the double-escape peak, both in arbitrary units.

converted to energies by means of a cubic calibration curve obtained by a least-squares fit to ten well-known contamination peaks in the spectrum. The internal consistency of the energies determined by this means is excellent. In more than 20 cases where strong isolated lines are involved, the sums of energies of cascade transitions differ from the energies of the cross-over transitions by less than 1.5 keV, and in all but three of these the difference is less than 0.5 keV. In a total of 149 observed cases, the rms deviation is less than 1 keV.

The peak heights were converted to relative intensity by use of an efficiency curve which was constructed, again, from contaminant peaks in the spectrum. This curve is shown in Fig. 198. Also shown here are the ratios of the various multiple peak heights as a function of energy. All of these curves represent gross smoothing of the actual data. In particular, the region of the efficiency curves below 2 MeV may be in error by as much as a factor 1.5.

The next step in the data reduction consisted in the elimination of multiple peaks. In this process the precise energy determination and knowledge of the multiple-peak-height ratios were essential. The result of this step was a list of 432 transition energies and their relative intensities. Of these transitions, 61 are in known contaminants, leaving 371 which are in Mg^{26} or are transitions in unknown contaminants. Of these, 202 can be fitted into a decay scheme for Mg^{26} ;

141 of those remaining are quite weak, leaving 28 transitions of reasonable strength which cannot be assigned as involving known levels in Mg^{26} .

Thirty-eight primary transitions were observed. Their relative intensities are

shown in Fig. 199. The ordinate is the corrected yield in thousands of counts; and by normalizing the sum of the strengths to states 0, 1, 2, and 4 to the intensities

reported by Campion et al.,³ it turns out that the ordinate is also gammas per 500 neutron captures. From the figure, one sees that the total observed primary transition strength accounts for only 35% of the captures. It is difficult to explain this discrepancy. The capture state in Mg^{26} is unbound to a decay by 478 keV. However, a simple barrier-penetration calculation gives an alpha width of only 10^{-6} eV, so it is doubtful that this mechanism contributes appreciably. Possible sources of error are missed low-energy primaries, errors in the efficiency curve, errors in the measured capture cross section,^{*} and errors in published intensities of the transitions to the lowest states. The circles in this figure are results of $\text{Mg}^{25}(\text{d}, \text{p})$ cross-section measurements by Cujec,² who tabulated the cross sections at 10° , 15° , 25° , and 40° . The circles

Fig. 199. Relative intensities of primary transitions in Mg^{26} from the $\text{Mg}^{25}(\text{n}, \gamma)$ reaction. The circles are relative yields of the $\text{Mg}^{25}(\text{d}, \text{p})\text{Mg}^{26}$ reaction to the same final states.

³ L. V. Groshev, V. N. Lutsenko, A. M. Demidov, and V. I. Pelekhov, Atlas of γ -Ray Spectra from Radiative Capture of Thermal Neutrons (Pergamon Press, London, 1959).

* Note added in proof: The capture cross section has recently been remeasured by P. Spilling, H. Gruppelaar, and A. M. F. Op Den Kamp [Nucl. Phys. A102, 209 (1967)]. If Campion's intensities are altered according to the new value, the total primary intensity observed in the present work is 100% within errors.

Fig. 200. Branching ratios in the decays of three of the excited states populated by primary γ -ray transitions. Asterisks signify that the assignment of this much yield is ambiguous.

Fig. 201. Branched decays of three additional interesting cases of excited states populated by primary transitions. The spins of most of the levels above the third excited state should be regarded as tentative.

represent the sums of these numbers. A general correlation, with a few exceptions, is observed. Circles with arrows represent lower limits as reported by Cujec.

We have also obtained a number of branching ratios from this work, and had hoped this might be the most significant type of result that can be obtained from it. Figure 200 shows some of the good and some of the bad. Both lines from the decay of the second excited state are among the 113 transitions that can be assigned unique positions in the decay scheme. The observed branching ratio—89% to the first excited state—compares favorably with the published value of 92.5%.⁴ The actual yields are shown in parentheses. The decay of the third and

⁴A recent measurement of gamma rays from the $Mg^{26}(p,p')$ reaction by O. Häusser, T. K. Alexander, and C. Broude [Can J. Phys. 46, 1035 (1968)] finds 88% for this ratio.

fourth excited states is not so clearcut. For the state at 3578 keV, all of the transitions feeding the state are clear. However, both secondaries are of the same energy (within 2 keV) as other possible transitions. The most one can say is that the transition to the 2938-keV level must occur with a relative strength of at least 570 to achieve the rate balance. For the fourth excited state the situation is worse, since not all the transitions feeding the state are clean. However, again one can say that the transition to the 2938-keV level must occur with a strength of at least 6560. Information of this type, although in most cases of more significance than these last two cases, have been obtained for 35 excited states.

In Fig. 201 we show three more which are particularly interesting. On the left is a case in which all transitions into and out of the state are clean. The total intensity feeding the state is observed to be 22 240, while the sum of the de-excitation strengths is 23 400. The discrepancy of 1160, a relative error of 5%, can reflect errors in the efficiency curve or some missed transitions which feed the state. In the middle diagram we see an example—by now not so unusual—of an E3 transition successfully competing with two E1 transitions. There are some ambiguous transitions not shown, but the intensities relative to the transition to the 2938-keV level may be obtained and are shown. In the decay scheme on the right, we see an example of an intense low-energy primary (991-keV) followed by several high-energy secondaries. The 10 101-keV transition is, in fact, of the same intensity as the primary transition to the ground state and is stronger than the primary transitions to states 3, 13, 14, 17, and 18. Since the state decays to states with spins of 1^+ and 2^+ , and since it is fed from the capture state which has a strong 2^+ component, I have indicated a tentative assignment of 1^- .

* * *

O. W. B. SCHULT, Technical University, Munich and Brookhaven National Laboratory: Do you have an explanation for the high E3 strength?

CARPENTER: I do not actually know the transition probabilities for any of these states; I know only the relative intensities. If someone would measure the lifetime of one of them, I could give the probability in single-particle units. Similar high values are found in several neighboring nuclei.

It is tempting to try an explanation in terms of an octupole excitation for the initial state, but I am not aware of any actual calculations.

Note added in proof: The mean life of the 6881-keV state in Mg^{26} has recently been measured by Häusser, Alexander, and Broude,⁴ who report $\tau = 1.0^{+0.6}_{-0.5} \times 10^{-13}$ sec. Using the above branching ratio then gives an E3 width of $8.4^{+8.4}_{-3.2} \times 10^{-5}$ eV. With Wilkinson's numerical factors,⁵ the single-particle estimate is 1.13×10^{-5} eV. Thus the transition is enhanced by a factor of $7.4^{+7.4}_{-2.8}$. This is typical for this range of nuclei.

⁵D. H. Wilkinson, in Nuclear Spectroscopy, edited by Fay Ajzenberg-Selove (Academic Press, New York, 1960), Part B, p. 859.

4. THE LEVEL SCHEME OF Cd^{114} , BASED ON (n, γ) AND (d, p) EXPERIMENTS*

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The level scheme of Cd^{114} has been used for many years as the classic example of a spherical nucleus with low-lying vibrational states.¹ Its 0^+ ground state, its 2^+ first excited state combined with 0^+ , 2^+ , and 4^+ states at about twice the energy of the first excited state, and enhanced E2 transitions between these two-phonon and one-phonon states—all fit this picture. The main object of the work reported in this paper is to extend the level scheme of Cd^{114} to 3 MeV excitation and look for higher-order vibrational states.

In order to approach this problem in a straightforward manner, it is necessary to obtain model-independent spin and parity assignments for all known low-lying levels. To do this and to avoid missing any of the low-lying levels, it is necessary to study the level scheme with more than one approach. For the present work, we have chosen a series of (n, γ) and charged-particle experiments as indicated in Table XXXIII. The low-energy portion of the (n, γ) spectrum (40 keV to 2 MeV) was investigated with the large bent-crystal

TABLE XXXIII. Summary of (n, γ) and charged-particle experiments employed in the present research to extend the level scheme of Cd^{114} .

Technique		Energy range
<u>(n, γ)</u>		
Bent crystal		40 keV—2 MeV
Conversion electron		" "
Ge diode		1 MeV—9 MeV
γ - γ coincidences		low-low high-low
<u>Charged particle</u>		
(d, p)	Ang. dist.	$E_d = 12 \text{ MeV}$ $E_{\text{exc}} = 0-3 \text{ MeV}$
(p, p')	" "	
(d, d')	" "	
(α, α')	" "	
$(\text{O}^{16}, \text{O}^{16'})$	" "	

* Work performed under the auspices of the U. S. Atomic Energy Commission.

¹ For a list of early references, see H. J. Motz, Phys. Rev. 104, 1353 (1956); R. K. Smither, Phys. Rev. 124, 183 (1961).

Fig. 202. The relationship between the angular momentum l_n of the captured neutron and the spin and parity J^π of the levels for $\text{Cd}^{113}(\text{d}, \text{p})\text{Cd}^{114}$.

spectrometer here at Argonne.

The conversion-electron studies were made in Sweden by Bäcklin, Holmberg, and Backström.²

The Ge-diode work (1—9 MeV) and γ - γ coincidences as well as the (d,p) studies were done here at Argonne. The inelastic-scattering studies published previously by other authors³ were used mainly to identify the 3^- one-phonon octupole state. In view of the limited time available and the excellent previous talks on the subject, I will not go into the

experimental details of the (n, γ) experiments. However, I would like to mention some of the details in the analysis of the (d,p) work which some of you may not be aware of.

On the left side of Fig. 202, I have indicated the relation between the observed value of l_n (the angular momentum of the captured neutron as obtained from the angular distribution of the proton group) and the spin and parity of the corresponding level. Positive-parity states are associated only with even values of l_n , negative-parity states are associated with odd values of l_n . The spin of the ground state of the target nucleus Cd^{113} is $\frac{1}{2}^+$ so the value of J can differ from the value of

²A. Bäcklin, N. E. Holmberg, and G. Backström, Nucl. Phys. 80, 154 (1966).

³P. H. Stelson and F. K. McGowan, Phys. Rev. 121, 209 (1961); O. Hansen and O. Nathan, Nucl. Phys. 42, 197 (1963); F. K. McGowan, R. L. Robinson, P. H. Stelson, and S. L. C. Ford, Jr., Nucl. Phys. 66, 97 (1965); M. Sakai, H. Ikegami, Y. Nakagima, K. Yagi, H. Ejiri, and G. R. Satchler, Phys. Letters 8, 197 (1964); J. A. Cookson and W. Darcey, Phys. Rev. 118, 1582 (1960).

ℓ_n by only one unit and admixtures of ℓ_n values are limited to pairs of adjacent even ℓ 's or odd ℓ 's. This simplicity would not hold if the spin of the target nucleus were larger ($\frac{3}{2}$, $\frac{5}{2}$, etc.) and the analysis of the (d,p) data would become much more difficult.

The well established low-lying levels in Cd^{114} are shown on the right. Here we see the 0^+ ground state, the 2^+ first excited state, and a group of possible two-phonon states at about twice the energy of the first excited state. These levels are used as a base on which we shall build the rest of the level scheme.

Fig. 203. Schematic comparison of the different kinds of data used in this work to generate the level scheme of Cd^{114} .

Figure 203 illustrates the way in which the three kinds of data are combined to generate a level scheme. The (d,p) levels correspond to proton groups, the Ge-diode levels correspond to direct transitions from the neutron-capture state, and the bent-crystal levels correspond to levels suggested by the energy fit of low-energy gammas or by γ - γ coincidences. Note that the levels seen in the (d,p) data are not always seen in the Ge-diode (n, γ) data, for which the limits on the spin of a level that can be reached by a direct gamma transition from the capture state are more limited (0, 1, 2). The reverse is also true. This comes about when the collective nature of the level inhibits the (d,p) reaction so strongly (i.e., by a factor of 10^{-2} — 10^{-3}) that one cannot be sure of its existence or excitation energy without recourse to other experimental results. A typical example of this is the second 2^+ state which is inhibited by a factor of 2000. That is to say, its spectroscopic factor based on DWBA calculations is $S = 0.0005$.

Part of the Cd^{114} level scheme obtained by combining all available experimental data is shown in Fig. 204. The energies of

Fig. 204. Level scheme of Cd^{114} . Excitation energies and spin and parity assignments are given at the left; J^π and ℓ_n are at the right. Not all of the gamma decays from the upper levels are shown. The arrowheads on the right indicate gamma transitions from the primary neutron-capture state.

the levels, given in keV on the left, are followed by the proposed spins and parities. The gamma transitions are shown as solid lines or shaded arrows whose widths are meant to suggest their intensities. The dotted lines are pure E0 transitions. Only some of the gamma transitions are shown. Gamma transitions from the neutron-capture state to the levels are indicated on the right. Some of the ℓ_n values for the levels are also listed at the far right. A dashed level is one which is seen in the (d,p) work and which has relatively few gamma transitions connecting it to the rest of the level scheme. Their existence is based mainly on the (d,p) experiments.

The details of the positive-parity levels in this region are shown in Fig. 205. Here we see the 0^+ ground state, the 2^+ one-phonon state, and the 0^+ , 2^+ , and 4^+ members of the two-phonon triplet; then farther up are four positive-parity states which exhibit the characteristics of members of the three-phonon quadrupole vibrational quintet with spins of 0^+ , 2^+ , 3^+ , and 4^+ . At the left I have shown the theoretical predictions of the vibrational model. The quantum numbers n_2 and n_3 give the numbers of quadrupole and octupole phonons used to generate the levels. Given the level energies of the one-phonon and two-phonon states and the splittings of the 2-phonon states, it is possible to predict the approximate positions and separations of the three-phonon states from second-order perturbation theory.⁴

⁴ D. M. Brink, in International Conference on Nuclear Physics with Reactor Neutrons, edited by F. E. Thow (Argonne National Laboratory, Argonne, Illinois, 1963), Report No. ANL-6797, p. 194; A. K. Kerman and C. M. Shakin, Phys. Letters 1, 151 (1962).

Fig. 205. Details of the gamma transitions associated with the higher-energy positive-parity levels. The labeling is similar to that in Fig. 204. The associated phonon states are shown to the right of the level scheme; N_2 and N_3 , respectively, indicate the numbers of quadrupole and octupole phonons associated with a level.

The results of such a calculation appear in Fig. 206. The two-phonon quadrupole states ($N_2 = 2$, $N_3 = 0$) agree exactly since they are input parameters. The energies and level spacings predicted for the three-phonon states agree with the experimentally observed states quite well. The ordering of the spins of the lower four states, however, is different from the experimental data. This may be related to the presence of the unassigned 0^+ and 2^+ states which lie just above the two-phonon triplet and which were not considered in this analysis. Although the comparison between theory and experiment is not perfect, it is as good as or better than any published previously—even when the spins and parities of these states were uncertain and therefore some flexibility of assignment was possible.

A similar picture for the negative-parity states appears in Fig. 207. The vibrational picture predicts a 3^- state based on a one-phonon octupole vibration ($n_2 = 0$, $n_3 = 1$) and a quintet of negative-parity states (1^- , 2^- , 3^- , 4^- , 5^-) based on quadrupole vibrations and on octupole vibrations.

Three negative-parity levels appear to be good candidates for this type of excitation. At the right I have shown a fourth-order perturbation calculation⁵ for the splitting of the two-phonon quadrupole-octupole vibrational quintet using parameters which are consistent with the observed $B(E3)$ value

⁵ P. O. Lipas, Nucl. Phys. 82, 91 (1966).

Fig. 206. Comparison between the theoretically predicted energies of the 3-quadrupole-phonon levels and the values found experimentally.

Fig. 207. Details of the gamma transitions associated with the higher-energy negative-parity levels. The labeling is similar to that in Figs. 204 and 205.

Fig. 208. Comparison between the Cd^{114} energy levels up to 3.5 MeV and the predictions of the phonon model. The theoretical predictions for positive-parity states are shown to the left, those for negative-parity states at the right. In the middle are the experimental results, with the positive-parity states displaced to the left and the negative-parity states displaced to the right. The dashed lines indicate states of unknown parity.

obtained from Coulomb-excitation experiments for the 3^- one-phonon octupole state. The parity of the high-spin state at 1933 keV was not determined in this work; so while it may be interpreted as the 3^+ or 4^+ member of the three-phonon quadrupole vibrational quintet, it can also be interpreted as the 2^- , 3^- , or 4^- state in the quadrupole plus octupole quintet. (Note added in proof: Later work suggests that the 1933-keV level is a 3^+ state.) What is important here is that the energy splitting between members of the quintet is consistent with the observed levels.

Figure 208 shows the full level scheme. The theoretical vibrational states with negative parity are shown on the right, while the theoretical positive-parity states are shown on the left. The notation N_2, N_3 specifies the numbers of quadrupole and octupole phonons in the state, respectively. Most of these levels are degenerate groups of states whose spins are indicated in small numbers above the level. The experimental states appear in the center, with the negative-parity states

shifted to the right and the positive-parity states shifted to the left. Although the level density is increasing rapidly toward higher energies, there is a grouping of negative-parity states in the vicinity of the one-quadrupole-phonon and one-octupole-phonon level at 2.5 MeV. Also there is a bunching of positive-parity levels in the vicinity of the 4-phonon quadrupole levels. The interpretation of these states awaits further analysis.

* * *

O. W. B. SCHULT, Technical University, Munich and Brookhaven National Laboratory: Do you have an explanation for the energy gap between the group of levels below approximately 1300 keV and those above 1700 keV?

SMITHER: You expect quadrupole vibrational levels to be spaced one phonon of energy apart—and indeed, as you saw, they were.

SCHULT: Right. But there are two additional levels close to the two-phonon group, and the others are something like 400 keV higher. Can you explain where the gap comes from?

SMITHER: I have not assigned the 1305-keV 0^+ and 1364-keV 2^+ levels to any particular configuration. In the comparison between theory and experiment, I assumed that certain levels arise from the two-phonon and three-phonon excitations. The two states I have not interpreted will obviously influence the level scheme; the problem is that their character is debatable. I have not tried to take them into account, but there have been calculations that did try.⁶ Their influence might be related to the fact that the 0^+ and 2^+ levels are above the 4^+ instead of below. If there is some repulsion between these levels, it might be the perturbation that inverted the three-phonon states.

⁶T. Tamura and T. Udagawa, Nucl. Phys. 53, 33 (1964).

Of course other things could be happening. For example, some of these collective states could be split. Indeed, if the centroid of the two 0^+ states at 1134 and 1305 keV are taken to form a hypothetical 0^+ state at 1220 keV and similarly the centroid of the two 2^+ states at 1209 and 1364 keV and that of the two 4^+ states at 1283 and 1732 keV are taken to form hypothetical 2^+ and 4^+ states at 1286 and 1508 keV, respectively, then the energy-spacing ratio $\Delta E(4^+ \rightarrow 0^+)/\Delta E(2^+ \rightarrow 0^+) = 4.4$ is not too different from the ratio of 3.3 predicted for a rotational band. Until one has a theory, of course, this is just numerology.

21:15665
G-5. THE COMBINED USE OF NEUTRON-CAPTURE AND
CHARGED-PARTICLE REACTIONS

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Although neutron-capture and charged-particle reaction studies independently permit the investigation of nuclear levels, a combination of both classes of experiments is more powerful because of their complementary features. A brief review of the capabilities of each of these techniques may help to clarify this fact. It is far beyond the scope of this short note to aim at completeness when different experiments are considered. We will only mention the more common methods and then present a few examples.

Numerous excited levels are defined through primary (n, γ) transitions. In addition, many other states can be inferred if the low-energy part of the (n, γ) spectrum is measured with sufficient accuracy so that the energy combination principle can be applied. Conversion-electron (n, e^-) data yield multipolarities, mixing ratios, parities of most of the levels, and frequently their spins. In cases in which the one-dimensional measurements mentioned above are insufficient, multidimensional studies can be carried out as, for example, in coincidence (γ, γ) , (e^-, γ) , (e^-, e^-) angular-correlation and polarization-correlation measurements following neutron capture. Lifetime measurements deserve particular interest. Furthermore, (n, n') experiments, nuclear-resonance studies, and many others could be mentioned.

Charged-particle reactions for the study of isobaric analogue states and (α, xn) —or (heavy particle, xn)—reactions, which are mainly used to extensively study ground-state rotational bands, are of general importance.

During Coulomb-excitation and multiple-Coulomb-excitation experiments, levels are populated which are connected with the ground state through a sufficiently large matrix element. For projectile energies well below the Coulomb barrier, reduced transition probabilities can be deduced from the experimentally observed cross sections. However, high-lying levels (vibrational states around 1 MeV) are generally only weakly excited. These states are clearly seen in (p, p') and (d, d') reactions when the projectile energy is around 12 MeV.

We are mostly concerned here with (d, p) and (d, t) reactions which populate neutron excited states. Not only do these reactions result in nuclei often produced in neutron-capture reactions, but the states populated in these nuclei generally have a wider variation in spin than do those from the neutron-capture reaction. On the other hand, they are incapable of populating proton excited states while in principle the neutron-capture reaction can. For deformed nuclei, a comparison between the theoretical and experimental cross sections within the patterns of individual rotational bands yields Nilsson configurations for the quasi-particle states. Reactions of the types (He^3, d) , (He^4, t) , (d, He^3) , (t, He^4) , etc. should be of great interest in the near future since they will populate proton excited configurations. Two-nucleon transfer reactions [e.g., the (t, p) process] are expected to be of considerable interest in studying pairing vibrational levels.

Summarizing these well known features, we conclude that neutron-capture studies help in establishing nuclear level schemes and aid in determining spins and parities; and by providing detailed knowledge of the decay of the individual states and the systematics of level energies

(which can be determined with high accuracy), they permit some insight into the nuclear structure of the levels populated.

Charged-particle reactions, on the other hand, allow the deduction of reduced transition probabilities between the ground state and low-lying excited levels, allow a wider variety of spins to be populated, and give evidence for the configurations of the levels excited. However, the resolution which is usually obtained in (d,p), (d,t), etc. reactions does not always permit the unambiguous construction of level diagrams, especially if nuclei in the rare earth region are studied. A combination of charged-particle-reaction data with neutron-capture data permits a more reliable analysis.

Now, let us consider a few examples. Figure 209 gives the level scheme for Dy^{162} . Clearly, the most information on the ground-state rotational band and on the gamma band in Dy^{162} comes from neutron-capture data,^{1,2} which also give strong evidence for several states of $K = 2^-$ and $K = 4^+$ bands. The $K = 2^-$, $I = 3^-$ level is also strongly excited during the (d,d') process; this indicates that this state is in part collective in nature. The $K = 4^+$ band is excited in the (d,t) reaction, and a comparison of the experimental and theoretically predicted cross sections for the members of this band defines the two-quasiparticle configuration.

In the case of the odd-A nucleus Dy^{163} , whose level scheme is shown in Fig. 210, a $K = \frac{1}{2}^-$ band has been found at 351 keV.³ The

¹O. W. B. Schult, U. Gruber, and B. P. K. Maier, Proceedings of the International Conference on the Study of Nuclear Structure with Neutrons, Antwerp, 19—23 July 1965 (North-Holland Publishing Co., Amsterdam, 1966), contribution 56.

²A. Bäcklin, A. Suarez, O. W. B. Schult, B. P. K. Maier, U. Gruber, E. B. Shera, D. W. Hafemeister, W. N. Shelton, and R. K. Sheline, Phys. Rev. 160, 1011 (1967).

³O. W. B. Schult, M. E. Bunker, D. W. Hafemeister, E. B. Shera, E. T. Journey, J. W. Starnes, A. Bäcklin, B. Fogelberg, U. Gruber, B. P. K. Maier, H. R. Koch, W. N. Shelton, M. Minor, and R. K. Sheline, Phys. Rev. 154, 1146 (1967).

Fig. 209. Level scheme of Dy^{162} as obtained in Ref. 2. For each level is given the quantum numbers K, I , and π and the energy in keV. For levels for which transitions have been observed in the (n, γ) or (n, e^-) reactions, the level energies have been obtained from the energies of these lines. Only levels for which an assignment could be made are shown in the scheme. A short arrow to a level indicates that the level is populated by a direct transition from the 2^+ or 3^+ compound state. A triangle below the left-hand edge of a level indicates a (d, t) -populated level, and a triangle at the right indicates a (d, p) -populated level. Hollow triangles and dashed levels and transitions mean that the data are not conclusive. Transitions stronger than 10% per neutron capture are indicated by broader lines. For each transition, the energy in keV is given.

observed decoupling parameter is not in agreement with the calculated value for a pure (521↓) band, although the (d,t) data clearly indicate that most of the nuclear configuration of this band is indeed (521↓). The exclusive use of (d,t) data for the construction of the Dy¹⁶³ level scheme is complicated because of the presence of another band which is also strongly excited during the charged-particle reaction. This band (521↑) is not only precisely located through the neutron-capture data, but its relationship to the [521↓] band at 351 keV is clarified.

On the basis of what has been found from Dy^{166} decay studies, it is possible to construct a considerable part⁴ of the level diagram of the odd-odd deformed nucleus Ho^{166} by utilizing neutron-capture data. Considerations of low-energy gamma branching ratios help to identify rotational bands; however, the two-quasiparticle assignments are deduced from a comparison of experimental and theoretical (d,p) cross sections. In cases in which theoretical (d,p) cross sections have not yet been calculated (e. g., for Rh^{104}), the availability of sufficiently accurate charged-particle reaction data serves to disclose levels whose proton configuration is mainly the same as in the target nucleus. The level density in Rh^{104} is rather large. Therefore, the detailed knowledge of the interesting part of the Rh^{104} diagram, which can be obtained from neutron capture studies, is basic for the interpretation of the (d,p) spectra.

The list of examples could be extended. However, it is hoped that these few are sufficient to illustrate the fact that more information about the nuclear structure can be gained during a given interval of time if neutron-capture and charged-particle reaction data are combined. Indeed, it appears probable that if states above 300—500 keV in odd-A and odd-odd nuclei and above 1000—1500 keV in even-even nuclei are to be understood, we will require a variety of experimental techniques—each capable of characterizing in detail a particular part of the complicated wave functions expected for these states.

⁴H. T. Motz, E. T. Journey, O. W. B. Schult, H. R. Koch, U. Gruber, B. P. Maier, H. Baader, G. L. Struble, Jean Kern, R. K. Sheline, T. von Egidy, Th. Elze, E. Bieber, and A. Bäcklin, *Phys. Rev.* 155, 1265 (1967).

G-6. 5-MeV GAMMA-RAY INTENSITY ANOMALY IN THE (d,p γ)
REACTION

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It is well known that an anomalously intense group of γ rays at about 5 MeV exists in the gamma spectra following thermal neutron capture^{1,2} in nuclei in the mass regions $A < 70$ and $180 < A < 208$. Recently similar effects were reported for the $110 \leq A \leq 140$ mass region.³ Near $A = 70$ and 208, Bergqvist and Starfelt^{4,5} have shown this anomalous bump to persist following capture of 300-keV neutrons. Lundberg and Starfelt⁶ have shown that the anomalous γ -ray bump is present after fast-neutron capture in Au with neutron energies at least as high as 4 MeV. The mean energy of the bump remains constant at about 5 MeV regardless of the neutron energy. Perkin and Starfelt⁷ found no evidence for such anomalous radiation in the spectra of γ rays

¹G. A. Bartholomew, in Proceedings of the Conference on Electromagnetic Lifetimes and Properties of Nuclear States, Gatlinburg, 1961 (National Academy of Sciences, Washington, D.C., 1962), Nuclear Science Series No. 37, p. 209.

²L. V. Groshev, A. M. Demidov, V. N. Lutsenko, and V. I. Pelekhov, in Proceedings of the Second United Nations International Conference on Peaceful Uses of Atomic Energy (United Nations, Geneva, 1958), Vol. 15, p. 138.

³I. Bergqvist and N. Starfelt, Nucl. Phys. 38, 529 (1962).

⁴I. Bergqvist and N. Starfelt, Nucl. Phys. 39, 353 (1962).

⁵I. Bergqvist and N. Starfelt, Nucl. Phys. 39, 529 (1962).

⁶B. Lundberg and N. Starfelt, Nucl. Phys. 67, 321 (1965).

⁷J. L. Perkin and N. Starfelt, Nucl. Phys. 63, 526 (1965).

following inelastic neutron scattering. The possible connection of the (n, γ) bump with some form of semi-direct or collective capture mechanism leads to the present attempt to observe the anomalous γ -ray bump in a reaction of direct type, i. e., in (d, p) stripping. In addition to being a reaction other than (n, γ) , this experiment allowed us to extend the region of examination to states below the binding energy.

A 12-MeV deuterium beam bombarded thin targets of Bi, Pb, ^{206}Pb , Tl, Au, Pt, Ir, Re, Ta, Gd, CsI, Cs_2CO_3 , Sb, In, and Ag. After the target, typically $500 \mu\text{g}/\text{cm}^2$ thick, the beam entered a beam catcher required to reduce the background.

A 6×5 -in. NaI crystal at 90° recorded γ rays coincident with particles detected in a Si(Li) detector at 135° to the beam direction. Two-dimensional analysis of the data was done with the aid of an on-line computer. The γ -ray axis contained 128 channels; and a selected region of the protons in coincidence was divided into 30 adjacent 200-keV-wide regions, thereby covering the excitation region 2–8 MeV in the product nucleus.

Figure 211 shows examples of the proton spectra for some of the targets studied. These are the proton spectra in coincidence with all γ rays. Note that the targets extend from $A = 206$ to 181. These spectra are similar to the ungated spectra obtained by Pflieger *et al.*⁸

⁸J. Pflieger, U. Schmidt-Rohr, V. Spiegel, P. Turek, and W. Yuckschwerd, Nucl. Phys. **48**, 22 (1963).

Fig. 211. Spectra of protons in coincidence with all gamma rays from stripping reactions $A-1Z(d,p\gamma)^AZ$ for $A = 206$ to 181.

Fig. 212. Three-dimensional plot showing the gamma-ray yield (counts per channel times gamma-ray energy) as a function of gamma-ray energy (front scale) and excitation energy (side scale) in ^{207}Pb .

The major difference is that here there is a sharp reduction in yield above the neutron threshold because of competition with neutron emission.

In the Bi, Pb, and Tl proton spectra, Pfleger identified the strong peaks with the single-particle levels $d_{5/2}$, $d_{3/2}$, and $s_{1/2}$. The ^{207}Pb proton spectrum also shows peaks corresponding to levels at 0.57, 0.89, 2.71, and 3.61 MeV identified by Cohen et al.^{9,10} as single-particle or hole states in ^{207}Pb .

Figure 212 shows the γ -ray spectra for ^{207}Pb in a graphical form. The E_{γ} axis is along the bottom, the proton energy axis is along the side but, for clarity, the scale is shown as excitation energy in ^{207}Pb . The vertical axis is counts per channel times E_{γ} . You can see that recorded here are 30 γ -ray spectra, each corresponding to a particular excitation region in ^{207}Pb . The γ rays in the large bump are associated with the strong peaks shown in Fig. 211 and can be assigned to the known level scheme of ^{207}Pb as transitions to low-lying states. In general, the other peaks can be identified with transitions between known levels.

⁹B. L. Cohen, R. H. Fulmer, A. L. McCarthy, and P. Mukherjee, *Rev. Mod. Phys.* 36, 332 (1963).

¹⁰P. Mukherjee and B. L. Cohen, *Phys. Rev.* 127, 1284 (1962).

Figure 213 shows the γ -ray spectra in coincidence with protons leaving the target nucleus in an excited region at the neutron binding energy. The percentage of the total decay invested in high-energy gamma rays increases from the 'near-statistical' spectrum of Ta to the predominantly high-energy transitions of Tl and Pb. An anomalous bump at ~ 5 MeV, similar to those observed in neutron capture, is clearly present in targets heavier than Ir. Gamma-ray spectra for Cs and Sb look similar to those for Au and Pt, while spectra for Ag look much like those from Ta. These curves have been smoothed to eliminate statistical fluctuations and the curves have been normalized to equal areas.

Fig. 213. Gamma-ray spectra in coincidence with protons leaving the target nucleus in an excited region at the neutron binding energy after the neutron-capture (d, p) reaction.

The experimental points used to obtain the Au gamma-ray spectrum are shown in Fig. 214, in which some typical errors are shown.

Figure 215 shows 18 of the 30 spectra obtained from the $^{197}\text{Au}(d, p\gamma)^{198}\text{Au}$ reaction. Again the curves have been normalized to equal areas and smoothed. The arrows on the spectra and the labels on the level diagram relate the curves to the initial excitation energies defined by the proton gates. The small graph below the level diagram shows the proton spectrum in coincidence with the gamma rays and shows the positions of selected energy gates. The figure shows that the

Fig. 214. A gamma-ray spectrum from $^{197}\text{Au}(d, p\gamma)^{198}\text{Au}$.

Fig. 215. Gamma-ray spectra from the $^{197}\text{Au}(d, p\gamma)^{198}\text{Au}$ reaction. The circled numbers on the curves may be used with reference to the two inserts on the right for determining the excitation region yielding the particular gamma-ray spectrum. A selection of spectra have arrows indicating the position of the ground-state transition.

anomalous bump remains constant at around 5 MeV from an excitation energy of 1.2 MeV above the neutron binding energy (curve 1) to about 1.5 MeV below (curve 9). As the excitation energy decreases further, the energy of the anomalous bump also decreases—remaining about

Fig. 216. Gamma-ray spectra from the $^{181}\text{Ta}(d,p\gamma)^{182}\text{Ta}$ reaction. The labels are as in Fig. 215.

0.5 MeV less than the excitation energy but the valley below the bump remains constant. Finally, there is no evidence for an excess of high-energy gamma rays below 4 MeV excitation (curve 16).

Figure 216 shows similar details for Ta. Here there is no evidence for the bump.

Several observations concerning the nature of the anomalous γ -ray bump can be made.

Evidence points to the bump being due to primary γ rays. In this experiment the Pb γ rays associated with strong proton groups at proton energies between 11 and 12 MeV are assigned to the known level scheme as primary gamma rays. Biggerstaff *et al.*¹¹ observed that the predominant γ rays from resonance neutron capture in Pb are primaries. Coincidence measurements on γ rays from thermal-neutron capture¹² in ^{199}Hg require many of the stronger bump gamma rays to be

¹¹ J. A. Biggerstaff, J. R. Bird, J. H. Gibbons, and W. M. Good (to be published).

¹² G. A. Bartholomew, E. D. Earle, and M. R. Gunye, in Nuclear Structure Study with Neutrons (Proceedings of the International Conference, Antwerp, 19–23 July 1965), edited by M. Nève de Mévergnies, P. Van Assche, and J. Vervier (North-Holland Publishing Co., Amsterdam, 1966), p. 512; Can. J. Phys. 45, 2063 (1967).

primary. Also, if the bump were due to secondary radiation, it would be difficult to understand why the intensity should be independent of excitation energy and why the bump is absent in the $(n, n'\gamma)$ reaction.⁷

A second observation is that there is no marked correlation between the size of the γ -ray bump and the proximity of the initial excitation energy to the position of the single-particle s and d states. This supports the conclusion that the bump is not simply a consequence of a direct single-particle process in which s (and d) states are populated and then subsequently decay by E1 emission to low-lying p (and f) states.

Finally the energies of two-particle one-hole (2P-1H with respect to the target) neutron and proton configurations (or doorway states) that decay by E1 emission in nuclei near Pb were estimated by means of methods similar to those of Shakin.¹³ It was found that these configurations begin at an excitation energy of ~ 4.2 MeV and are more or less evenly distributed to 8 MeV and above; the average E1 decay energy is 5.5 MeV. This approach, which gives the observed bump energy and its independence of excitation energy above 4 MeV, inspires confidence that the doorway-state formalism can be used to account for this anomalous radiation. In the same excitation region, a smaller number of 2P-1H configurations were also found to give M1 decay energies near 5 MeV. If this picture is valid, then it follows that the gross-structure bump near Pb is predominantly E1 with some strong M1 radiation contributing.

The present experimental evidence on the multipolarity of the bump gamma rays is limited. The bump γ rays following thermal-neutron capture¹² in Hg are E1, but in Pb several high-energy M1 radiative transitions¹¹ have been seen following resonance neutron

¹³ C. Shakin, *Ann. Phys. (N. Y.)* 22, 375 (1963).

capture. I should add here that we heard this morning that the bump γ rays in Au following the neutron capture are E1 also. The anomalous bump certainly requires additional study and further neutron-capture experiments can yield valuable information concerning the fine structure and multipolarity of these gamma rays.

At present we are attempting to separate each observed spectrum into its primary and secondary components. The separation is done by solving a set of linear equations for the total spectrum in terms of the primary spectrum, proceeding successively from the lowest excitation region to the highest. The experimental gamma-ray intensities are the only known quantities. Preliminary results obtained for Au and Ta suggest that the bump arises from primary transitions.

SESSION H

3 NOVEMBER 1966

THEORY

G. T. EMERY, CHAIRMAN

H-f. ENERGY LEVELS OF Sc^{46}

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C.E.N. -S.C.K. , Mol, Belgium

The energy levels of Sc^{46} have recently been studied by the (d,p), (d,He³), and (d, α) reactions¹⁻³ and by neutron-capture gamma rays.⁴ In the present paper, we compare the most recent (d,p) and (n, γ) experimental data^{1,4} with the results of theoretical calculations on this nucleus.

The energy levels of Sc^{46} have been calculated in the framework of the shell model under the following hypotheses. The proton and the three neutron holes outside the closed shells $Z = 20$ and $N = 28$ are assumed to be in the $1f_{7/2}$ orbit, i.e., in the $\pi f_{7/2}$ and $(\nu f_{7/2})^{-3}$ configurations, respectively. The effective neutron-neutron interaction in the $(\nu f_{7/2})^{-3}$ configuration is deduced from experimental data on Ca^{45} and Ca^{46} , whereas the effective proton-neutron interaction in the $(\pi f_{7/2})(\nu f_{7/2})^{-1}$ configuration is extracted from the empirical spectra of Sc^{42} and Sc^{48} . The wave functions obtained after construction and diagonalization of the matrices of the effective interactions have been used to compute the quantities $(2J_f + 1)S$, where S is the spectroscopic factor for populating the various levels with spin J_f in Sc^{46} by the $\text{Sc}^{45}(\text{d,p})\text{Sc}^{46}$ reaction, as well as the reduced M1 transition possibilities $B(\text{M1})$ between the levels of Sc^{46} ; the latter calculations made use of the effective gyromagnetic ratios for a

¹J. Rapaport, A. Sperduto, and W. W. Buechner, Phys. Rev. 151, 939 (1966).

²J. L. Yntema and G. R. Satchler, Phys. Rev. 134, B976 (1964).

³J. H. Bjerregaard, P. F. Dahl, O. Hansen, and G. Sidenius, Nucl. Phys. 51, 641 (1964).

⁴P. Van Assche, U. Gruber, B. P. Maier, H. R. Koch, and O. W. B. Schult, Nucl. Phys. 84, 661 (1966).

Fig. 217. Energy levels of Sc^{46} .

proton and a neutron in the $1f_{7/2}$ shell deduced previously.⁵ The present study has many features in common with previous investigations of the $1f_{7/2}$ shell,^{6,7} except for the choice of the effective interactions and for the computation of the $B(M1)$.

In Fig. 217 and Table XXXIV, the results of the calculations are compared with the experimental data.¹⁻⁴ Only the positive-parity levels that are populated by $\ell_n = 3$ transitions [i.e., those corresponding to a $1f_{7/2}$ neutron capture in the (d,p) reaction] have to be included in this comparison. In Fig. 217, the

lengths of the thick solid lines are proportional to $(2J_f + 1)S$; the empirical and theoretical spectroscopic factors have been normalized to the 4^+ ground-state transition. The agreement between experiment and calculation is satisfactory for the energy level positions and the $(2J_f + 1)S$ quantities in the (d,p) reactions. Except for the inversion of the lowest 4^+ and 6^+ states, the empirical level order is correctly reproduced up to 1 MeV and the differences between the two sets of excitation energies are within the uncertainties of the calculations. The relative $(2J_f + 1)S$ are also satisfactorily accounted for—at least qualitatively and, in most cases, quantitatively.

The first 5^+ level is populated by a mixed $\ell_n = 1$ and 3 transition in the (d,p) reaction. The $\ell_n = 3$ spectroscopic factor cannot

⁵B. F. Bayman, J. D. McCullen, and Larry Zamick, Phys. Rev. Letters 11, 215 (1963).

⁶J. D. McCullen, B. F. Bayman, and Larry Zamick, Phys. Rev. 134, B515 (1964).

⁷R. A. Ristinen and A. W. Sunyar, Phys. Rev. 153, 1209 (1967).

TABLE XXXIV. Reduced M1 transition probabilities in Sc^{46} .

Initial level		Transition		B(M1)	
$J_{\text{in.}}$	$E_{\text{in.}}$ (keV)	$J_{\text{fin.}}$	$E_{\text{trans.}}$ (keV)	Exp.	Theor.
5^+	280.7	4^+	280.7	0.35	0.005
		6^+	228.7	9.65	9.995
5^+	773.9	4^+	773.9	4.43	8.75
		6^+	721.9	5.57	0.93
		5^+	[493.2]	<0.10	0.32
4^+	835.2	4^+	835.2	0.21	0.24
		3^+	[607.5]	<0.01	0.54
		5^+	554.5	9.79	8.61
		5^+	[61.3]	<1.25	0.61

be extracted from the experimental data. Hence it is not displayed in Fig. 217 and no comparison with calculations is possible; it seems to be rather small, however. On the other hand, the one for the second 5^+ state is significantly larger than the predicted value. It thus seems that the two lowest 5^+ levels are inverted with respect to their calculated positions, the upper one having most of the $l_n = 3$ strength to the 5^+ states in Sc^{46} .

Another difficulty encountered by the theory is the apparent absence of a 7^+ level in the experimental spectrum. No state with as large a $(2J_f + 1)S$ quantity as that of the lowest calculated 7^+ level has been seen in the (d,p) data. Since the lowest 7^+ state of the $(\pi f_{7/2})(\nu f_{7/2})^{-3}$ configuration should be strongly favored over the levels with a lower spin in this neighborhood, in the (d,p) reaction, because of the $(2J_f + 1)$ factor—more or less independently of the effective interactions used—this absence is a puzzling problem in Sc^{46} .

The experimental and calculated reduced M1 transition probabilities in the decay of some levels of Sc^{46} are compared in Table XXXIV; they have been normalized to a sum of 10 for the decay of each state. There is a very satisfactory qualitative agreement between the two sets of numbers. The theory thus explains some apparent selection rules—for instance why the first 5^+ level preferentially decays to the first 6^+ , and the second 4^+ to the first 5^+ .

It also explains why transitions from the first 5^+ level to the 4^+ ground state, from the second to the first 5^+ , and from the second 4^+ at 835 keV to the 4^+ ground state and to the first 3^+ and second 5^+ excited levels are absent, or weak, in the experimental neutron-capture gamma-ray spectrum. There is no complete quantitative agreement, however; but the absolute ratios between the $B(M1)$ depend rather strongly on the effective gyromagnetic ratios adopted and on the coefficients of the various components in the wave functions, so that no better agreement with experiment is to be expected from this type of calculations.

Some levels in Sc^{46} below 1 MeV (the ones at 143, 289 and 585 keV) seem to pertain to a different category of states.⁴ They have been assigned a negative parity⁴ on the basis of an interpretation of these levels as arising from configurations with holes in the closed shells of Ca^{48} , more specifically $1d_{3/2}$ proton-hole states.² However, recent data⁷ on the related nucleus Sc^{44} could be interpreted as indicating the presence of configurations with two holes in the low-lying spectrum of Sc^{44} , i. e., $1d_{3/2}$ proton- and neutron-hole states, combining to positive-parity levels. These considerations, if confirmed, would raise some doubts about the parity of the 143-, 284-, and 585-keV states in Sc^{46} .

To summarize, the present calculations have been able to account successfully for the properties of the low-lying Sc^{46} levels reached by $l_n = 3$ transitions in the (d,p) reaction, namely their energies, their $(2J_f + 1)S$ quantities, and their reduced M1 transition probabilities. Further theoretical work is needed to take into account the influence of the 1-hole and maybe 2-hole states on the spectrum of this nucleus.

* * *

O. W. B. SCHULT, Technical University, Munich and Brookhaven National Laboratory: I would like to emphasize that Van Assche has done the main work to establish the level diagram of Sc^{46} .

L. M. BOLLINGER, Argonne National Laboratory: Are you sure enough of the theory for any of these nuclides that you would want to use your theoretical approach as a spectroscopic tool for assigning spins.

VERVIER: I would do so for V^{52} , which I think is the best case. In Nb^{94} , most of the intensity in the low-energy capture spectrum is not yet assigned. Journey mentioned to me yesterday that there are more recent data indicating the existence of some negative-parity levels at low energies in Nb^{94} , where these low-energy transitions could be fitted and theory could be used as a guide in assigning spin.

BOLLINGER: What I meant to ask was: Can you identify any classes of states for which gamma-ray intensities may confidently be used to establish spins and parities?

VERVIER: I feel that the theory enables us to make meaningful spin assignments; and these assignments then suggest further experiments. For instance, if an assignment suggests that one level should decay mainly to a particular better-known low-lying level, the experimenter is prompted to look in the spectrum for this transition. However, I do not think that the theory in itself is a convincing argument; it only suggests further experimental work.

H-2. ENERGY LEVELS OF THE Co ISOTOPES

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The energy levels of Co^{58} have recently been studied by the (d,t), (p,d), and (p,n) reactions¹⁻⁵ and those of Co^{60} by the (d,p) reaction and neutron-capture gamma rays.⁶⁻⁷ In the present paper, we compare these experimental data with the results of theoretical calculations on the Co isotopes.

The energy levels of the Co isotopes ($Z = 27$) with a neutron number N between 30 and 33 have been calculated in the framework of the shell model under the following hypotheses. The orbits available for the proton hole and the neutrons outside the closed shells $Z = N = 28$ are assumed to be $1f_{7/2}$ for the proton hole, and $2p_{3/2}$, $2p_{1/2}$, and $1f_{5/2}$ for the neutrons. The relative positions of the neutron orbits and the matrix elements of the effective neutron-neutron interaction in these orbits are taken from the work of Auerbach⁸ (for his case b): only the states with lowest seniority (i.e., $v = 0$ for even values of $N - 28$, and $v = 1$ for odd values of $N - 28$) are taken into

¹ B. Zeidman, J. L. Yntema, and B. J. Raz, Phys. Rev. 120, 1723 (1960).

² J. C. Legg and E. Rost, Phys. Rev. 134, B752 (1964).

³ J. B. Ball and R. F. Sweet, Phys. Rev. 140, B904 (1965).

⁴ M. Croissiaux, E. Dally, H. Distelzwey, and C. Gehringer, J. Phys. (Paris) 25, 906 (1964).

⁵ S. Gorodetzky, C. Gehringer, P. Chevallier, S. Cottin, R. S. Drouin, G. Sutter, P. Siffert, and L. Stab, Phys. Letters 19, 313 (1965).

⁶ H. A. Enge, D. L. Jarrel, and C. C. Angleman, Phys. Rev. 119, 735 (1960).

⁷ E. Brooks Shera and D. W. Hafemeister, Phys. Rev. 150, 894 (1966).

⁸ N. Auerbach, Nucl. Phys. 76, 331 (1966).

account. The matrix elements of the effective proton-neutron interaction in the various configurations are those obtained previously⁹ when studying the energy levels of the nuclei with 29 neutrons; a zero-range internucleon force is assumed, whose strength and spin contribution are determined by an analysis of the energy levels of Co^{56} and of the motion of the $2p_{1/2}$ and $1f_{5/2}$ neutron orbits with respect to $2p_{3/2}$ between Ca^{49} and Ni^{57} .

The results of these calculations for Co^{58} and Co^{60} are compared in Figs. 218 and 219 with the experimental data recently obtained by pickup¹⁻³ and stripping⁶ reactions on Co^{59} , by neutron-capture gamma rays,⁷ and by (p,n) studies.⁴⁻⁵ In each figure, the lengths of the thick solid and dashed lines are proportional to S for Co^{58} and to $(2J_f + 1)S$ for Co^{60} , where S is the spectroscopic factor of

Fig. 218. Energy levels of Co^{58} .

Fig. 219. Energy levels of Co^{60} .

⁹ J. Vervier, Nucl. Phys. 78, 497 (1966).

the level considered for the pickup (Co^{58}) and stripping (Co^{60}) of a neutron with $\ell_n = 1$ (solid lines) or $\ell_n = 3$ (dashed lines), and J_f is the spin of the final level in Co^{60} for the (d,p) reaction. The experimental data for these quantities, taken from Ref. 3 for Co^{58} and Ref. 6 for Co^{60} , and the results of the calculations are properly normalized to each other.

The comparison between experiment and calculation shows that the agreement obtained is only qualitative. A general remark is that the calculated 3^+ and 4^+ levels are systematically too low and the 2^+ and 5^+ too high with respect to experiment in both nuclei.

Low-lying 2^+ and 5^+ states are correctly predicted in Co^{58} , with however the reversed order and with a 4^+ level in between. The 0.35- and 0.44-MeV states can probably be associated with the first 4^+ and 3^+ levels of the calculated spectrum, respectively; however, they are displaced by about 0.35 MeV from their theoretical positions, and the experimental intensities of the corresponding deuteron groups in the (p,d) reaction³ are higher than the calculated ones by about a factor of two. Fig. 218 also suggests that the empirical "ground-state" and "0.09-MeV" groups in the (p,d) reaction are probably complex, as indicated by the experimental data,³ and that more levels than those shown in the experimental spectrum of Fig. 218 very likely exist below 0.5 MeV in Co^{58} ; a pickup experiment on Co^{59} with a better resolution is thus desirable at this point. Above 0.5 MeV, the qualitative agreement between experiment and calculation is satisfactory. Some levels with non-negligible $\ell_n = 3$ strengths in the pickup reaction are predicted below 2 MeV, and should be sought experimentally. Finally, there is no single state in the calculated spectrum of Co^{58} for which the theoretical spectroscopic factor for an $\ell_n = 3$ pickup is as large as the one of the 2.61-MeV level, for which $S = 2.2$ (Ref. 2). This would suggest that this $\ell_n = 3$ transition involves a $1f_{7/2}$ neutron pickup rather than the $1f_{5/2}$ proposed in Ref. 2.

The comparison (Fig. 219) for Co^{60} does confirm the tentative spin assignments proposed for some experimental levels up to 1.5 MeV on the basis of neutron-capture gamma-ray data.⁷ Corresponding states with the required spin and dominant l_n value in the stripping reaction, and with a spectroscopic factor of the expected order of magnitude, do exist in the calculated spectrum, though somewhat displaced as shown by the indicated tentative assignments of theoretical levels to empirical states. Only the (3^+) and $(1^+, 2^+)$ levels at 0.613 and 0.738 MeV cannot be accounted for by the present model up to 1 MeV. The main defect of the calculation is the inversion, with respect to experiment, of the two lowest 5^+ states with predominantly $l_n = 1$ and 3. The empirical $(2J_f + 1)S$ quantities for $l_n = 3$ transitions⁶ are generally much larger than the theoretical predictions. This is certainly true for the second 2^+ state at 0.540 MeV with $l_n = 3$. If one (very tentatively) associates the $l_n = 3$ levels with the largest $(2J_f + 1)S$ in the experimental and calculated spectra (i.e., the 1.799-MeV state⁶ and the first 6^+ level), a discrepancy of a factor of 4 exists between the spectroscopic factors. There are also low-lying states with comparable $l_n = 1$ and 3 strengths in the theoretical spectrum, which should be sought experimentally. It should be noted here that the (d, p) results⁶ have been analyzed with plane-wave calculations, so that the quoted spectroscopic factors may not be very reliable; a DWBA analysis is needed at this point.

The shortcomings of the calculation are probably due to the neglect of seniority mixing in the neutron orbits. This is apparently justified in the Ni isotopes.¹⁰ The proton-neutron interaction should, however, mix the levels with different seniorities. That a more complete calculation, taking the $v = 2$ and 3 states into account, could maybe reproduce the spectrum of the Co isotopes better than the

¹⁰ N. Auerbach, Phys. Letters 21, 57 (1966).

present one is shown by the success of a recent investigation¹¹ of Cr^{54} and $\text{Fe}^{56,57}$; the same matrix elements of the effective proton-neutron interaction as here⁹ were used, together with an effective neutron-neutron interaction deduced from the analysis of the Ni isotopes.¹² Such computations for the Co isotopes would, however, be quite lengthy: for Co^{60} , they would involve six nucleons into four orbits and require the construction and diagonalization of matrices up to order 119. The case of Co^{58} would be easier (matrices up to 37×37).

To summarize, the present calculation can be considered as a first step towards the theoretical investigation of the Co isotopes. It is able to account qualitatively for the experimental data on these nuclei, and confirms tentative spin assignments to low-lying levels in Co^{60} . It suggests further experiments (higher-resolution pickup reactions on Co^{59} , better DWBA analysis of the stripping data, and a search for $l_n = 3$ transitions in the pickup reaction and mixed $l_n = 1$ and 3 transitions in stripping) and calculations (to include the higher-seniority neutron states).

Recently, McGrory¹³ has carried out a preliminary calculation of the energy levels of the Co isotopes in the way suggested above. His first results do not agree with experiment much better than the present study does; more theoretical work is required on this point.

¹¹ J. B. McGrory, Phys. Letters 21, 64 (1966).

¹² S. Cohen, R. D. Lawson, M. H. Macfarlane, S. Pandya, and M. Soga, Phys. Rev. 160, 903 (1967).

¹³ J. B. McGrory (private communication).

H-3. THEORY OF CAPTURE REACTIONS

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It is becoming clear that experimental and theoretical studies of capture reactions are capable of giving considerable information both on the nature of the final states reached and on the initial scattering state. The following remarks will be confined to very-low-energy neutron capture in the resonant region and to low-lying states in the final nucleus. There are then two experimental studies to examine. First we may look at the cross sections to different final states at a given energy. Secondly we may examine the cross section to a given final state as a function of energy, say over several resonances. Both types of experiment show divergences from results expected on the basis of a statistical compound-nucleus theory. They occur particularly in the mass regions in which single-particle p states are unoccupied ($A \approx 40-70$ and $170-208$) and $E1$ transitions are allowed from the continuum. We shall see how some of these features can be understood theoretically. The basic idea is that there is a correlation between the formation and decay of the compound nucleus when the initial and final states are simply related.

For simplicity we specialize to the case of dipole capture on an even-even spin-zero nucleus. The total cross section to a definite final state ψ_f is then

$$\sigma_{\text{tot}} = \frac{8\pi}{9} \frac{M^2}{\hbar^2 k} K_Y^3 \sum_{\text{mag}} |\langle \psi_f j_f m_f | D_{1m} | \Psi^{(+)} \rangle|^2, \quad (1)$$

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where M' is the nucleon mass, k and K_Y are the wave numbers for the neutron and the photon, and the dipole operator is

$$D_{1m} = \sum \bar{e}_i r_i Y_{1m}(\theta_i \phi_i),$$

where $\bar{e}_i$ is the effective charge of the i th nucleon.

The wave functions ψ_f and $\Psi^{(+)}$ are both eigenfunctions of the total nuclear Hamiltonian H corresponding to the final bound state and the initial scattering state.

From the inverse reaction we see that we are looking for the component of $\Psi^{(+)}$ corresponding to the dipole state of the final nucleus.

In the following we neglect antisymmetry between the incident neutron and the target. This will not change the results, at least for the resonant part of $\Psi^{(+)}$. Then ψ_f can be expressed as a linear combination of states λ of the target nucleus and single-particle neutron states ϕ_p . They are eigenfunctions of $H_0 + T + U$, where H_0 refers to the target and U is a single-particle potential. Thus

$$\psi_f = \sum_{\mu\lambda} a_{\mu\lambda} \phi_{\mu}(\vec{r}_n) | \lambda \rangle .$$

We are particularly interested in the part containing the ground state $|0\rangle$ of the target, which is the part of ψ_f reached by a (d, p) stripping reaction on the target. We write this as $S \phi_p(\vec{r}_n) |0\rangle$, where S^2 would be the stripping spectroscopic factor and ϕ_p is a single-particle p state. (As in stripping it should be a mixture of states of different μ if defined by a fixed potential U .)

The dipole operator can be rigorously divided into two parts corresponding to the dipole operator for the target and the dipole operator for the neutron, i. e.,

$$D = D_n + D_T .$$

The matrix element in Eq. (1) can now be written as

$$M = S \left[\left\langle \phi_p(r_n) D_n \mid 0 \mid \Psi^{(+)} \right\rangle + \left\langle 0 \mid D_T \mid \phi_p \Psi^{(+)} \right\rangle \right] + C, \quad (2)$$

where C is a correction term for final-state components not reached in a (d, p) reaction.

In so far as we can neglect C and the dependence of ϕ_p on the energy of the final state, the cross sections to different final states after removal of the kinematical factors should be proportional to the stripping spectroscopic factor.

The two terms in Eq. (2) will have different behaviors as functions of the incident energy. We will now examine the first term and show that it is intimately related to the elastic-scattering matrix element and thus has a similar resonant behavior. To do this we can use any one of the resonance theories recently correlated by Lane and Robson.¹ If we take the same Hamiltonian as used in the final state we can write

$$H = H_0 + T + U + H',$$

where H' is the residual interaction between the neutron and target nucleus. Then

$$\Psi^{(+)} = \chi_0^{(+)} \mid 0 \rangle + \frac{1}{E - H + i\epsilon} H' \chi_0^{(+)} \mid 0 \rangle,$$

where $\chi_0^{(+)}$ is the neutron wave function defined by the single-particle well depth U .

¹ A. M. Lane and D. Robson, Phys. Rev. (to be published).

The first matrix element in Eq. (2) becomes

$$M_1 = \langle \phi_p(r_n) D_n \chi_0^{(+)} \rangle + \left\langle \phi_p(r_n) D_n \left\langle 0 \left| \frac{1}{E - H + i\epsilon} H' \chi_0^{(+)} \right| 0 \right\rangle \right\rangle.$$

The first term corresponds to the 'direct' single-particle matrix element treated by Beck² and by Lane and Lynn,³ whereas the second term gives the resonant contribution.

If the resonances are isolated and only one resonant state is important, the second term can be written as

$$M_{1R} = \frac{\langle \phi_p(r_n) D_n \langle 0 X_r \rangle \rangle \langle X_r H' \chi_0^{(+)} | 0 \rangle}{E - \epsilon_r}, \quad (3)$$

where ϵ_r is the complex resonant energy.

We compare this with the resonant contribution to the elastic-scattering amplitude, namely

$$M_{e1R} = \frac{\langle \chi^{(-)}(r_n) \langle 0 | H' X_r \rangle \rangle \langle X_r H' \chi_0^{(+)} | 0 \rangle}{E - \epsilon_r}.$$

The final matrix element in the latter can be written as

$$\langle \chi^{(-)}(r_n) [E_n - T - U] \langle 0 X_r \rangle \rangle$$

and can be evaluated by using the boundary conditions on the single-particle wave functions.

Thus both final matrix elements contain the overlap of the ground state of the target with the resonant state—i.e., the factor $\langle 0 X_r \rangle$.

²F. Beck, Nucl. Phys. 9, 140 (1959).

³A. M. Lane and J. E. Lynn, Nucl. Phys. 11, 646 (1959).

The two single-particle integrals are almost independent of energy and thus the resonant-capture cross section arising from M_1 is expected to be proportional to the elastic cross section over resonances. Another way of putting this result is that the photon decay of the compound nucleus to states containing the ground state of the target nucleus is not independent of the formation of the compound nucleus. In quantitative terms, by relating the nuclear matrix element to Γ_n , we have for neutron S-wave resonances

$$\frac{\Gamma_{\gamma f}}{\Gamma_n} = S^2 (2j_f + 1) \frac{2}{9} \frac{M'}{\hbar^2 k} \frac{\bar{e}^2}{e^2} K_{\gamma}^3 \frac{1}{R^2} I^2,$$

where R is the nuclear radius and the integral is

$$I = \int_0^{\infty} r^3 u_{fp}(r) \frac{u_0(r)}{u_0(R)} dr,$$

where $u_{fp}(r)$ is the radial wave function of the final p state and $u_0(r)$ is the radial wave function of the resonant state contained in $\langle 0 X_r \rangle$.

If we make the integral dimensionless, we obtain

$$\frac{\Gamma_{\gamma f}}{\Gamma_n} = (2j_f + 1) S^2 \left(\frac{\bar{e}}{e} \right)^2 \frac{E^3}{\sqrt{E_n}} A I^2(p) \times 10^{-8},$$

where the energies are in MeV.

We see why large experimental results are restricted to heavy nuclei at very low energies. For $A = 170$, $S^2 \sim 1$, $\bar{e}/e = \frac{1}{2}$, $E_{\gamma} \approx 8$, and $E_n = 10^{-6}$ MeV (1 eV), the ratio becomes $0.2 (2j_f + 1) I^2(p)$.

We will comment only briefly here on the second term in Eq. (2). For the 'direct' part of $\Psi^{(+)}$, namely $\chi_0^{(+)}$, the term has been found to contribute largely to the capture cross section at energies

between 10 and 15 MeV.^{4,5} In the low-energy region it may add a factor of 2 or more to the direct capture.⁶ However, the term has not been treated correctly as yet in the deformed region where the giant dipole resonance is split. By a process similar to that followed above, it can be shown that the compound part of $\Psi^{(+)}$ gives a contribution over resonances which adds coherently to the single-particle term given by Eq. (3). This arises from the coupling of the $|1^- \rangle$ state given by $D_T|0\rangle$ to $\langle 0 \Psi^{(+)} \rangle$ by means of the matrix element

$$\langle 1^- | \phi_p(r_n) H' | 0 \rangle \langle 0 \Psi^{(+)} \rangle.$$

However, there may be additional terms corresponding to the coupling to other states of the target nucleus, e. g., to $\langle 2 + \Psi^{(+)} \rangle$. The contribution of such terms to Γ_{yf} will not be directly proportional to Γ_n and, by investigating the ratio Γ_{yf}/Γ_n over several resonances, we should be able to get some idea of the magnitude of these terms.

The above considerations suggest that there are relatively large capture cross sections to final states having stripping widths to the initial state. In the deformed region ($A \approx 170$) we are somewhat handicapped in giving a detailed description of reactions because the Nilsson model used for bound states is not easily correlated with scattering theory. However, it is clear that the $\frac{3}{2}^- [512]$ Nilsson state should not have an overlap with the target nucleus and a single-particle p state because the intrinsic single-particle orbital-angular-momentum component along the deformation axis is 2, which rules out a single-particle orbital angular momentum of 1 in the laboratory system.

⁴G. E. Brown, Nucl. Phys. 57, 339 (1964).

⁵C. F. Clement, A. M. Lane, and J. R. Rook, Nucl. Phys. 66, 273 and 293 (1965).

⁶A. M. Lane, Nuclear Structure Study with Neutrons (North-Holland Publishing Co., Amsterdam, 1966), p. 343.

In the above we have considered only capture to states containing the target ground state as a component and have shown that this will give a correlation between $\Gamma_{\gamma f}$ and Γ_n . If we extend the discussion to states that are strongly coupled to the target ground state by single-particle transitions (i. e. , coupled particle-hole states), we might also expect relatively strong radiation widths to final states made from these plus a single-particle state (i. e. , final 2p-1h states in which there is p-h coupling to produce a state of the target). In the lighter nuclei there is some evidence for such transitions.⁷

* * *

L. M. BOLLINGER, Argonne National Laboratory: One of your more definite predictions seems to be that the neutron width and the radiation width are correlated for the high-energy gamma rays. But although this is one of the easier things to look for, I know of no experimental evidence that such a correlation exists. Do you care to comment on this?

CLEMENT: I would emphasize that the correlation exists only when transitions to a definite final state are measured.

BOLLINGER: Perhaps I can clarify my statement a bit by being more explicit about the experiment. It is relatively easy to measure the sum of the widths of transitions to several final states by use of a sodium iodide detector. Quite a few measurements of this kind have been reported, but no correlation effects have been detected.

CLEMENT: If all kinds of different final states are contributing to the detected intensity, then the experiment does not really say anything. It is necessary to pick one definite final state (preferably a single-particle state) that shows up strongly in stripping.

⁷H. Ikegami and G. T. Emery, Phys. Rev. Letters 13, 26 (1964).

M. BEER, State University of New York at Stony Brook and Brookhaven National Laboratory: At Brookhaven we are looking for just this type of correlation between the partial radiation width and the reduced width. We are doing this for the even-even tungsten targets and also for other types of targets—but the work is far from complete.

CLEMENT: That is very interesting.

G. T. EMERY, Indiana University: Would you like to comment on Earle's work (paper G-6)?

CLEMENT: I have heard him speak on this work before, but I still do not understand his results. I would guess that he is seeing transitions between two-particle one-hole states. These may generally be regarded as a single particle weakly coupled to a strongly coupled particle-hole state. If so, there are two possibilities: either the single particle makes the transition, or the transition is from one coupled particle-hole state to another. I rather lean to the former view. The particle-hole state is coupled up in many ways, and another state 5 MeV away must be coupled up in some way. Since these states are much more numerous than single-particle states, I find it hard to understand why there should be a constant energy of 5 MeV. But I might be wrong; the single-particle transition may not be responsible.

E. D. EARLE, Chalk River Nuclear Laboratories: Our preferred view is that the 5.5-MeV gamma ray results from the particle returning to the hole from which it was excited.

CLEMENT: You could be right.

J. A. HARVEY, Oak Ridge National Laboratory: In our capture gamma-ray measurements with the isotopes of tin, several strong M1 gamma rays were observed from the capturing state to low-lying $s_{1/2}$ and $d_{3/2}$ states. Several years ago Shakin calculated the s-wave neutron strength function for the tin isotopes considering 3-quasiparticle states (2-particle 1-hole states) and it was in good agreement with experiment.

Some of these 2-particle 1-hole states in Shakin's calculations have the proper neutron configurations, such as ($s_{1/2}, g_{7/2}, g_{9/2}^{-1}$) and ($d_{3/2}, g_{7/2}, g_{9/2}^{-1}$) states, to decay by M1 particle-hole transitions to the low-lying $s_{1/2}$ and $d_{3/2}$ neutron states. The expected M1 strengths for such transitions have not been calculated from theory.

CLEMENT: I see. Everything I have said applies exactly to other single-particle transitions. For any single-particle transition there is a corresponding M1 factor.

O. A. WASSON, Brookhaven National Laboratory: In the interference between direct capture and resonance capture, what would you expect the phase to be on the low-energy side of a resonance? Would it be constructive or destructive?

CLEMENT: In general it is not possible to give the relative phase for a reaction—in contrast to the neutron elastic-scattering situation. However, in the case I've considered (the capture of the single neutron), the phase can be determined if one makes assumptions about the single-particle component of the resonant state. This would imply that the phase would be different for different nuclei and it may be possible to predict it. I hope to discuss this point further elsewhere.

SESSION I

4 NOVEMBER 1966

**RESONANCE-NEUTRON CAPTURE
GAMMA-RAY EXPERIMENTS**

J. VERVIER, CHAIRMAN

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X

11. USE OF A FAST CHOPPER IN RESONANCE-NEUTRON-CAPTURE
GAMMA-RAY STUDIES*

R. E. Coté

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The point of view that will be taken in this talk is slightly different from the one Slaughter adopted Wednesday morning. It will be more or less what we have done and are doing with a fast chopper in the absence of any expectation of getting a linear accelerator in the near future.

I might first mention that most of the work I will discuss this morning has been done at Argonne. I should also like to say that significant contributions have been made by the fast-chopper groups at Brookhaven and at Oak Ridge, and, of course, the Brookhaven-Chalk River collaboration. A great deal of the work I will discuss today has been done in collaboration with L. M. Bollinger, T. J. Kennett, R. T. Carpenter, W. V. Prestwich, G. E. Thomas, and possibly several others.

I will not give a figure of merit for this system that shows it is by far the best system in the world. I think I will ignore that point; it has been belabored in the past at many conferences and the fast chopper somehow always seems to show up at the bottom of the list. Still we have gone on making measurements with the fast chopper which are of rather acceptable quality in spite of its poor figure of merit.

One quickly comes to the conclusion that there are two types of measurements that can be made with the chopper in the field of gamma-ray spectroscopy. The first uses the gamma-ray spectra

*Work performed under the auspices of the U. S. Atomic Energy Commission.

as a tool to determine some of the properties of the neutron levels. In other words, neutron spectroscopy is the primary aim. The second use is to utilize the variable neutron energy that a chopper provides to study the gamma-ray spectra as a function of neutron energy to see if there are differences in the spectra resulting from capture in different resonances. If differences do appear, the hope is that they can be interpreted in terms of fundamental considerations.

Neither of these applications is independent of the other. In the study of the gamma-ray spectra it is always helpful to know the character and spin and parity of the state from which the transitions start. It is just as helpful to know the spins of the resonances for the study of the resonances themselves.

I think it is expedient to review some of the history of the work by summarizing some of the accomplishments of fast choppers in the past six or seven years. It was during this time that most of the capture gamma-ray spectral studies have been made. During this time, you will realize, pulsed linear accelerators have existed and have been used in parallel with the choppers. I think that in this competition, the chopper has given a good account of itself.

This emphasizes one point, namely that the chopper is only one part of the system. It is only the source of pulsed neutrons. The detector and the spectrometer are equally important, so that one needs development along all three lines. Of course, this has been part of the story in the past. In the future I do not know if it will be quite the same, but at the moment I think we are still in a competitive position in this regard.

As you know, the very first resonance gamma-ray spectra were observed at Yale with the Linac, 7 or 8 years ago.¹ Shortly after this, similar programs were initiated both here and at Brookhaven to

¹C. A. Fenstermacher, R. G. Bennett, A. E. Walters, C. K. Bockelman, and H. L. Schultz, Phys. Rev. 107, 1650 (1957).

study gamma-ray spectra in resonances. One of the prime motivations for this came from the success of Landon and Ray² in determining the spin of the 34-eV resonance in Hg. As all of you know who have ever tried to measure resonance parameters, the determination of the spin of the resonance is one of the most difficult tasks—and it looked, in this case, as if this were an easy way to do it. So everybody, at least all the people with choppers, tried immediately to find the easy way out. It soon became apparent that it was not quite as easy as it appeared to be; there were difficulties. Although in many cases one could make the spin assignment if the gamma ray was observed, what could be said if the gamma ray was not seen at that particular neutron energy? One could not say definitely that the spin was different from the case in which you saw this transition. All you could say was that the gamma ray was weaker. The question then posed was: What is the distribution of the partial gamma-ray widths? This topic kept quite a few of us busy for quite a few years, and it is a topic that is still being discussed and worked on to some extent. It will be discussed later in this talk and again later this afternoon.

Certainly the early work of Hughes and Harvey³ on the distribution of reduced neutron widths led Porter and Thomas to study the problem theoretically. They came up with the answer that the reduced neutron widths obeyed what we call the Porter-Thomas distribution,⁴ i. e., a χ^2 distribution with one degree of freedom. It was not immediately appreciated that this distribution also governed the partial radiation widths; but after a long period of experimentation and a little haggling, the matter seemed to have been settled. I think it is settled reasonably

²H. H. Landon and E. R. Rae, Phys. Rev. 107, 1333 (1957).

³D. J. Hughes and J. A. Harvey, Phys. Rev. 99, 1032 (1955).

⁴C. E. Porter and R. G. Thomas, Phys. Rev. 104, 483 (1956).

well by now. By this I mean I think it is believed with a high degree of certainty that in reactions that proceed from the compound nucleus, the relative partial radiation widths appear to be drawn from a χ^2 distribution of one degree of freedom. Any strong departures from this behavior suggest a different mechanism. It is this kind of thing that I think people will be looking for in the future.

As you know, this distribution is a very broad one with a high probability for small widths. There are two immediate consequences. First, the failure to observe a transition shows only that it is below the sensitivity of the experiment and does not establish as a definite fact that the transition probability is zero. Secondly, it requires a rather large statistical sample to obtain a meaningful average for the transition strengths which, of course, are interesting numbers that can be compared with theory. For instance, if one sets out to measure average partial radiation widths, as Carpenter and Bollinger⁵ did some years ago, one finds that (even in working with samples of rare earth nuclides, in which the resolution of the chopper enables one to reach eight or ten resonances with ease) the desired quantity has been measured only to $\pm 60\%$. This is not an adequate reward to an experimenter for really quite a bit of work; at least it was a considerable effort in those days. But what is worse is that there is little hope for improving this situation by any significant factor unless one is expecting a high-powered accelerator in the near future.

I have placed a great deal of emphasis on this distribution, but it has been instrumental in the development of this branch of the work, and I think it remains a dominant factor in determining the direction of future work. I think, therefore, it deserves a rather heavy emphasis.

⁵R. T. Carpenter, Argonne National Laboratory Report ANL-6589 (unpublished).

Fig. 220. Sum-coincidence spectra of the Hf^{177} resonances. The characteristics of the spectra allow them to be classified into two distinct subgroups corresponding to the two possible spins ($J = 3$ or 4) of an s -wave resonance.

Now, what other things have been done with fast choppers in the way of gamma-ray spectroscopy and neutron spectroscopy with the aid of gamma rays? One use has been to determine spins. Figure 220 shows the results of a measurement made some years ago by Jackson and myself⁶ on the spins of some hafnium resonances. I show this here particularly because the last talk of this session (paper I-10) is related to this measurement in that it raises a question about the assignment of the 2.38-eV level in hafnium. Before these measurements were made, DuMond and co-workers at Mol⁷ had measured the spins of the 1.1- and 2.38-eV resonances and obtained spins of 3

⁶L. M. Bollinger, R. E. Coté, and H. E. Jackson, in *Comptes Rendus du Congrès International de Physique Nucléaire, Paris, 2—8 July 1964*, edited by Mme. P. Gugenberger (Centre National de la Recherche Scientifique, Paris, 1964), Vol. II, p. 673.

⁷H. Ceulemans and F. Poortmans, *Nucl. Phys.* **62**, 641 (1965).

Fig. 221. The low-energy NaI spectra for the resonances in Hg. The distinctive character of each spectrum permits isotopic identification of the corresponding resonance.

saw no transition to this state from the other set. These results indicate that one of the groups certainly has a spin of 3. He was not able to say anything about whether the other group has a spin of 4. Altogether a consistent picture of the spin assignments in Hf has been deduced from these capture gamma-ray studies. This is one application.

Figure 221 concerns itself with the second application.

This figure, based on the work of Carpenter and Bollinger,⁸ is designed

⁸R. T. Carpenter and L. M. Bollinger, Nucl. Phys. 21, 66 (1960).

and 4, respectively. In our experiment, completely independent and without bias of any kind, we obtained these sum-coincidence spectra by using two large sodium iodide scintillators. I think you can see these data group themselves into two very nice groups. The major difference concerns the transitions to the 93-keV 2^+ first excited state in Hf¹⁷⁸. In one group this level is not populated much at all. In the second group it is populated rather well.

This is the major point on which the spin determination is made. These groupings are as expected for spin-3 and spin-4 resonances.

Now, the experiments of Carpenter⁵ which were done before this, also shed some light on this question. He was able to observe the transitions to the 2^+ state in the singles spectrum for one set of initial levels, but

to show the way in which one can make isotopic assignments for resonances by looking at the low-energy spectra. These low-energy spectra are quite characteristic of the particular product nucleus. When the low-lying levels are well understood, these assignments can be made with a great deal of ease.

Another thing that can be done is to measure the parity of the level. Figure 222 shows the results of an experiment done several years ago by Jackson,⁹ again with sodium iodide. By showing that a particular transition (the 9.15-MeV gamma ray) was present in the spectrum from capture in this resonance but was not observed in the spectra from the others, he was able to show for the first time that the 107-eV resonance in Mo^{95} was p wave. Other evidence showed that this resonance was indeed a p-wave level. He went on to several other cases in this same fashion.

Now in addition to measurements like these, it was possible (even in the days of sodium iodide) to measure the neutron separation energies of several nuclei with greater precision than had been attained before. Figure 223 concerns this type of measurement. Of course, all of these measurements can be run just as well, if not better, with the use of germanium detectors; in many cases germanium can do a

Fig. 222. High-energy gamma-ray spectra of the resonances in Mo. The strong ground-state transition in the spectrum of the 107-eV resonance is evidence of the p-wave character of this resonance.

⁹H. E. Jackson, Phys. Rev. 131, 2153 (1963); Phys. Rev. 134, B931 (1964).

Fig. 223. Gamma radiation from neutron capture in lanthanum. (a) Gamma-ray yield as a function of neutron flight time. (b) Gamma-ray spectrum corresponding to thermal capture. There is negligible decay from the capture state to the 2^- state at 165 keV. (c) Gamma-ray spectrum corresponding to the 72-eV resonance of La^{139} . The strong transitions to the 2^- states at 35 and 165 keV indicate $J^\pi = 3^+$ for this resonance.

lot better. The only difficulty is that the size of the germanium does limit counting rates and forces some of us to use much poorer resolution than we have been used to. In Fig. 223(a) we see an illustration of a rather simple experiment, in a sense. This is total capture in lanthanum — primarily La^{139} , though there is a small contaminant of La^{138} . We are interested in measuring the spin of the 72.3-eV resonance. There is also a resonance at 20.5 eV that was discovered several years ago by Harvey and Slaughter.¹⁰ Figure 223(b) shows the thermal-neutron capture spectrum in La. Quite a few transitions are present. Some go

¹⁰ J. A. Harvey and G. G. Slaughter, Oak Ridge National Laboratory Report ORNL-3924, p. 28 (1965).

to the 2^- states and the rest go to 3^- states or to states of undetermined spin at excitation energies of 35, 64, and 162 keV. Figure 223(c) shows the spectrum at the 72-eV resonance of La. We see very strong transitions from this resonance to the 2^- state, but the strong transitions observed at thermal energies have disappeared. This quite dramatic change in the structure can be taken as a reflection of the fluctuations in the Porter-Thomas distribution. We also know that this particular resonance contributes very little to thermal capture, so we are not surprised at the large differences. However, the strong transitions to the 2^- states enable us to make a spin assignment of 3^+ for this resonance. I think that it is also possible to make an isotopic assignment for the 20-eV resonances of La^{139} on the basis of additional spectra which I will not show here.

We will now proceed to another experiment (Fig. 224) which we have done on tungsten. This is an investigation that almost everyone else has also done. The data in Fig. 224(a) were obtained with natural tungsten targets, but still the 4.14- and 7.62-eV resonances are clearly separated from anything else. We had a little difficulty in separating the 18- and 21-eV resonances, but one can analyze this blob fairly well. At higher energies, analysis gets quite difficult because of the large amount of capture in W^{183} . In Fig. 224(b) we are interested in studying states that proceed to rather simple low-lying configurations specified by the Nilsson orbits and the rotational bands built upon them. I show these spectra largely to provide some comparison between some of the different experiments. Since so many people have measured these, it is convenient to look at them and have a very direct comparison of what one can and cannot do. These spectra were accumulated in about $5\frac{1}{2}$ days. The thermal spectrum shows the kind of pattern Bolotin (paper G-1) discussed for the Hf isotopes, namely greatly enhanced transitions to the $\frac{1}{2}^-$ member of the [510] band and an absence of

Fig. 224. Gamma radiation from neutron capture in tungsten.
 (a) Yield curve for natural W.
 (b) Comparison of resonance spectra for the even-A tungsten targets. Although decay of the $J^\pi = \frac{1}{2}^-$ capture state of W^{183} to the $[512] \frac{3}{2}^-$ final state is negligible at 4.14 eV, it is significant at 21.2 eV.

transitions to the $[512]$ band. But at the 21-eV resonance one begins to see the transition to the $[512]$ band. There is also a very strong transition to the state at about 57 keV in W^{183} . The strengths of these transitions change dramatically between thermal energies and these resonances.

Let me close now by returning to the Porter-Thomas distribution. We have restudied Pt^{195} and in a later talk (paper I-8)

I will discuss one particular aspect of it. Figure 225 shows the distribution of the partial radiation widths and compares it with the Porter-Thomas distribution. The dashed line is the Porter-Thomas distribution—the χ^2 distribution with one degree of freedom. The histogram summarizes the partial radiation widths of 107 transitions. These transitions were those observed from the 11.9-, 19.6-, and 68-eV resonances. When I say 68 eV, I of course mean the two resonances near 67 eV. They are separated by only a fraction of a microsecond in the flight path in which we are working, so there is no way of separating them in this experiment. When we did this experiment using sodium iodide at a flight path of 25 m, we were able to do a little bit more since the separation then corresponded to something like 0.8 μ sec in flight time. These latter spectra will be shown in my talk (paper I-8) on platinum. These results are included in the histogram; Fig. 225 is the distribution of partial radiation widths for all the levels we have seen in platinum at the 11.9-, 19.6-, and "68-eV" resonances. Because of the Porter-Thomas fluctuations, one needs fairly large samples. We were not able to do the experiment, for instance, that was done at Saclay, where they studied perhaps of the order of 60 partial radiation widths, but selected only the three highest-energy transitions and covered a large number of resonances. We could not do that since our neutron resolution is so limited at the flight path (~ 6.5 m) at which we have been working.

Fig. 225. Distribution of reduced radiative widths ($\gamma = \Gamma_{\gamma}/E^3$) observed for three resonance spectra of Pt^{195} .

I think this points out that one direction which the experiments with choppers will have to go is to concentrate on the low-energy resonances. This is probably obvious, but it is worth while to make the point and to study the spectra in detail to as low an energy as possible. Of course, a great advantage of resonance capture is that it allows observation of transitions from resonances to levels in many cases in which Porter-Thomas fluctuations obscure them in thermal-capture spectra.

* * *

R. E. CHRIEN, Brookhaven National Laboratory: When you compare your results with a χ^2 distribution, as you did in Fig. 225, do you make any correction for possible energy variation of the matrix elements over the wide energy range you looked at?

COTÉ: We assumed an E^3 dependence and divided that factor out. This is a very unsophisticated comparison, but it was all we did.

CHRIEN: Do you think there is any residual energy factor that would not be removed in this way? Do you think the matrix elements may be energy dependent?

COTÉ: I do not have the slightest idea; but if there is a residual effect, it certainly does not show up here.

CHRIEN: It would result in an increased broadening of the distribution.

COTÉ: There is no such broadening in our data.

CHRIEN: Was that $5\frac{1}{2}$ days running time gross or net?

COTÉ: The two figures are about the same in this case.

J. A. HARVEY, Oak Ridge National Laboratory: In your last figure (Fig. 225), did you make any selection based on the final states?

COTÉ: We just took all that we saw.

HARVEY: If these low-lying states were quite similar, one might expect deviations from a Porter-Thomas distribution since this distribution assumes complicated states. This might be a technique for looking for a correlation between the low-lying states.

COTÉ: That is true and we plan to do it later. However, this comparison was made only because we had the data and thought it would be interesting to show. It was not the primary reason for doing the experiment.

1-2. RESONANCE-NEUTRON CAPTURE GAMMA-RAY STUDIES AT THE MTR*

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The development of lithium-drifted germanium gamma-ray detectors of moderately large volume has prompted a program of investigation of resonance neutron-capture gamma-ray spectra at the Materials Testing Reactor (MTR). Heretofore, this field of study has been largely neglected at the MTR—primarily because of a limited staff and our more direct concern with the needs of the Division of Reactor Development of the A. E. C. However, the greatly improved resolution attainable with germanium detectors, as compared with sodium iodide detectors, may make possible experiments more in accord with our "charter" so it was desirable to become familiar with the properties and use of these devices.

A simple facility was designed to provide a beam of monochromatic resonance-energy neutrons for use in capture gamma-ray studies. The primary consideration in the design was the elimination or reduction of both gamma-ray and fast-neutron backgrounds. A shortage of funds made simplicity desirable. Since some previous experience with other beam holes at the MTR indicated fairly high levels of both these kinds of backgrounds, the new facility was planned for use with the only large through hole in the reactor, one end of which was available on a part-time basis. A brief description of the geometry of this particular beam hole (HT-1 South) should explain this choice. HT-1 is a $4\frac{11}{32}$ -in. -square hole passing through the reactor tank very near one edge of the rectangular fuel-rod array. The maximum neutron flux in this hole is approximately 1×10^{14} per cm^2 -sec when the reactor

* Work performed under the auspices of the U. S. Atomic Energy Commission.

is at a 40-MW power level. The north end of this hole contains a velocity selector used in inelastic-scattering studies. The source¹ of neutrons for this device, which also constitutes a source for the south end of HT-1, is a 2-in. -thick sample of water situated in the hole near the east-west center line of the reactor. This source produces an external beam of neutrons by scattering; hence, the beam is relatively freer of gamma rays and fast neutrons than are those from the other beam holes in the reactor which look directly at fuel. This fact makes this beam hole far superior to any other in the reactor for gamma-ray studies.

The neutron monochromator used in conjunction with the HT-1 beam hole consists of a beryllium single crystal surrounded by a considerable quantity of shielding. Bragg diffraction from the crystal produces a gamma-ray-free beam of neutrons with energy variable from about 0.005 eV to perhaps 20 eV. Gold foil activations indicate a flux of over 7×10^8 neutrons per cm^2 -sec incident on the crystal which is situated approximately 19 ft from the east-west center line of the reactor. The cadmium ratio obtained for gold was 3.7 for this beam. Similar measurements at the crystal position of the MTR crystal spectrometer, whose beam hole (HB-4) looks directly at fuel, indicates a flux of 7.8×10^8 neutrons per cm^2 -sec and a cadmium ratio of 4.7. Thus, although the HT-1 beam appears to have slightly fewer thermal neutrons than HB-4, it probably has an enhanced $1/E$ flux (i. e., measurements in Ref. 1 indicate a reduced fast-neutron flux from HT-1).

Figure 226 shows the monochromator shielding and experimental arrangement schematically. The beryllium crystal is mounted on a motor-driven goniometer. Surrounding the crystal are 2 in. of borated polyethylene, 4 in. of lead, and 2 ft of borated paraffin. The paraffin was poured a few inches at a time into a welded aluminum vessel containing appropriate ports for the incident beam and Bragg

¹R. M. Brugger, Nucl. Instr. Methods 32, 303 (1965).

Fig. 226. The neutron monochromator and experimental arrangement.

beam. The entire shielding (except the lid) rests on a 6-ft-diameter motor-driven milling table. Bragg diffraction conditions may be set up by choosing the milling-table position (arm angle) for the desired neutron energy and then "rocking in" the desired planes by driving the crystal table. "Roll" and "tilt" changes must be made manually with the goniometer. The milling-table angle may be read to 1 min of arc by means of a vernier. Crystal positions are displayed electronically to 0.1° by means of a commercially available angle indicator. No 2:1 gearing for maintaining the Bragg relationship was provided. Since the resonance-capture experiments require very long running times at each energy, it was felt that 2:1 gearing was not essential although it certainly is desirable for locating the resonances by transmission measurements.

In all the experiments done thus far, a 2-min-divergence Soller-slit collimator in the Bragg beam has been used. The incident beam is defined to a $\frac{3}{4}$ -in. $\times$ 1-in. area in the beam-hole plug. Thus the neutron resolution of the system in the resonance region is determined primarily by the 6-min mosaic of the beryllium crystal and the plane

spacing. Figure 227 indicates the approximate width at half height of the resolution function (bars below the curve) compared with the low-energy tungsten resonances given by the cross-section data in BNL-325. The bars at 19 eV correspond to the beryllium ($10\bar{1}3$) planes; the rest correspond to the ($10\bar{1}1$) planes.

The primary

advantages of using resonance neutrons in capture gamma-ray studies are twofold: first, isotopic assignments of gamma rays may be made in many cases with targets of natural isotopic abundance; second, since the compound system is formed in a state of specific angular momentum, more information may be obtained concerning spins of resonances in some cases, or spins of lower excited levels although coincidence measurements may be required in these determinations. Figure 228 gives a simple example of each of these advantages. The top and center portions of this figure show the high-energy capture gamma rays from the 7.6-eV resonance in W^{183} . A natural tungsten target was used. Since thermal capture in a natural target takes place primarily in W^{182} and W^{186} with a small contribution from W^{183} , enriched isotopes would be required to assign gamma rays to a specific isotope. Since the possible spins for the compound state are 0^- and 1^- , the observation of the 7413-keV transition to the 0^+ ground state of W^{184} assures that the 7.6-eV resonance is 1^- . This was pointed out a number of years ago from NaI spectra by Bollinger *et al.*² A slightly

Fig. 227. Low-energy neutron cross section of tungsten, showing monochromator resolution.

²L. M. Bollinger, R. E. Coté, R. T. Carpenter, and J. P. Marion, Phys. Rev. 132, 1640 (1963).

Fig. 228. High-energy W^{184} gamma-ray spectrum from resonant capture in W^{183} . Top and center: capture in the 7.6-eV resonance. Bottom: capture in the resonance at $E_n = 4.1 \text{ eV}$.

more complicated example of a spin determination will be pointed out in a later paper (paper I-10) by Ken Faler.

It might be of interest to mention some of the major problems which limit the productivity of this facility. Foremost among these is the limited memory and versatility of the pulse-height analyzer. The use of only 1024 channels has forced studies of only the high-energy portion of the gamma-ray spectrum since this yields information about the final states more directly. Another problem is detector size. The present detector is only 2 cm³ active volume. No completely satisfactory detector of much larger volume has been available, although this situation may be corrected in the near future. Of lesser importance is the fact that the beam hole is presently being shared with another experiment, thus increasing set-up time and decreasing running time. The difficulty of obtaining reasonable quantities of Li⁶-loaded shielding which can be easily shaped to our experimental geometry is disconcerting. As detector size increases it is going to become more important to soak up unused and background neutrons without subsequent gamma-ray emission. The limited neutron energy range of this device prohibits any serious study of gamma-ray partial-width fluctuations from resonance to resonance.

Experiments in the immediate future will involve targets of even Z and odd N. Emphasis will be placed on some nuclei for which spin determinations may be possible. Eventually it is hoped that studies of capture gamma rays in resonances of some fissionable nuclei might be carried out.

* * *

E. B. SHERA, Los Alamos Scientific Laboratory: How large a flux did you have for the 7-eV resonance in tungsten?

SPENCER: I'm sorry, but I can't even make an estimate.

R. K. SMITHER, Argonne National Laboratory: Do you have to cool the water scatterer in the reactor?

SPENCER: Yes. The beam plug extends approximately to the reactor tank and the hole continues on through the tank. They just extended the cooling pipes for the plug on into the center of this beam hole and put a can on the end. So cooling water (ordinary light water) flows continuously through it.

G. E. THOMAS, Argonne National Laboratory: I would like to ask a couple of questions. (1) What was the nature of your background problems? (2) Did you have any difficulties with having the lead cast in the aluminum; and just how satisfactory do you consider it to be?

SPENCER: First, the background problems. As you have seen, our gamma-ray spectra ran only from 4 to perhaps 7.5 MeV. Purely on the basis of what we see in this region, we do not find the scattered room background to be a real problem—even with the beam door open. After all, the detector is almost completely surrounded by 12 in. or so of lead. The room background that penetrates this is only something like a quarter of our background. Most of our background appears to be associated with the Bragg beam itself—e. g. , from capture of low-energy neutrons scattered from the target itself, or from the $\text{Be}(\gamma, n)$ reaction giving fast neutrons coming down the Bragg beam. A few gamma rays are bound to come down the Bragg beam. A combination of these possibilities makes up most of our background.

So far as particular lines in the background are concerned, we have put a carbon scatterer in the Bragg beam and looked again at the spectra in the same region. We always see some iron lines and a high-energy peak from lead at approximately 7.4 MeV. Some of the background turns out to be very useful. Although we put some shielding around the pipes where the cooling water from the plug comes out on the

face of the reactor, the water is activated and we get a strong O^{16} gamma ray at 6128 keV, which we use for an energy calibration. We do not have to worry much about background until we get up to a very high neutron energy or unless we do not have much signal.

In the study of the 7.6-eV resonance, the room background may contribute 4 counts/min to a total background (including the Bragg beam) of possibly 15 counts/min. The signal might be 80 counts/min in this particular region.

The lead shielding was machined and drilled and tapped. We just lifted it on the hoist and dropped it in place around the crystal.

THOMAS: Did you see the aluminum lines?

SPENCER: We have not looked. The one above 7 MeV is a little outside of the range in which we have been operating. The lower ones are weak and we have not seen any of them.

M. BEER, State University of New York at Stony Brook and Brookhaven National Laboratory: I noticed a line that appeared in both the 4- and the 18-eV resonances. Does this mean that the tail of the 18-eV is seen in the 4-eV resonance?

SPENCER: Yes. The 18-eV resonance is extremely strong. It is a big resonance and very broad, and we do indeed apparently see a little bit of the tail. As you can see in Fig. 227, the energy spread in the beam from the neutron monochromator pretty well covers the 4.1-eV resonance. Thus one would certainly expect some capture in nearby resonances. I think the 18-eV resonance is contributing to the 4-eV data (Fig. 228, bottom spectrum).

BEER: I think we can identify a gamma ray in W^{183} at just that place in the 4-eV resonance.

W. R. KANE, Brookhaven National Laboratory: It is interesting to compare your results on the 7-eV resonance in tungsten with those obtained from a well-designed time-of-flight facility—specifically the

fast chopper at Brookhaven. Of course your device is a single-channel one, whereas the chopper gets data at all energies at once. In both experiments, the runs for the 7-eV resonance lasted 3—4 days each. The Idaho flux is about 10^{14} neutrons $\text{cm}^{-2} \text{sec}^{-1}$ and the Brookhaven flux is about 10^{15} . The detector volume was 2 cm^3 in Idaho, 4 cm^3 at Brookhaven. For the same running time, the Idaho peak heights were about twice the Brookhaven ones. Thus if one is interested in investigating the properties of one particular resonance at this energy, then the Bragg-diffraction method is about 40 times as efficient as the time-of-flight method.

SPENCER: One reason for doing this experiment was to see if we do indeed have sufficient intensity to do coincidence experiments in the region of low neutron energies where one is willing to measure at one energy at a time. Certainly we will never come close to competing with the chopper in the study of many resonances.

X
1-3. THE BNL FAST-CHOPPER FACILITY AT HFBR^{*}

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A fast chopper specifically designed for studies of γ rays following neutron capture in resonances has been in operation at the HFBR reactor at BNL since June 1966. This report summarizes its characteristics and describes operating features of this instrument.

Although much effort has been directed toward a study of (n, γ) reactions induced by thermal neutrons, relatively little effort has been put into resonance-capture experiments. Practical considerations such as available intensity have limited this effort. It is clear, however, that resonance-capture experiments possess several clear advantages over thermal capture which compensate for the low flux of a chopped beam. Some of the obvious advantages are these:

- (1) The possibility of observation of several distinct capturing states yielding transitions to the same final state.
- (2) The possibility of observation of spectra free from contamination by unwanted isotopes without the use of monoisotopic samples.
- (3) The observation of reactions induced by $\ell=1$ neutrons.
- (4) The freedom to study the mechanism of the (n, γ) reaction by a study of systematic properties of the capturing states, including interference effects between resonances.
- (5) The use of a pulsed beam to reject fast-neutron and γ -ray background by timing considerations.

It seems then that the time-of-flight studies can play a complementary role to thermal capture in the determination of level

*This work was supported by the U. S. Atomic Energy Commission.

TABLE XXXV. Parameters of the BNL fast chopper at the High Flux Beam Reactor.

H-2 beam tube at the HFBR	
ϕ_{th}	$= 7 \times 10^{14} \text{ n/sec/cm}^2$
ϕ_{ep1}	$= 2.9 \times 10^{13} \text{ n/sec/cm}^2 \text{ per ln E interval}$
$\phi_{fission}$	$= 4.6 \times 10^{13} \text{ n/sec/cm}^2$
Chopped-beam flux at sample	$= \begin{cases} 8 \times 10^3 \text{ n/sec/cm}^2 \text{ per ln E interval} \\ \times \text{transmission function} \end{cases}$
Burst width	$= 5.0 \text{ } \mu\text{sec at 15 000 rpm with 0.1 in. slit pkg.}$
Repetition rate	$= 1000/\text{sec at 15 000 rpm}$
Flight path	$= 22 \text{ m}$

schemes and, in addition, provide information on the nature of the states just above the neutron separation energy.

The HFBR fast chopper has been designed for the purpose of observing neutron-capture γ rays in resonances in the lower range of epithermal neutron energies. The basic aim of the design has been the production of a high-intensity chopped beam of narrow divergence.

The building of the High Flux Beam Reactor at BNL has made such a facility feasible. At HFBR beam H-2, the radial beam tube provides an intense epithermal beam. Table XXXV lists the parameters of this beam hole. Of particular importance is the available epithermal $(1/E)$ flux of $2.9 \times 10^{13} \text{ n/cm}^2/\text{sec per ln E interval}$ at the thimble tip, and the fission flux of $4.6 \times 10^{13} \text{ n/cm}^2/\text{sec}$. Figure 229 shows the layout of the equipment at the pile face. A rather novel in-pile collimator is used, consisting of 112 rectangular holes, each $0.1 \text{ in.} \times 0.12 \text{ in.} \times 36 \text{ in.}$ long, arranged in a $2 \text{ in.} \times 2 \text{ in.}$ array. The severe collimation in both vertical and horizontal directions limits the beam size to about 3 in. FWHM at 22 m, of which 2 in. is due to the separation of the extreme slits of the collimator. The relatively narrow beam allows the use of samples of as little as 10 g of material.

Fig. 229. Assembly of the fast chopper at beam H-2 of the Brookhaven High Flux Beam Reactor (HFBR).

Figure 230 shows the fast-chopper rotor. The rotor contains four nickel slit packages, separated by pie-shaped sintered tungsten pieces, and sandwiched between forgings of maraging steel.* The total weight is nearly 700 lb of which 200 lb is due to the tungsten pies, which provide excellent shielding between beam bursts. At a rotational speed of 15 000 rpm the slit packages, each consisting of eight slits 0.1 in. wide and 2 in. long, produce bursts 5 μ sec long at a rate of 1000 pulses/sec. The chopped-beam intensity at the sample position has been measured by a U^{235} fission counter and a He^3 detector and is approximately 8×10^3 n/cm²/sec per ln E interval, at 40 MW reactor power.

*A maraging steel is a low-carbon high-nickel alloy steel with exceptionally high strength and toughness.

Fig. 230. Rotor of the fast chopper.

Fig. 231. Comparison between the measured (points) and calculated (solid line) transmission function of the fast-chopper rotor. The time of flight increases toward the right.

Fig. 232. Layout of the detector station, showing the sample position and the detector cryostat.

Figure 231 shows the measured and calculated transmission function, which is nearly linearly decreasing with time-of-flight. The rotor position is stable dynamically to about ± 0.002 in. in operation. Data have been recorded at rotor speeds from 1000 to 12 000 rpm, covering the range from thermal energies to several hundred eV.

Capture γ rays are detected at the end of a 22-m evacuated pipe by use of Ge(Li) detectors of 4, 10, and 30 cm³ volume. Data are encoded into 11 bits of pulse-height information and 10 bits of flight time, buffered in an SDS-910 computer, and written on tape. Details are given in an accompanying paper (paper C-5).

Operating experience has shown that excellent spectra with low backgrounds are obtainable at flight times greater than 150 μ sec, which correspond to neutron energies below 100 eV. No shielding is used except for $\frac{1}{8}$ in. of metallic Li⁶ between the detector and the sample. Figure 232 shows the sample position and detector cryostat. With the

Fig. 233. Oscilloscope showing discrete events in the burst observed at 10 000 rpm.

chopper there is no flash pulse at $t = 0$; instead discrete events are observable as shown in Fig. 233, taken at 10 000 rpm. The background has been studied as a function of the time of flight, and Fig. 234 shows a plot of all

events in excess of 0.46 MeV deposited in the crystal versus flight time, with and without a thick (3-in.) carbon scatterer in the beam. A resonance in Ge is clearly visible. Most of the beam-dependent background arises from the fast-neutron burst at $t = 0$, which is responsible for a level of 50 rem/hr at the sample position. Figure 235 shows the smoothed background spectrum for flight times greater than 150 μsec , with and without the carbon scatterer. The vertical scale is in counts/min per μsec time channel per 4-keV pulse-height channel. A careful examination of the plot will show that in most experiments background is completely negligible in the region $E_\gamma \geq 1 \text{ MeV}$. Figures 236 and 237 display the peak position and line width of a precision pulser as a function of time-of-flight for single RC clipping and 1 μsec rise and fall times,

Fig. 234. Plot of all background events for which more than 0.46 MeV was deposited in the absorber. The solid curve is the open-beam counting rate per 1- μsec interval in time of flight. The dashed curve shows the corresponding background with a 3-in.-thick carbon scatterer in the beam. The time of flight increases toward the right.

Fig. 235. Smoothed background spectra for flight times greater than 150 μsec with (dashed curve) and without (solid curve) the carbon scatterer.

and a thick scatterer in the sample position. Double differentiation is generally used for these thick samples and leads to no appreciable shifts or broadening below 200 eV.

Figure 238 shows a typical spectrum obtained with this facility with a 192-g sample of Tm. The running time was 72 hours. The significance of this spectrum will be discussed in detail in paper I-5 at this conference. Such spectra have been obtained with the 10-cc detector placed 19.2 cm from the median position of the sample, a solid angle $d\Omega/4\pi = 0.065\%$, and an intrinsic efficiency of 0.67% in the double-escape peak, leading to an

Fig. 236. Peak position vs flight time for a precision pulser. The curves were obtained with single RC clipping, $\tau_{\text{rise}} = \tau_{\text{fall}} = 1 \mu\text{sec}$, and a thick scatterer in the sample position. Two pulse amplitudes are shown.

Fig. 237. Line width vs flight time for a precision pulser. This curve was obtained under the conditions indicated in Fig. 236.

Fig. 238. Typical spectrum obtained with this facility. The sample was 192 g of Tm_2O_3 ; the running time was 72 h.

over-all efficiency of 4.4×10^{-6} . The over-all efficiency can be made much higher for most samples.

A comparison of this facility with a Linac time-of-flight experiment recently performed at Saclay shows an intensity factor of from 30 to 40 in favor of the chopper, but a resolution figure some 50 times worse. It would seem probable that the HFBR chopper would be most prudently used in investigations below 100 eV where its high intensity and low backgrounds make it a very useful instrument. It is expected that a proposed flight-path extension to 45 m will extend its useful neutron energy range to several hundred electron volts.

We wish to acknowledge the contributions of Hobart Kraner and Marco Jamini of the Instrumentation Division, Brookhaven National Laboratory, for the manufacture of the detectors used in these experiments.

* * *

L. M. BOLLINGER, Argonne National Laboratory: I noticed that in addition to the usual vertical collimator slits you had diaphragms with horizontal slits. This is a new departure in choppers. Would you explain why you have these?

CHRIEN: The idea was simply to confine the beam to about a 3-in. spot at the detector position. The diameter of the sample is rarely larger than this, so any beam outside this area is not useful in producing gamma rays at the sample position. Since we do not need this outer part of the beam, we get rid of it in-pile rather than outside where it can produce background.

I may add that no beam stop is used. The beam is allowed to emerge from the reactor building through a blind duct extending 5 ft out beyond the wall. This is about 20—30 ft off the ground so the neutrons are allowed to diffuse out into the atmosphere. This avoids the back-scatter problem.

BOLLINGER: I should also like to ask why you have made the burst width as wide as 5 μ sec.

CHRIEN: We do it to get intensity, which is proportional to the square of the burst width. This instrument has a duty cycle of 1 part in 200. We have given up neutron resolution in order to gain neutron intensity.

BOLLINGER: One last question: In your plot of the transmission function for the open beam (Fig. 231) I noticed that the data points end somewhat above zero intensity, and the curve you drew showed a rather sharp decline to zero intensity. Are you in fact as free of a tail on the cutoff function as this curve indicates?

CHRIEN: There is a tail, but it is too small to be observable. Of course, we would not be able to see a small tail because the burst of fast neutrons makes it difficult for us to take measurements at flight times lower than 100 μ sec.

H. M. MANN, Argonne National Laboratory: Would you discuss the value of larger detector volumes in experiments such as these?

CHRIEN: The quality of the experimental data from the 30-cc detector certainly is not three times as good as that from the 10-cc

detector. The complexity introduced by using a 30-cc detector partly counteracts the advantage of higher counting rate. In other words, with the larger detector you have many significant single-escape and full-energy peaks in the spectrum—and the additional problem of resolving these peaks and separating them from the double-escape peaks you are interested in looking at. You have to know the intensity ratios between these peaks very accurately. I am not convinced that a small detector would not ultimately be a better choice for most experiments.

✓
14.0 RESONANCE (n, γ) SPECTRA IN TUNGSTEN ISOTOPES*

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We have observed γ rays from resonance-energy neutron capture in the tungsten isotopes. Gamma-ray events due to neutrons incident on a 30-mil-thick natural tungsten target were observed with 4- and 10-cc Ge(Li) detectors and were sorted according to their neutron time-of-flight[‡] and their γ -ray pulse heights. Work is continuing with W^{182} , W^{184} , and W^{186} separated-isotope targets and a 30-cc detector.

Figure 239 shows the number of high-energy γ -ray counts per time-of-flight channel for the natural tungsten target. The upper and lower spectra are taken at chopper speeds of 10 000 and 6000 rpm, respectively. The difference in resolution of the two graphs is especially noticeable in the higher energy region. The 4.14-eV W^{182} resonance and the 7.65-, 27.1-, and 66.0-eV W^{183} resonances are quite well resolved. The strongly scattering 18.8-eV W^{186} resonance and the 21.2-eV W^{182} resonance are not well separated, but this does not cause a serious deterioration in the information to be gained from either resonance. The small 41-eV resonance and those at 46.1 and 47.8 eV are not well resolved in the 6000-rpm run but useful information about them may, nevertheless, be obtained. Again, the W^{183} 101-eV and the W^{182} 114-eV resonances appear together. In the next peak are seen the W^{186} 175-eV, the W^{184} 185-eV, and some W^{183} resonances. On the lower graph are shown the various neutron-energy scan gates used to determine the γ -ray pulse-height spectra.

* This work was supported by the U. S. Atomic Energy Commission.

[†] Guest Research Associate from the State University of New York at Stony Brook, Stony Brook, New York.

[‡] A 22-m flight path was used.

Fig. 239. High-energy γ -ray yield vs time of flight for a natural tungsten target. Upper spectrum: $1.8 < E_\gamma < 7.2 \text{ MeV}$, rotor speed = 10 000 rpm. Lower spectrum: $2.3 < E_\gamma < 7.7 \text{ MeV}$, rotor speed = 6000 rpm. The scan limits shown on the lower graph are the neutron-energy gates used to determine the γ -ray pulse-height spectra.

Figure 240 shows pulse-height spectra from capture in the 4-, 21-, and 114-eV resonances of W^{182} target nuclei. These spectra and those in the following figures were taken with the use of the 4-cc detector* and a natural W target with a 62-hour running time. Starting

* Detector resolution width is 10 keV FWHM at 6.193 MeV under actual running conditions.

Fig. 240. Gamma-ray pulse-height spectra from resonance capture in natural tungsten. Upper spectrum: capture in the 114-eV resonance of W^{182} . Middle spectrum: capture in the 21-eV resonance of W^{182} . Lower spectrum: capture in the 4-eV resonance of W^{182} . The numbers on the peaks correspond to those in Tables XXXVI–XXXVIII.

at the upper energy end it is seen that the 6.193-MeV transition to the ground state $\frac{1}{2}-[510]$ (line 7) occurs strongly in all three resonances. On the other hand, the transition to the 46-keV $\frac{3}{2}-[510]$ first excited state (line 8) appears only weakly in the 114-eV resonance. A transition to the 209-keV $\frac{3}{2}-[512]$ state (line 11) appears weakly in the 4-eV resonance, is of medium strength in the 21-eV resonance, and is very strong in the 114-eV resonance. A 5.254-MeV transition to the 939-keV level (line 28) seen in (d,p) work¹ is also found. Confirmation that this is not the 5.264-MeV γ ray of the W^{186} 19-eV resonance tail was gained by scanning the region between the 4- and 19-eV resonances and noting that the sought-after transition did not occur. Furthermore, a spectrum of the 4-eV resonance taken with a W^{182} target of 94.4% isotopic purity displayed the same line. It will be observed that the strong transition to the 1.030-MeV level occurring in the 4-eV resonance is seen only weakly in the other two. Generally, a large intensity variation from one resonance to another seems to occur.

Turning to W^{186} resonances, Fig. 241 shows the 19- and 175-eV scans. The 5.469-MeV transition to the $\frac{3}{2}-[512]$ state (line 20) appears weakly in both. The peak appearing at channel 1200.8 in the upper scan is really the transition to the ground state of W^{185} , some 5.754 MeV below its binding energy. This peak was seen very clearly in a W^{184} sample of isotopic purity 94.3%. It should be noted that this γ -ray capture in the W^{184} 184-eV resonance is strong enough to fully account for its appearance in thermal capture. It does not appear in any of the W^{182} resonances, and it is, therefore, difficult to see how it can be attributed to capture in W^{182} as asserted by Treado and Chagnon.²

¹J. R. Erskine, Phys. Rev. 138, B66 (1965).

²P. A. Treado, P. R. Chagnon, Nucl. Phys. 34, 623 (1962). Also see Ref. 4.

Fig. 241. Gamma-ray pulse-height spectra from resonance capture in natural tungsten. Upper spectrum: capture in the 175-eV resonance of W^{186} . Lower spectrum: capture in the 19-eV resonance of W^{186} . The peak numbers are as in the tables.

Figure 242 shows the W^{183} and W^{187} energy-level diagrams given by this work and in the (d,p) work by Erskine.¹ It will be noted that at energies below 0.8—1.0 MeV, one usually finds (n, γ) levels coinciding with those found in (d,p) work. This is not true, generally, at higher excitations. Nevertheless, where the two methods show the same level, one may conclude that a primary transition occurs in neutron

Fig. 242. Energy-level diagrams of W^{183} and W^{187} . The (d,p) results are those of Erskine, Ref. 1.

TABLE XXXVI. Energy levels of W^{183} and indications of transition strengths in resonances of the $W^{182}(n,\gamma)$ reaction.

Peak	Channel	E_γ	Excitation	Close-by ^a	Appearance in resonance ^b		
No.	No.	(MeV)	energy (MeV)	(d,p) level (MeV)	4.14-eV	21.2-eV	114.4-eV
7	1316.8	6.193	0	0	S	S	S
8	1304.8	6.147	0.046	0.046	S	S	W
11	1263.0	5.984	0.209	0.209	W	S	S
28	1074.0	5.254	0.939	0.939	W		W
30	1050.2	5.163	1.030		S	W	W
41	977	4.882	1.311		W		
46	943.5	4.753	1.440	1.437	W	W	
53	912	4.632	1.561	1.558	W	W	S
53a	906	4.609	1.584		W	W	S
58a	898	4.578	1.615		W		W
60	893.7	4.560	1.633	1.636	W		
61	882.7	4.518	1.675		S	S	S
62a	876	4.492	1.701	1.689?	W		
64	868	4.477	1.716		W		W
66	860	4.446	1.747	1.743	W		
69	843.2	4.366	1.827	1.820	W		
77	827.0	4.303	1.890	1.893	S	S	S
81	811.8	4.245	1.948	1.942	S	W	
88	772.0	4.092	2.101	2.092?	W		W
92	764.3	4.062	2.131	2.130	W		
95	754.5	4.025	2.168		S	S	S
98	737	3.957	2.236	2.226?	W		
105	713.0	3.865	2.328	2.330	S	W	
110	703	3.827	2.366		S	S	
111	695.8	3.799	2.394		S	W	S
116a	689	3.773	2.420	2.412	W		
116	686	3.761	2.432		S	W	W
117	678	3.731	2.462		W		
120	672.3	3.709	2.484		S		W
126	636.0	3.569	2.624		S		

^aReference 2. A question mark after a number in this column indicates the question: Do (n, γ) and (d,p) refer to the same level?

^bS indicates strong, W weak, N none. Blank space indicates lack of information.

capture. Tables XXXVI and XXXVII give the energies of the transitions in W^{182} and W^{186} , respectively, as seen in this work.

TABLE XXXVII. Energy levels of W^{187} excited at the 18.8-eV resonance of the $W^{186}(n,\gamma)$ reaction.

Peak No.	Channel No.	E_γ (MeV)	Excitation energy (MeV)	Close-by ^a (d,p) level (MeV)
20	1129	5.469	0	0
25	1091.3	5.324	0.145	
28	1075.8	5.264	0.205	0.205
49	925.8	4.684	0.785	0.782
53	917	4.652	0.817	0.813
54	910.7	4.625	0.844	0.844
55	903.6	4.599	0.870	
58	897.0	4.572	0.897	0.889?
59	893	4.557	0.912	0.974
62	874.0	4.484	0.985	0.992
65	864	4.446	1.023	
65a	855.3	4.413	1.056	
67	847.3	4.382	1.087	1.087
74	834.0	4.331	1.138	1.145
80	812.7	4.249	1.220	
83	800	4.200	1.269	1.266
84	788.8	4.157	1.312	1.316
87	779	4.119	1.350	1.349
91	767	4.073	1.396	
93	761	4.050	1.419	1.416
99	738.5	3.963	1.506	
102	727	3.919	1.550	
103	722	3.900	1.569	
109	708.5	3.848	1.621	
112	690	3.777	1.692	
113	687	3.765	1.704	
118	680	3.738	1.731	
119	672	3.708	1.761	1.755

^aReference 2. The question mark after the 0.889-MeV level indicates the question: Do (n, γ) and (d,p) refer to the same level?

In Fig. 243 (left) we see the pulse-height spectra for the $W^{183} J=1^-$ resonances at 7, 27, and 66 eV. The binding energy is given by line 2 as 7.414 MeV. The large number of peaks seen is very striking. Capture in W^{183} accounts for 65 of some 130 γ -ray peaks seen with energy >3.5 MeV. Large intensity variations occur from resonance to resonance. Thus, of 47 peaks below 2.8 MeV excitation, only 27

were identified in the 7-eV resonance. (Spencer and Faler³ identified 20 of those in this resonance.) An example of this is the doublet at 6.284 and 6.293 MeV seen in the 66- and 27-eV resonances. Only the latter peak shows up in the 7-eV resonance (line 6). The importance of having several resonances available for γ -ray energy identification is clearly indicated.

Figure 243 (right) shows 3 scans, the two lowest both containing the 46.0-eV $J=1^-$ and the 47.8-eV $J=0^-$ W^{183} resonances. The upper one involves the 101-eV $J=0^-$ resonance. The 48.8—54.6-eV scan contains a relatively larger proportion of the 47.8-eV resonance relative to the 46.0-eV one than does the 41.2—48.0-eV scan. (The latter scan also has a contribution from the 40.6-eV resonance which is small.)

The predominant E1 transition mode allows γ rays from a 1^- resonance to 0^+ , 1^+ , 2^+ final states; but only 1^+ final states may be reached from a 0^- resonance. On the other hand, only even-spin states (i.e., 0^+ , 2^+ , etc.) are expected at low excitation in even-even deformed nuclei. Therefore, 0^- resonances should contain very few γ rays to low-lying states. This is clearly indicated in the 101-eV resonance, for which the seven highest-energy γ rays (those with final states below 1.670 MeV) do not appear. It is concluded that this resonance has 0 spin, contrary to some experiments which measure the g factor by area analysis of the transmission, scattering, and capture of neutrons.⁴ The 47.8-eV resonance too has spin 0^- . The latter statement is based on the constant relative intensities of the uppermost γ rays in the 48.8—54.6-eV scan vis-à-vis the 41.2—48.0-eV scan. Lower-energy γ rays often show marked changes between the two scans. An

³ R. R. Spencer and Kenneth T. Faler (preprint: Neutron Capture Gamma-Ray Studies in Isotopes of Tungsten).

⁴ Nuclear Data, Sec. 6, No. 1 (1966).

Fig. 243. Gamma-ray pulse-height spectra from resonance capture in W^{183} in a natural tungsten target. Left page: capture in the $J=1^-$ resonances at 66 eV (top), 27 eV (center), and 7 eV (bottom). Right page: three scans over the indicated ranges of neutron energy.

The upper spectrum involves the $J=0^-$ resonance at 101 eV, the two lower spectra are from capture in the $J=1^-$ resonance at 46.0 eV and the $J=0^-$ resonance at 47.8 eV. The bottom spectrum includes a small contribution from the 40.6-eV resonance.

Fig. 244. Energy levels excited in the $W^{183}(n, \gamma)W^{184}$ reaction.

example is line 25 at 2.102 MeV excitation which is smaller, relative to line 24, in the 41.2—48.0-eV scan than in the 48.9—54.6-eV scan—an indication that it belongs to the 47.8-eV resonance. It, therefore, has a final-state spin 1^+ . Similarly, as shown in Fig. 244, states at 1.715, 2.426, * 2.511, 2.536, 2.558, and 2.633 MeV have spin 1^+ by the above method or by their appearance in the 101-eV resonance. Energy levels in W^{184} are given in Table XXXVIII. The variation in transition strength in going from resonance to resonance is also indicated there.

In conclusion, one may summarize this paper as follows:

- (1) The use of several resonances in the determination of energy-level assignments often significantly increases the number of levels found. This is especially evident in $W^{183} + n$.

* Not shown in Fig. 244.

TABLE XXXVIII. Energy levels of W^{184} and indications of transition strengths in the listed resonances of the $W^{184}(n,\gamma)$ reaction. The 47 transitions listed here are those with $E_\gamma > 4.590$ MeV. An additional 18 had $E_\gamma > 3.5$ MeV.

Peak No.	Channel No.	E_γ (MeV)	Excitation energy (MeV)	Appearance in resonance ^a						
				7.65-eV	27.1-eV	46.1-eV	47.8-eV	66.0-eV	101-eV	145—218-eV
2	1633.4	7.414	0	S	W	S		S	N	W
3	1604.7	7.304	0.110	W	S	S		S	N	S
4	1399.6	6.512	0.902	W	S			W	N	N
5	1373.6	6.412	1.002	S	S	S		S	N	W
6	1342.8	6.293	1.121	S	W	W		S	N	W
6a	1340.5	6.284	1.130	N	W	N		S	N	
9	1305.8	6.151	1.263	N	W	N		S	N	
10a	1291	6.094	1.320	N	W					W
10	1274.2	6.027	1.387	S	S	W				
11a	1262.5	5.982	1.432	W				W		S
12	1245	5.915	1.499	W	W					
13	1214.5	5.798	1.616	W	S	S			W	
14	1211.8	5.787	1.626	W	S	W			W	
15	1200.3	5.743	1.671	W	N					
16	1188.8	5.699	1.715	N	W			W	S	
17	1172.8	5.638	1.776	S	W	W				
18	1165.3	5.609	1.805	W	N					
19	1145.7	5.534	1.880	N	W					
21	1126.9	5.461	1.953	W	N	W				
22	1111.2	5.401	2.013	N	W					
23	1106.3	5.382	2.032	N	W	S	W		W	
24	1098.3	5.352	2.041	S	W	S			N	
25a	1091	5.322	2.092	N	W	W				
25	1088.3	5.312	2.102	N	N	W	S			
26	1081.7	5.287	2.127	S	W	N				
29	1070.7	5.242	2.172	S	S	W				
29a	1058	5.193	2.221	N	W				S	
30	1051.2	5.167	2.247	S	W	W			W	
32	1037.5	5.116	2.298	W	S	S				
35	1011.6	5.016	2.398	N	S	S				
36	1004	4.988	2.426						S	
37	1000.5	4.974	2.440		W					
38	992.4	4.941	2.473	W	S					
38a	989	4.928	2.486	W	N					S
39	982.5	4.903	2.511	S	W		W			
40	980	4.893	2.521	S	W					
41	976	4.878	2.536		W			S	S	
42	970.2	4.856	2.558	S	W			S		
45a	950.7	4.781	2.633			W	S	S	S	
45	945	4.759	2.655	W	S					
47	935	4.720	2.694	W	W					
48	928	4.694	2.720		W				W	
50	924	4.679	2.735	W	W		W			
51	918	4.656	2.758	S	S	W				
52	915.5	4.646	2.768	S	S				W	
56	907	4.611	2.803	S	S	W	W	W		
57	902.8	4.597	2.817	N	S					

^aS means strong, W weak, N none. A blank space indicates lack of information due to poor statistics or other reasons.

- (2) Spins of the $W^{183} + n$ resonances are determined as 1^- for the 7-, 27-, 46.0-, and 66-eV levels and 0^- for the 47.8- and 101-eV resonances. Some spins of low-lying states are also shown to be 1^+ .
- (3) In $W^{182} + n$, it is shown that transitions to the 209-keV $\frac{3}{2}-[512]$ Nilsson state exist quite strongly in the 21- and 114-eV resonances, but weakly in the 4-eV level. No inhibiting selection rule seems to be in operation. A transition to the 939-keV level seen in (d,p) work is clearly noticed. Weak transitions occur to the W^{187} ground state ($\frac{3}{2}-[512]$ level) in both the 19- and 175-eV resonances.

* * *

W. V. PRESTWICH, Argonne National Laboratory: Is your first step to subtract the off-resonance background—i. e., to set windows just off the resonance and subtract those contributions from the spectrum.

BEER: We scan on either side of the resonance and find that there is really very little background.

PRESTWICH: I think W^{182} has resonances in the 200-eV region. We could not resolve them from other resonances, but we did set a window on that region. Again we think we see the transition to the $[510]$ band.

BEER: I can't say very much about that right now, but we are now working with separated isotopes and should have some word on that later.

PRESTWICH: We have worked only with a target of natural tungsten, but we do see gamma rays corresponding to transitions to the $[510]$ and to the $[512]$ bands.

BEER: Yes. We will have to look for these.

(71)
C-5. GAMMA-RAY SPECTRA FOLLOWING NEUTRON CAPTURE IN
RESONANCES OF Tm^{169}

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Tm^{169} is an interesting case for resonance-neutron-capture γ -ray studies. Recently R. K. Sheline *et al.*¹ reported an extensive study of $\text{Tm}^{169}(\text{d}, \text{p})\text{Tm}^{170}$ and $\text{Tm}^{169}(\text{n}_{\text{thermal}}, \gamma)\text{Tm}^{170}$ reactions for determining the energy levels of Tm^{170} . $\text{Tm}^{169} + \text{n}$ has quite a few resonances below 100 eV and for several of these the spin assignments are in doubt.² Thus, resonance-capture spectra would be helpful in assigning these spins and checking the level scheme reported by Sheline *et al.*

The present work was done at the fast chopper facility of BNL, reported by R. E. Chrien *et al.* in paper I-3 at this conference.

A sample in the form of 192 g of powdered Tm_2O_3 inside a 3 in. $\times$ 3 in. aluminum container was placed at a distance of 22 m from the chopper. A 10-cm³ Ge(Li) detector with a resolution width of 12 keV at 7.6 MeV was used as γ -ray detector. The data-handling procedures are described by M. R. Bhat *et al.* in paper C-5 at this conference. At 12 000 rpm the neutron energy resolution is sufficient

[†] This work was supported by the U. S. Atomic Energy Commission. The results have now been published [M. Beer, M. A. Lone, R. E. Chrien, O. A. Wasson, M. R. Bhat, and H. R. Muether, *Phys. Rev. Letters* **20**, 340 (1968)].

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¹ R. K. Sheline, C. E. Watson, B. P. Maier, U. Gruber, R. H. Koch, O. W. B. Schult, H. T. Motz, E. T. Journey, G. L. Struble, T. v. Egidy, Th. Elze, and E. Bieber, *Phys. Rev.* **143**, 857 (1966).

² Sigma Center, Brookhaven National Laboratory, Upton, New York 11973.

Fig. 245. Typical time-of-flight spectrum for events above 2.5 MeV.

Fig. 246. The γ -ray spectrum from the 14-eV resonance in the $Tm^{69}(n, \gamma)$ reaction.

to resolve 9 resonances. A typical time-of-flight spectrum is shown in Fig. 245 for events above 2.5 MeV. The background-to-peak ratio is very good, and the weak 29-eV level shows up quite clearly. For this plot the background is 65 counts/channel and is negligible for the analysis.

The observed γ -ray spectrum from the 14-eV resonance is shown in Fig. 246. This is a typical case for $J=0$ resonance as subsequent discussion will show. Figure 247 shows a spectrum from

Fig. 247. The γ -ray spectrum from neutron capture in the $J=1$ resonance at $E_n = 3.9$ eV.

the $J=1$, 3.9-eV resonance. The relative intensities of 49 of the transitions were computed by measuring the areas under the double-escape peaks from the detector. The intensities in a particular resonance were obtained by dividing the area by the total number of γ rays observed in that resonance, above 2.5 MeV energy, and corrected for the energy dependence of the detector.

Figure 248 shows the relative response of the detector as determined from chlorine γ rays. The relative intensities are given in Table XXXIX. The spectrum due to capture of neutrons of near thermal energy was also observed by spinning the chopper at 880 rpm and an initial time delay of 3 msec, which gives neutrons between the energies 0.02 eV and 0.25 eV.

In Table XXXIX the last two columns are from Sheline *et al.*,¹ and Fig. 249 shows part of their proposed level scheme. An examination of the table permits one to classify all resonances into two groups: those that have transitions to the final states 0^- , 1^- , 2^- and those that have transitions to only 1^- final states, but no observable transitions to the 0^- or the three 2^- states. If the 14- and 17-eV

Fig. 248. Double-escape efficiency for the $10 \text{ cm}^2 \times 1 \text{ cm}$ Ge(Li) detector, as determined from the γ rays from thermal-neutron capture in chlorine.

TABLE XXXIX. Relative intensities of γ -ray transitions from resonances in $\text{Tm}^{169} + n$.

	E_γ (keV)	3.9 eV	14 eV	17 eV	29 eV	34.8 eV	38 eV	44 eV	50.7 eV	83 eV	Thermal	E_e^a	J_f^a
1	6593.9	4.4 ± 0.39	47.9 ± 1.6	7.1 ± 0.79	7.0 ± 1.7	1.5 ± 0.69	3.3 ± 1.9	3.0 ± 1.2	3.1 ± 1.1		1.4 ± 0.65	ground state	1^-
2	6556.4	18.0 ± 0.60			5.2 ± 1.7		3.3 ± 1.9	2.7 ± 1.2		3.3 ± 1.1	33.4 ± 0.87	37.5	2^-
3	6444.9	4.4 ± 0.41				1.8 ± 0.79	7.2 ± 2.4		1.1 ± 1.1		14.0 ± 0.75	149.0	0^-
4	6389.3	6.2 ± 0.50			3.0 ± 1.7	4.4 ± 0.94		4.2 ± 1.5			55.1 ± 0.99	204.6	2^-
5	6375.0	1.2 ± 0.23				3.2 ± 0.83	9.2 ± 2.5		1.4 ± 1.1			218.9	2^-
6	6356.0	6.3 ± 0.44		1.7 ± 0.66		2.3 ± 0.79	5.4 ± 2.3	9.4 ± 1.7		5.0 ± 4.7	13.2 ± 0.83	237.7	1^-
7	6003.3	4.1 ± 0.44	32.3 ± 1.7	4.1 ± 0.82			2.6 ± 2.3	2.5 ± 1.6			41.0 ± 1.0	590.6	1^-
8a	5954.2								3.7 ± 1.4			639.7	
8	5944.8	13.8 ± 0.55	1.9 ± 0.89	2.3 ± 0.81	6.5 ± 2.2		10.5 ± 2.7			3.7 ± 1.6	53.7 ± 1.1	649.1	
9	5910.8	5.6 ± 0.49			3.7 ± 2.0						22.5 ± 1.0	683.1	
10	5899.5					7.3 ± 1.2					21.8 ± 0.98		
11	5858.0	3.5 ± 0.46				6.7 ± 1.2	2.6 ± 2.4	8.2 ± 1.9			16.1 ± 1.0		
12a	5815.8												
12	5812.7		2.3 ± 0.91							3.0 ± 1.7			
12b	5808.9			7.9 ± 0.99					1.7 ± 1.4				
13	5771.2		1.9 ± 0.94							1.9 ± 1.5			
14	5736.5	10.2 ± 0.53				1.6 ± 1.1		2.5 ± 1.7		2.8 ± 1.6	60.8 ± 1.1		
14b	5729.7			9.3 ± 1.1					8.2 ± 1.6				
15	5684.4					4.0 ± 1.1		7.6 ± 1.9	7.8 ± 1.7		4.1 ± 1.0		
16	5661.7										4.6 ± 1.0		
17	5631.6			0.68 ± 0.83							1.2 ± 0.93		
18	5567.4			1.6 ± 1.0							2.5 ± 0.98		
19	5518.3	4.3 ± 0.49		2.3 ± 3.1		1.8 ± 1.2			1.2 ± 1.6	2.4 ± 1.8	7.9 ± 1.1		
20	5453.1	5.0 ± 0.52	2.3 ± 1.1	6.6 ± 1.3	4.2 ± 2.5								
20b	5446.6									3.2 ± 2.0	2.5 ± 1.1		

21	5431.0		12.4 ± 1.3	2.3 ± 0.83	0.91 ± 1.3	1.7 ± 1.7	
21b	5425.9	3.2 ± 0.47					12.7 ± 1.1
22	5416.4	4.7 ± 0.57					21.4 ± 1.2
23	5397.6	5.2 ± 0.53				2.5 ± 1.8	12.0 ± 1.1
24	5382.5	3.4 ± 0.52					4.4 ± 1.5
25b	5367.4				1.3 ± 1.4	2.3 ± 2.1	4.1 ± 1.9
25	5356.1	2.6 ± 0.51	3.1 ± 1.2				5.3 ± 1.1
25a	5334.9				7.1 ± 1.5 (Marked 26a on graph.)		
25c	5325.8						6.7 ± 1.1
25d	5318.3						3.0 ± 1.1
26	5213.4		2.3 ± 1.2	3.7 ± 1.2	6.7 ± 1.6		
27	5174.9	0.16 ± 0.54	2.0 ± 1.2				
28	5158.7	6.6 ± 0.59	1.6 ± 1.3	4.6 ± 2.8			45.7 ± 1.8
28b	5148.5			7.6 ± 1.4			
29a	5122.1						13.3 ± 1.3
29	5076.8	3.3 ± 0.58					14.4 ± 1.1
30a	5054.1			3.8 ± 1.4			
30	5046.1		2.8 ± 1.3				
31	4982.4	1.9 ± 0.6					
32a	4950.4	0.73 ± 0.6	3.6 ± 1.4	4.3 ± 1.4			
32	4929.6						
33	4918.3	4.7 ± 0.75		3.8 ± 1.5			
34	4879.3		1.6 ± 1.4				
35							
36	4771.1	0.92 ± 0.67					
37	4748.0		4.1 ± 1.6				
38	4733.3	3.1 ± 0.7	2.4 ± 1.6				

^aSheline et al., Ref. 1.

Fig. 249. Higher energy levels in Tm. From Sheline et al. (Ref. 1).

TABLE XL. Confidence factors for the resonances.

Resonance (eV)	3.9	14	17	29	34.8	38.0	44.0	50.7	83
Weakest line	32 _a	28	18	4	25 _b	25 _b	7	3	13
Confidence factor	96%	80%	80%	52%	85%	66%	62%	86%	73%

resonances were both $J = 1$, then there is $< 20\%$ probability that the unobservability of the γ -ray transitions marked 2, 3, 4, and 5 in Table XXXIX is due to poor sensitivity. This is a very conservative upper limit and is obtained by considering a Porter-Thomas distribution for which the mean value for the transition probabilities is computed from the average of the seven lines in this energy region over all nine resonances. Then the limit for sensitivity of detection is set equal to the weakest line in either the 14- or 17-eV spectrum. Line 28 is considered weakest in the 14-eV resonance and line 18 the weakest in the 17-eV resonance. The confidence factors for the resonances are given in Table XL; these factors represent the probability of detection of at least one of these four transitions to final states with spins 0^- or 2^- for each resonance.

Assuming that most transitions observed here are electric dipole, we arrive at the spin assignments given in Table XLI. In this table our spin assignments are compared with previously reported

TABLE XLI. Spin assignment of $Tm^{169} + n$ resonances.

Resonance (eV)	Spin assignment		
	Singh ^a	Asghar ^b	Present work
3.9	1		1
14.3	0	0	0
17	0	1	1
29			1
34.8	1	1	1
38.0			1
44.8	1	1	1
50.7	1	1	1
83.5	1	1	1

^aP. Singh, in Ref. 2.

^bM. Asghar, in Ref. 2.

Fig. 250. The γ -ray spectrum from thermal-neutron capture in Tm^{169} .

Fig. 251. The γ -ray spectrum from capture in the $J=0$ resonances at 14 and 17 eV and the $J=1$ resonances at 3.9 and 29 eV.

Fig. 252. The γ -ray spectrum from capture in the $J=1$ resonances at 34.8, 38, 50.7, and 83.5 eV.

values.³ It is interesting to compare the spectrum from thermal capture with that obtained from all the resonances. Figure 250 shows the thermal spectrum. The γ rays labeled on the horizontal axis are observed in

³In later work, the comparison of the experimental and the calculated values of $\sigma_{n\gamma f}/\sigma_{n\gamma}$ as a function of neutron energy (interference analysis) indicates that the spin of the 17-eV resonance is 1, and thus the weakness of transitions 2, 3, 4, and 5 in the 17-eV resonance results merely from statistical fluctuations.

TABLE XLII. Dependence of the transition on the spin of the final state. In taking these averages, only the seven transitions of highest energy were considered, and they are normalized to $1^+ \rightarrow 1^-$ values.

J_i	J_f	$\langle I \rangle$ (average over 7 resonances)
1^+	0^- $k = 0^-$	0.89 ± 0.47^a
1^+	1^- $k = 1^-, 0^-, \dots$	1.0 ± 0.31
1^+	2^- $k = 1^-, 2^-, 0^-, \dots$	1.15 ± 0.36
0^+	1^- $k = 1^-, 0^-, \dots$	5.7 ± 3.3 (average over 2 resonances)

^aErrors were computed from the asymptotic approximation

$$E = \sqrt{\frac{2}{m}},$$

where m is the sample population.

resonances but not in the thermal-capture spectrum. Figures 251 and 252 show resonance-capture spectra in which most of these weak lines are clearly visible.

The dependence of the transition on the spin of the final state is shown in Table XLII. Table XLII shows that there is no evidence for dependence on the final-state spin, although $\langle I \rangle$ does depend significantly on the initial-state spin.

* * *

L. M. BOLLINGER, Argonne National Laboratory: Wouldn't the average intensity of the transitions from a $J=0$ state be expected to be considerably stronger than that for transitions from a $J=1$ initial state?

LONE: It is. But I do not understand why the intensity does not also depend on the spin of the final state. We have looked at transitions from states with one value of J to final states of all different spins, and the intensities are all the same.

I-6. COMPARISON OF THE γ -RAY SPECTRA PRODUCED BY $^{130}\text{Co}^{\dagger}$ AND THERMAL NEUTRON CAPTURE IN ^{59}Co

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1. Introduction

The existence of a direct-reaction mechanism in the radiative capture of low-energy neutrons has not been confirmed experimentally. A nucleus which provides an excellent test is ^{59}Co which lies in the region of the periodic table where Lane and Lynn¹ predict the direct neutron-capture cross section to be large. Furthermore, from (d,p) work² it is known that ^{60}Co has several low-lying p states which are expected to be populated in the direct-capture process. The purpose of the present paper is to report the observation of interference between direct capture and resonance capture in the 132-eV state and the determination of the direct-capture cross section for the emission of the ground-state γ ray following neutron capture in the target nucleus ^{59}Co .

2. Experimental Arrangement

The experiment was performed at the 22-meter flight path of the Brookhaven Fast Chopper facility. The chopper speed was 10 000 rpm. The thick 3 in. $\times$ 3 in. $\times$ 0.25 in. Co metal sample, when oriented at 45° to the incident neutron beam, had $n\sigma_{\text{total}} = 1$ at 70 eV.

[†] This work was supported by the U. S. Atomic Energy Commission.

* Guest Research Associate from the State University of New York at Stony Brook, Stony Brook, New York.

¹ A. M. Lane and J. E. Lynn, Nucl. Phys. 17, 586 (1960).

² H. A. Enge, D. L. Jarrell, and C. C. Angleman, Phys. Rev. 119, 735 (1960).

Fig. 253. Typical time-of-flight spectrum for $E_\gamma > 2.0$ MeV.

Fig. 254. Typical γ -ray spectrum for $2.2 < E_n < 5.5$ eV.

The γ rays were detected by the 10-cm^3 planar Ge(Li) diode which was positioned 19 cm from the center of the sample. Single RC clipping with rise and fall times of $1.0 \mu\text{sec}$ was used in the amplifier. The flight time and pulse amplitude of each event were recorded on magnetic tape and subsequently analyzed. For this experiment, the time gate position and the discriminator bias were set to record only those events that corresponded to neutron energies in the interval $2.3 < E_n < 1000$ eV and γ -ray energies exceeding 4.5 MeV. The total running time was 12 hours.

3. Experimental Results

A typical time-of-flight spectrum obtained in a separate run for gamma-ray energies greater than 2.0 MeV is shown in Fig. 253. The channel width was $1 \mu\text{sec}$. The shape of the curve near the 132-eV resonance demonstrates the effect of scattering followed by capture in the thick sample. It was determined from a carbon-sample measurement that the background contribution for channel numbers exceeding 50 was less than 4%.

A typical γ -ray energy spectrum is shown in Fig. 254, corresponding to a neutron energy interval $2.2 < E_n < 5.5$ eV. Only the smooth curve was drawn in order to reduce the draftsman's work

load. The peak widths are 10 keV (FWHM). The peak numbers were chosen to correspond to the thermal capture γ -ray spectrum of Shera and Hafemeister.³ Although most of the peaks are due to two-photon escape following pair production, the energy scale refers to the incident γ -ray energy. The labels S and F refer to single-escape and full-energy peaks, respectively. The net peak areas for ten of the stronger γ rays were obtained by subtracting from the total peak area the background level as determined

from neighboring channels. The weak peaks, numbers 2 and 7, were not observed in the 132-eV resonance spectrum, thus supporting the conclusion of Shera and Hafemeister³ that these γ rays are primary transitions from a 3^- capturing state to 2^+ final state. Peak number 16 is also very weak in the resonance, indicating that it may also result from the 3^- to 2^+ transition.

The variation with neutron energy of the peak areas of nine of the stronger γ rays was measured for the neutron energy range $2.2 < E_n < 300$ eV. Figure 255 shows this variation for the 5.98-MeV γ ray. The points represent the γ -ray peak area per microsecond flight time while the solid curve represents the total area per microsecond in the γ -ray spectrum for $E_\gamma > 4.5$ MeV. The two shapes are similar, demonstrating lack of variation in the 5.98-MeV γ -ray intensity as a function of neutron energy. Figure 256 shows a similar plot for the

Fig. 255. Time-of-flight spectrum for the 5.97-MeV gamma ray. The datum points refer to the γ -ray peak area while the solid curve indicates the total γ -ray spectrum for $E_\gamma > 4.5$ MeV.

³ E. B. Shera and D. W. Hafemeister, Phys. Rev. 150, 894 (1966).

Fig. 256. Time-of-flight spectrum for the 7.210-MeV doublet. The datum points refer to the γ -ray peak area while the solid curve represents the total γ -ray spectrum for $E_\gamma > 4.5$ MeV.

doublet at 7.210 MeV. The two curves were normalized to the same value at the 132-eV resonance. For this example the γ ray is $\sim 50\%$ more intense in the 4-eV region.

Let us denote by the quantity R the ratio of the peak area of a single γ ray to the area of the total γ -ray spectrum, i. e. ,

$$R \equiv \text{Peak area} / \text{Total area}.$$

Since the total γ -ray spectrum for $E_\gamma > 4.5$ MeV contains contributions from at least forty γ rays, this total spectrum is proportional to the total capture cross section. Then R is proportional to the partial capture cross section $\sigma_{n\gamma f}$ divided by the total capture cross section $\sigma_{n\gamma}$, i. e. ,

$$R = k \sigma_{n\gamma f} / \sigma_{n\gamma}.$$

If the value of R for each γ ray is arbitrarily normalized to a value of 1.00 at the 132-eV resonance, the resultant curves of Fig. 257 are obtained. The vertical axis is a log scale for R . The horizontal scale represents decreasing neutron energy at the top and neutron flight time below. For six of the γ rays the value of R is constant within the statistical uncertainty. For the 6.705-MeV γ ray, R is about 10% less at 3 eV than at the 132-eV resonance. However, for the 7.490-MeV ground-state transition and the 7.210-MeV doublet the value of R is $\sim 50\%$ larger at 3 eV than in the resonance.

Fig. 257. Ratio of γ -ray peak area to total γ -ray spectrum as a function of neutron energy. This ratio is arbitrarily normalized to unity in the 132-eV resonance. The corresponding γ -ray transitions are shown at the right. The dashed curve is calculated for no interference effects.

4. Interpretation

Let us now focus our attention on the ground-state transition. According to the polarization measurements of Schermer,⁴ 22% of the thermal total capture cross section is due to a 3^- capturing state. Since the ground state of Co^{60} has spin and parity 5^+ , electric-dipole radiation to the ground state is forbidden for this 3^- capturing state. The 132-eV resonance is 4^- , thus permitting electric-dipole radiation to the ground state. This means that the 3^- capturing states do not contribute to the partial capture cross section for the 7.49-MeV γ ray but do contribute to the total capture cross section. If only the simple resonance cross sections of the 4^- level at 132 eV and a 3^- bound level (at -268 eV) contribute to the capture cross sections in this region, then R should vary as the dotted line shown on the 7.49-MeV data; that is, $R \propto \sigma_{n\gamma f} / [\sigma_{n\gamma}(132) + \sigma_{n\gamma}(-268)]$. The fact that the data points lie above this curve indicates that interference must be present for $E < 100$ eV since the total contribution of all the strong positive 4^- resonances for $E_n < 10$ keV to the total capture cross section at 1 eV is less than 0.5% of that of the 132-eV level.⁵

Assume that the partial capture cross section contains a direct-interaction amplitude which interferes with the 132-eV resonance amplitude so that

$$\sigma_{n\gamma f} = \pi \lambda_0 \lambda g \left| A_0 + \frac{(\Gamma_n^0 \Gamma_{\gamma f})^{1/2}}{(E - E_r) + i\Gamma/2} \right|^2,$$

where 0 refers to the value at 1 eV, r refers to the resonance, and A_0 is the direct amplitude at 1 eV. The partial cross section will then

⁴R. I. Schermer, Phys. Rev. 130, 1907 (1963).

⁵M. D. Goldberg, S. F. Mughabghab, B. A. Magurno, and V. M. May, Brookhaven National Laboratory Report BNL-325, Second Edition, Supplement No. 2, 27-0-3 (1966).

consist of three terms: direct, interference, and resonance. That is, $\sigma_{n\gamma f} = \sigma_{n\gamma f}(\text{direct}) + \sigma_{n\gamma f}(\text{interference}) + \sigma_{n\gamma f}(\text{resonance})$. The interference terms will be negligible in the total capture cross section which will consist of two resonance terms only, so that

$$\sigma_{n\gamma} = \sigma_{n\gamma}(4^- \text{ res}) + \sigma_{n\gamma}(3^- \text{ res}).$$

The quantity R may be expressed in the form

$$R = k \frac{\sigma_{n\gamma f}}{\sigma_{n\gamma}} = k \frac{\Gamma_{\gamma f}}{\Gamma_{\gamma}} \frac{C^2 (1 + X^2) + 2CX + 1}{1 + [\sigma_{n\gamma}(\text{res } 3^-) / \sigma_{n\gamma}(\text{res } 4^-)]},$$

where

$$C^2 = A_0^2 \Gamma^2 / 4\Gamma_n \Gamma_{\gamma f},$$

$$X = \frac{\Gamma}{2}(E - E_{\gamma}),$$

and k is a normalizing constant. All the resonance parameters refer to the 132-eV resonance. The value of the partial radiation width $\Gamma_{\gamma f}$ of the 132-eV resonance was determined from the thermal absolute γ -ray intensity I_{γ} by Shera and Hafemeister.³ These values are, respectively,

$$I_{\gamma} = 0.030 \pm 0.005 \text{ photon per neutron captured,}$$

$$\Gamma_{\gamma f} = 0.022 \Gamma_{\gamma}.$$

The experimental average value of R for the neutron-energy interval $2.2 < E_n < 5.5$ eV was 1.35 ± 0.08 . Using the above expression for R , the value of the direct-capture cross section required to produce this experimental value with constructive interference is

$$\sigma_{n\gamma f}(\text{direct}) = (9.2 \pm 2.4) \times [E_0/E]^{1/2} \text{ mb}$$

Further values are given in Table XLIII. The interference cross section at 1 eV is six times the direct cross section. The listed uncertainties include only the error in the experimental value of R .

TABLE XLIII. Partial cross sections for the 7.49-MeV gamma ray, all evaluated at 1 eV.

$$\sigma_{n\gamma f}(\text{direct}) = (9.2 \pm 2.4) \text{ mb}$$

$$\sigma_{n\gamma f}(\text{interference}) = +(59 \pm 15) \text{ mb}$$

$$\sigma_{n\gamma f}(\text{res}) = 96 \text{ mb}$$

$$\sigma_{n\gamma f}(\text{total}) = 164 \text{ mb}$$

The calculated variation of R , which is shown by the solid curve in Fig. 258, is in good agreement with the experimental data. Data for the bound-state parameter are taken from the work of Schermer⁴ and from unpublished calculations of Pearlstein.⁶ The dashed curve is obtained for destructive interference and does not fit the data points.

Can any interference mechanism other than direct capture explain this experiment? One possibility is resonance-resonance interference between the 132-eV 4^- level and a bound level of the same spin. However, no such 4^- bound level is required to fit the total cross section measurements to several kilovolts.⁶ Furthermore, a strong argument against the presence of a nearby 4^- bound state is presented by the observation of no interference effect for six of the strongest γ rays observed in the present experiment. Such interference effects would be expected to be present for all γ rays, not just the ground-state γ ray. Thus, there is strong evidence against the presence of a 4^- bound level whose amplitude could simulate a direct amplitude in the region just above the neutron binding energy.

Fig. 258. The value of R for the 7.49-MeV ground-state γ ray. The datum points represent the experimental values. The solid curves were calculated for the indicated values for the direct capture cross section.

⁶S. Pearlstein (private communication).

From data of Enge,² the ground state of Co^{60} is known to be strongly excited by the (d,p) reaction. This leads to the expectation of a direct-capture effect in the $\text{Co}^{59}(\text{n},\gamma)$ reaction. Lane and Lynn¹ have calculated the hard-sphere capture cross section. For $\text{Co}^{59} + \text{n}$ their calculation gives at 1 eV

$$\sigma_{\text{hard sphere}} = 39.2 \theta_n^2 \text{ mb},$$

where θ_n^2 is the reduced width of the final state. On the reasonable assumption that about $\frac{1}{3}$ of the $\text{P}_{3/2}$ strength resides in the 5^+ Co^{60} ground state, the result of this experiment is in good agreement with this calculation.

No strong statement can be made about the other transitions terminating in 3^+ or 4^+ final states, because of the presence of the 3^- bound state.

The present experiment therefore constitutes clear evidence of a direct-capture component in the radiative-capture cross section.

(71)
~~I-T.~~ GAMMA-RAY SPECTRA OF Co^{60} AND Mn^{56} FOLLOWING
 RESONANCE CAPTURE IN Co^{59} AND Mn^{55} [†]

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The cobalt and manganese data¹ I would like to report here were obtained around Christmas 1965 after the reactor CP-5 resumed operation. We were also interested in looking for another feature which might be implied by a direct-capture mechanism at various resonances in these two nuclides. We used the Argonne fast chopper to look at the

130-eV resonance in cobalt, the 333-eV resonance in manganese, and the two Mn resonances at roughly 1 and 2 keV.

Fig. 259. The time-of-flight spectrum of all neutron captures on Co^{59} .

Figure 259 is a plot of the gamma-ray yield as a function of time of flight for cobalt and shows the 132-eV resonance. We used a sample about 1 in. thick, and the distortion in the resonances is due to multiple-scattering events. We set a window on the resonance and off the resonance, and subtracted the off-resonance contribution.

[†] Work performed under the auspices of the U. S. Atomic Energy Commission.

¹ W. V. Prestwich and R. E. Coté, Phys. Rev. 155, 1223 (1967).

Fig. 260. The gamma-ray spectra associated with the $\text{Co}^{59}(n, \gamma)\text{Co}^{60}$ reaction. Upper curve: capture of thermal neutrons. Lower curve: capture of neutrons at the resonance energy (132 eV).

Figure 260 compares the 132-eV spectrum with the (n, γ) spectrum for thermal neutrons. Qualitatively, these spectra are similar except that a few transitions, such as those marked 21 and 22, have disappeared. Thus the negative-energy resonance at thermal energy is confirmed. And, of course, the $J=4$ assignment is also confirmed for the 132-eV resonance, because the ground-state transition going to the 5^+ level is observed in the resonance.

Fig. 261. The correlation between the reduced widths and the values of l_n for the final states in Co⁶⁰. The number in parentheses is a possible alternative value of l_n .

The effect shown in Fig. 261 was tentatively taken as evidence for direct capture, and seems to be consistent with what is observed by Wasson. If the reduced radiative widths for various transitions for which there is known (d,p) information can be compared with the observed l value for the corresponding (d,p) transition to the same final state, then it appears that the average reduced radiative width for states for which $l_n = 1$ is approximately 5 times that for states for which $l_n = 3$. This, in turn is consistent with a direct-capture phenomenon, since the $l_n = 3$ states carry a large fraction of the single-particle f-wave strength and the $l_n = 1$ states carry a large fraction of the single-particle p-wave strength. If the initial state does look like an s-wave nucleon coupled to the target, then the $s \rightarrow f$ selection rule would reflect this sort of behavior.

Let us now turn to manganese. In the time-of-flight spectrum (Fig. 262), the 336-eV resonance again is distorted by multiple scattering. The small peak at $\sim 50 \mu\text{sec}$ is the 100-eV germanium resonance which results from a large amount of scattering in the high-energy resonances. As you can see, we don't really resolve the 1098- and 2355-eV resonances; instead we set windows on what we consider to be the major portion of each resonance. Thus both resonances contribute to the observed spectra, the relative sizes of the contributions depending on the placement of the window.

The curve at the top in Fig. 263 is a thermal spectrum for manganese. For both Co and Mn we use the thermal spectrum basically as a calibration. I should also say that the runs to collect these data took approximately 1 week each. No gain stabilization was used and the resolution width is roughly 9–12 keV. Let me also apologize for the poor statistics in the 1- and 2-keV resonances. Here we are hampered by the drop-off of the flux with energy—but one can see that there is quite a significant change from resonance to resonance. The ground-state transition is more prominent at the 336-eV resonance than in any of the other spectra. Note also that the transition marked No. 4 is strong on both the 1098- and the 2355-eV resonance.

Now as regards the separation of the two resonances—what we did do was to compare the data for transitions No. 3–6 with the sodium iodide gamma-gamma coincidence data. The latter work was done by Kennett et al. several years ago at flight path of 25 meters, with which they were able to resolve the resonances. This work and the present work are in good basic agreement on the relative widths for the two resonances.

The Yale and McMaster groups have reported that the reduced gamma-ray widths in the thermal spectrum are somewhat correlated with the (d,p) intensities. To see if this effect persists at resonance, the (d,p) reduced widths were compared (Fig. 264) with the

Fig. 262. The time-of-flight spectrum of all neutron captures in Mn^{55} .

Fig. 263. Gamma-ray spectra from the $\text{Mn}^{55}(n, \gamma)\text{Mn}^{56}$ reaction for neutrons at thermal energy and at the resonance energies indicated.

Fig. 264. The reduced widths for the $\ell_n=1$ transitions in manganese compared with the reduced neutron (d,p) widths.

Fig. 265. Comparison between the reduced neutron (d,p) widths and the reduced widths for the $\ell_n=1$ transitions for manganese, averaged over the spectra for thermal energy and the 1098- and 2355-eV resonances.

gamma-ray reduced widths at the various resonances. The figure also shows the correlation coefficient—defined such that 1 represents 100% correlation. As you see, the 336-eV resonance displays no correlation at all—primarily because the ground state and first excited state are strongly populated at this resonance, even though they carry very little of the p-wave strength. The spectra at thermal energies and at the 2355- and 1098-eV resonances all have correlation coefficients of approximately 70% or greater. This is mainly because of the strength of the transition corresponding to line No. 4, which was strong in these three spectra and corresponds to the state that carries the greatest fraction of the single-particle p-wave strength.

Fig. 266. The integral covariance distribution for a sample consisting of $N = 11$ independently distributed variates.

One other point that might be brought out is that the thermal spectrum, which displays correlation, contains contributions from known resonances at negative energies. They presumably display an even greater correlation with the (d, p) intensities, because we know there are large contributions to the thermal spectrum from the 336-eV resonance—and these would tend to wash out the correlation, since that resonance itself displays no significant correlation.

I might also add that if one restricts oneself to the $\ell_n = 1$ subset of gamma widths in cobalt, there is no significant correlation with the (d, p) intensities. In addition, we have (completely without any justification) averaged the reduced widths for the three spectra which displayed correlation but have considered the 336-eV resonance to be of some different character. The resulting comparison is shown in Fig. 265. In the averaged data, the correlation coefficient is increased to 87%. These changes in the correlation coefficient are rather significant.

Figure 266 shows the distribution for the correlation coefficient which one observes for random independent variables. As one can see, the probability of observing correlations as large as 70–80% is less than 10^{-3} . For capture in both Co and Mn, we feel there are indications of some form of capture mechanism in which a purely random-matrix hypothesis may not be a complete description.

* * *

C. F. CLEMENT, Florida State University: Much better types of correlations might be found if the spins of the intermediate resonances were taken into account. The reason is that in stripping the strength should be proportional to, say, $(2J_f + 1)$ times the square of the spectroscopic factor; but if the capture reaction goes through an intermediate state with a definite spin J , there is an additional spin factor that depends on the spins of the intermediate state and the final state. These should really be included, if possible, in comparing (n, γ) and (d, p) reactions.

PRESTWICH: If we had the spins of all the final states, we might be able to do that; but this usually doesn't happen.

M. BEER, State University of New York at Stony Brook and Brookhaven National Laboratory: What were the assumptions in the calculation of the distribution (Fig. 266) of the correlation coefficients ρ .

PRESTWICH: There was no assumption. It is defined as

$$\rho = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\left[\sum_i (x_i - \bar{x})^2 \right] \left[\sum_i (y_i - \bar{y})^2 \right]}} .$$

It merely reflects the degree to which large departures from the mean value of x are followed by large departures from the mean value of y , where x represents one of the variables under comparison (say, the reduced gamma-ray widths) and y represents the other—e.g., the (d, p) strength function. The distribution curve comes from statistical theory.

J. VERVIER, C.E.N.-S.C.K., Mol: Did I correctly understand you to say that there is no correlation when considering only transitions to states with $\ell_n = 1$?

PRESTWICH: There is no correlation in the 130-eV resonance in cobalt nor in the 330-eV resonance in manganese; but there are significant correlations in the thermal capture and the 1- and 2-keV resonances in manganese.

1-8. THE $\text{Pt}^{195}(n, \gamma)\text{Pt}^{196}$ REACTION AS A ONE-CHANNEL PROCESS*

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A problem that was of great interest several years ago was whether the de-excitation of a compound state formed by neutron capture exhibited the single-channel nature that elastic neutron scattering was known to show. The effects of this single-channel nature were expected to be evident in the distribution of the partial radiation widths and in the energy dependence of the partial cross section. The first piece of evidence has already been discussed at this meeting (paper I-1). This talk will be concerned only with the variation of the partial cross section with neutron energy.

Quite early in the study of the shapes of neutron resonances, it was recognized that resonances whose radiation widths were nearly equal to the total widths did not show the asymmetries found for scattering and fission resonances. It was tacitly assumed that this was the result of the complex nature of the decay of the compound state, the random phases associated with the amplitudes for the many modes of decay leading to a cancellation of the interference effects caused by the coherent summing of the amplitudes for each mode. It was felt that if the cross section for the emission of a single gamma ray were observed as a function of energy, the expected asymmetry would be observed.

As mentioned earlier in this conference (paper I-1), evidence for the existence of this interference effect was presented several years ago by Coté and Bollinger,¹ who studied the ground-state transition following neutron capture in Pt^{195} in the energy region between

* Work performed under the auspices of the U. S. Atomic Energy Commission.

¹R. E. Coté and L. M. Bollinger, Phys. Rev. Letters 6, 523 (1961).

a few electron volts and 25 eV—a region dominated by strong resonances at 11.9 and 19.6 eV, both of which are known to have $J = 1$. This has remained the only observed example of this effect. They also sought for the effect in hafnium in the vicinity of the resonances at 1.1 and 2.38 eV, with a negative result. They concluded that interference did not take place or that the resonances had different spins. Ceulemans and Poortmans² had already reported that the latter was the case. Later measurements on the resonances of Hf^{177} by Côté and Jackson,³ who

used a two-step cascade method, confirmed this assignment.

Fig. 267. The total capture rate of $\text{Pt}^{195}(n, \gamma)\text{Pt}^{196}$ as a function of neutron flight time. The peak at 67 eV is known to consist of two unresolved resonances.

Since the interference had not been observed in any other case, it seemed important to repeat the experiment under the improved conditions that result from the use of the $\text{Ge}(\text{Li})$ gamma-ray spectrometer. Our earlier work had been done with a $\text{NaI}(\text{Tl})$ spectrometer, of course, and for that reason it was restricted to a study of the ground-state transition alone. Although it was possible to improve the resolution for gamma rays in the present experiment, it was necessary to use poorer neutron

²H. Ceulemans and F. Poortmans, *Nucl. Phys.* **62**, 641 (1965).

³L. M. Bollinger, R. E. Côté, and H. E. Jackson, in *Comptes Rendus du Congrès International de Physique Nucleaire*, Paris, 2–8 July 1964, edited by P. Gugenberger (Centre National de la Recherche Scientifique, Paris, 1964), Vol. II, p. 673.

Fig. 268. The γ -ray spectra associated with capture at the three indicated resonance energies.

resolution—a condition which is not of great importance for the present measurement.

The experimental arrangement is just the same as that described (paper I-7) for the measurements of the spectra of cobalt and

Fig. 269. The relative intensity of the 7917-keV ground-state transition as a function of neutron energy, as observed with the Ge(Li) detector. The solid curve shown is that used to fit the original NaI data, adjusted only by a scale factor.

manganese. The sample consisted of about 90 g of platinum, 3 in. wide by 5 in. high. The Ge(Li) spectrometer furnished by Harry Mann and his collaborators had an active volume of about 3.5 cc. The data were recorded on the magnetic tape of the 3-parameter analyzer.

Figure 267 shows the total number of captures as a function of the neutron flight time. The region of interest is that dominated by the resonances at 11.9 and 19.6 eV. The peak whose energy is indicated as 67 eV is known to consist of two resonances in Pt^{195} .

Figure 268 shows the gamma-ray spectra associated with neutron capture at the 11.9-, 19.6-, and 67-eV resonances. The ground-state transition is plainly evident in all three spectra. It is clear why this experiment was an ideal one for an initial study with NaI(Tl) and why the resolution of the Ge(Li) is needed to extend the measurements to other lines in the spectra.

Figure 269 shows the results for the 7920-keV ground-state transition. The strength for transitions to the ground state has been divided by the total number of captures to get the quantity R_γ plotted as the ordinate. The solid curve drawn through the points is the same curve as that drawn through the NaI(Tl) data shown on Fig. 270. The statistical quality of the earlier work is better, but the agreement of the two experiments taken under such drastically different conditions is indeed gratifying. In this figure there are two other curves: the

Fig. 270. Analysis of the interference pattern exhibited by the ground-state transition. The data shown were obtained with a NaI detector.

single-level fit is the pattern expected if no interference occurs, the dotted curve is obtained if interference is allowed between the amplitudes for the two resonances (in which the amplitudes are chosen to have opposite signs). The multilevel fit includes, in addition, contributions from the 67-eV resonance and a bound level at -13 eV chosen to give a best fit. It is clear that the question of the existence of interference in the radiative capture process can be answered simply by a consideration of the amplitudes associated with the 11.9- and 19.6-eV resonances alone, the very low value of R_0/R_γ above the 19.6-eV resonance being the definitive part of the curve.

Once the older experiment had been confirmed, two other tasks appeared worthwhile: (1) to find more cases of interference and (2) to find a case in which the interference pattern would be opposite to that for the ground state, i. e., one which would tend to produce a cancellation of the ground-state pattern and lead to the spectrum for total captures. Two other cases are presented here.

Figure 271 (left) shows the result for the transition at 6514 keV. The crosses and circles represent separate experiments. This figure shows only two curves simply because the curve based on only the amplitudes for the 11.9- and 19.6-eV resonances nearly coincides with that for amplitudes with relative signs $++-$. It should be stressed that the resonance parameters, other than the partial radiation widths,

Fig. 271. Analysis of the interference patterns exhibited by the transitions at 6514 keV (left) and 5998 keV (right). The relative phases of the contributions from the bound state and the states at 11.9, 19.6, and 67 eV are indicated on the curves. (When only two phases are shown, these are for the 11.9- and 19.6-eV contributions.)

are fixed from analysis of the total neutron cross section. The dashed curve shows the pattern to be expected if the signs of the amplitudes for the two resonances are the same. A dip should be observed between the resonances (rather than a peak) and the partial cross section should remain high above and below the pair of resonances. The transition at 6514 keV clearly presents a case similar to that observed for the ground-state transition, but with different values for the partial radiation widths.

Figure 271 (right) shows the pattern observed for the transition at 5998 keV. Although the statistical quality of this "spectrum" is not as good as the earlier ones, it is good enough to provide solid evidence for a case in which destructive interference takes place between two closely spaced resonances. The curves are labeled in the same manner as are those for the 6514-keV transition. The curve marked ++ shows that the neglect of other resonances does not destroy the distinguishing feature of the spectrum—namely the minimum between the resonances.

1-9. HIGH-RESOLUTION CAPTURE GAMMA-RAY MEASUREMENTS
FROM THERMAL AND RESONANCE NEUTRON CAPTURE
IN ^{119}Sn , ^{116}Sn , ^{122}Sn , AND $^{124}\text{Sn}^\dagger$

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1. Introduction

At the Antwerp meeting in July 1965, we reported¹ gamma-ray spectra from thermal and resonance neutron capture in ^{117}Sn , ^{118}Sn , and ^{120}Sn —all measured with lithium-drifted germanium detectors. We have extended our measurements to the other four abundant isotopes ^{119}Sn , ^{116}Sn , ^{122}Sn , and ^{124}Sn . Earlier measurements of the gamma rays from thermal-neutron capture and capture in individual resonances in the isotopes of tin with a NaI spectrometer had demonstrated the value of using both thermal and resonance-energy neutrons and the need for high resolution of the gamma rays.

2. Experimental Arrangement

To obtain a beam of "pure" thermal neutrons, the reactor beam from the ORR was reflected twice at small angles from Inconel mirrors (the collimators for our fast chopper) as described by E. B. Shera in paper A-1 of this conference. Measurements were made with and without cadmium in the beam to be sure that the observed gamma rays were caused by thermal neutrons. A cadmium-filtered reactor beam served as a source of resonance-energy neutrons. A thin boron filter

[†] Research sponsored by the U. S. Atomic Energy Commission under contract with the Union Carbide Corporation.

¹ J. A. Harvey and G. G. Slaughter, in Nuclear Structure Study with Neutrons (Proceedings of the International Conference, Antwerp, 19—23 July 1965), edited by M. Nève de Mévergnies, P. Van Assche, and J. Vervier (North-Holland Publishing Co., Amsterdam, 1966), p. 514.

can also be used to reduce the capture of epi-cadmium neutrons by the $1/v$ thermal tail. Measurements were also made with a ^{10}B filter in the beam to determine whether the gamma rays were caused by resonance-energy neutrons with energies $\lesssim 1$ keV. The resonance neutron beam contained many fast neutrons and gamma rays which complicated the measurements and their interpretation.

Most of the measurements were made with a 6-cm³ lithium-drifted detector (furnished by R. J. Fox, ORNL) located ~ 2 m from the second collimator. The electronics consisted of a Tennelec preamplifier and amplifier, and a 1024-channel TMC pulse-height analyzer. The integrated counting rate was restricted to ~ 500 counts/sec to avoid increasing the widths of the gamma-ray peaks. The energy resolution was not spectacular, being ~ 5 keV for 500-keV gamma rays and 15–20 keV for ~ 6 -MeV gamma rays for runs of a few days duration. The energies of the low-energy gamma rays were measured to an accuracy of ~ 1 keV, but the high-energy gamma rays were accurate only to ~ 5 keV, although the difference between the energies of high-energy gamma rays was more accurate (~ 2 keV).

3. Thermal and Resonance Capture in ^{119}Sn

A portion of the low-energy spectrum from thermal and resonance neutron capture in a 55-g sample of ^{119}Sn is shown in Fig. 272. From thermal neutron capture in ^{119}Sn , six full-energy gamma-ray peaks were observed in this energy region from 880 to 1200 keV. Three of these gamma rays (the lines at 925, 987, and 1169 keV) can be fitted between known low-lying levels of ^{120}Sn as will be shown later. The intense 1169-keV gamma ray is a transition from the first 2^+ state to the 0^+ ground state. The lower half of Fig. 272 shows the data obtained with the resonance neutron beam. Except for the 1169-keV gamma ray, the other lines observed with thermal neutrons

Fig. 272. A portion of the low-energy spectrum from thermal and resonance neutron capture in ^{119}Sn .

were not present. Three other gamma rays were observed in these data with energies of 898, 921, and 1067 keV. These energies agree exactly with energies of gamma rays from thermal-neutron capture in ^{118}Sn and with the energies of transitions between low-lying states in ^{119}Sn . However, the sample does not contain sufficient ^{118}Sn (3%) to account for these gamma rays from neutron capture in ^{118}Sn . Hence, we believe that these three gamma rays may arise from fast neutrons in the reactor beam being inelastically scattered by ^{119}Sn . These three lines were also present with a 1-keV ^{10}B filter in the neutron beam. It is unlikely that the inelastic gamma-ray scattering process could account for these three gamma rays.

Figure 273 shows a portion of the spectrum from both thermal and resonance neutron capture in ^{119}Sn from 3620 to 4530 keV energy in the crystal. From thermal capture, six double-escape gamma-ray peaks were observed in this energy region which corresponds to an excitation energy in ^{120}Sn from 3560 to 4470 keV if the gamma rays

Fig. 273. The 3620—4530-keV portion of the spectrum from thermal and resonance neutron capture in ^{119}Sn .

are assumed to be primary transitions. However, from resonance capture no definite peaks were observed in this region.

With thermal neutrons, higher-energy gamma rays were observed going to known low-lying excited states; however, the transition to the ground state was not observed. With resonance-energy neutrons, the ground-state transition was observed as well as transitions to the low-lying states. The results are summarized in Fig. 274, which shows the energy level diagram for ^{120}Sn .

Four low-energy gamma rays from thermal capture can be fitted to the decay scheme. The intense 1169-keV line from the first 2^+ level to the 0^+ ground state, a 703-keV line from a $(0^+, 1^+)$ state at 1872 keV to the 2^+ state at 1169 keV excitation, a 925-keV line from a state at 2094 keV to the 2^+ state at 1169 keV, and a 987-keV line from a $(0^+, 1^+)$ state at 2156 keV to the 2^+ state at 1169 keV. Other low-energy gamma rays were observed but these have not been assigned to the decay scheme. With resonance neutrons the only low-energy gamma rays observed were the 1169- and 703-keV lines. These were much weaker from resonance-neutron capture than from thermal-neutron capture.

The high-energy gamma rays observed from thermal and resonance neutron capture are also shown in Fig. 274. With thermal neutrons the ground-state transition was not observed; with resonance

neutrons the transition to the 1872-keV state was not observed. The solid horizontal lines show the positions of states deduced from the energies of the high-energy gamma rays on the assumption that the latter were primary transitions. The dashed lines are positions of levels determined from (d,p) measurements^{2,3} for which no high-energy gamma rays were observed. It is obvious that many more levels were observed in the (d,p) reaction than could be found in our (n,γ) measurements. For excitation energies up to ~3000 keV, all observed high-energy gamma rays correspond to states found in the (d,p) reaction. However, at higher excitation energies there are a few high-energy gamma rays which do not correspond to states observed from the (d,p) reaction. For example, with thermal neutrons only three of the six lines shown in Fig. 273 correspond to states from (d,p) work at ~4000 keV excitation; with resonance neutrons only one of the three lines corresponding to transitions to states at an excitation of ~3100 keV (Fig. 274) agrees with states from (d,p) work.

Fig. 274. The energy level diagram for ^{120}Sn . All energies are in keV.

4. ^{116}Sn , ^{122}Sn , and ^{124}Sn

The measurements with the three even-A tin isotopes were made upon ~40-g samples enriched in ^{116}Sn , ^{122}Sn , and ^{124}Sn .

² L. R. Norris and C. F. Moore, Phys. Rev. **136**, B40 (1964).

³ B. L. Cohen and R. E. Price, Phys. Rev. **118**, 1582 (1960).

Fig. 275. The energy level diagrams for ^{117}Sn , ^{123}Sn , and ^{125}Sn . All energies are in keV.

The predominant feature of the spectra from these three isotopes is the strong high-energy gamma rays to the low-lying $s_{1/2}$ and $d_{3/2}$ states from the capture of resonance neutrons.

However, these high-energy gamma rays occur from the capture of thermal neutrons although they are quite weak.

The results from the measurements upon these

three isotopes are summarized in Fig. 275.

Three low-energy gamma rays from thermal neutron

capture can be fitted to the low-lying levels of ^{117}Sn , but only the low-energy transitions from the $s_{1/2}$ to $d_{3/2}$ states were observed from capture in ^{122}Sn and ^{124}Sn . In ^{116}Sn the resonance capture is dominated by the s-wave resonance at 111.2 eV, in ^{124}Sn by the p-wave resonance at 62.0 eV, and in ^{122}Sn by the 107- and 260-eV resonances which may be p-wave.

Two weak high-energy gamma rays going to excited states at 813 and 1007 keV in ^{117}Sn were observed from both thermal and resonance neutron capture in ^{116}Sn , and one to an excited state at 936 keV in ^{125}Sn from both thermal and resonance capture in ^{124}Sn . Although many excited levels above 1000 keV excitation in these three nuclides are known from radioactive-decay studies⁴ and the (d,p)

⁴Nuclear Data Sheets, compiled by K. Way et al. (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C., 1962), NRC 60-3-131.

reaction^{5,6} no gamma rays were observed which would correspond to transitions to these states. A few weak gamma rays in the several-MeV energy range (~ 3 to ~ 5 MeV) were observed but these did not fit the level schemes obtained from the (d,p) reaction.

Also shown in Fig. 275 are the ratios of the intensities of the two high-energy transitions to the low-lying $s_{1/2}$ and $d_{3/2}$ states. The ratios of the intensities of these two transitions are quite similar for all three nuclides for both thermal and resonance capture. However, the intensities of these two lines are much stronger from resonance capture than from thermal capture, particularly for ^{124}Sn .

* * *

R. E. CHRIEN, Brookhaven National Laboratory: I can't resist asking why you don't spin the chopper.

HARVEY: If we had spun the chopper, our counting rates would have been too low for meaningful capture measurements in the tin resonances. For example, the high-energy spectrum I showed had a counting rate of < 1 count/min. If we had spun the chopper our counting rate would have dropped by a factor of 500. We will wait until we get our new linac which has thousands of times the intensity of our chopper.

CHRIEN: My point is that if you just sit on a resonance, the background would in effect be very much reduced. Although the counting rate would go down, some of these lines might still show clearly above background.

HARVEY: This is true when the background is approximately proportional to the intensity of the good neutrons. However, if the background is mainly "room" background, it is not true.

⁵ B. L. Cohen and R. E. Price, Phys. Rev. 121, 1441 (1961).

⁶ C. L. Nealy and R. K. Sheline, Phys. Rev. 135, B325 (1964).

I-10. RESULTS OF RESONANCE-NEUTRON CAPTURE STUDIES IN HAFNIUM

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In a previous paper by Bob Spencer (paper I-2), the equipment used at the MTR for resonance neutron-capture gamma-ray studies was described and some tungsten data were shown to illustrate the sort of results we have been able to obtain. This paper will describe our second set of data obtained with the new facility. All apparatus used was the same as that described before, including the 2 cm³ germanium detector, although we are now using a new 30 cm³ counter.

Our target this time was normal metallic hafnium. Hafnium differs from tungsten only in having two fewer protons and two more neutrons at the same mass number. Thus we might expect

some similarities in the gamma-ray de-excitation spectra. Studies have been made previously on this element. Most notable was the recent work of Namenson, Jackson, and Smither,¹ who used thermal neutrons and separated isotopes.

Figure 276 shows the low-energy neutron cross section of Hf, taken from BNL-325. Bars beneath the resonances indicate the neutron resolution of our spectrometer as it was

Fig. 276. Low-energy neutron cross section of hafnium.

¹A. I. Namenson, H. E. Jackson, and R. K. Smither, Phys. Rev. 146, 844 (1966).

Fig. 277. Off-resonance spectrum of hafnium. The target was natural hafnium.

used in this work. Several prominent resonances are evident which should allow us a choice of capturing states to study. Only one, however, leads to an even-odd product nucleus similar to the interesting even-odd isotopes of tungsten. This is the 7.8-eV resonance in Hf^{178} . Four other resonances, all in Hf^{177} leading to even-even Hf^{178} , are also relatively well-separated. In practice, however, we found that we could only isolate three of them with certainty using the counter then available. The resonance at 6.6 eV thus was not studied at that time but a run is now in progress with a new, larger detector.

Figure 277 shows off-resonance data taken at 0.06 eV where the cross section is made up of the tails of the resonances shown plus others at higher energies and possibly contributions from the resonances below the neutron binding energies of the Hf isotopes. The highest-energy transition is at 6.448 MeV and is labeled as peak number 3. Two other weak transitions (those at 7.529 and 7.314 MeV) should also be seen here, but the background effects when thermal neutrons were used in our facility apparently washed them out. The portion of the spectrum shown, from 5.4 to 6.5 MeV, shows 17 gamma rays which have been identified as being transitions in $\text{Hf}^{178,179,180}$. This spectrum is shown for comparative purposes only, since our experimental

Fig. 278. Spectrum from capture in the 7.8-eV resonance of $\text{Hf}^{178} + n$.

information actually comes from data obtained with resonance-energy neutrons.

Figure 278, for example, shows the spectrum obtained with 7.8-eV neutrons, corresponding to capture in the first resonance in Hf^{178} . A background peak in O^{16} is seen at 6.128 MeV. The capture state in Hf^{179} , with spin $\frac{1}{2}^+$, will decay by primary transitions to states of spin $\frac{1}{2}$ and $\frac{3}{2}$. The first known low-spin state in the nucleus is the $\frac{1}{2}^- [510]$ state at 377 keV. Peak 19 in the spectrum is from the gamma ray directly populating this state. The state populated by gamma ray number 23 is the $\frac{3}{2}^-$ rotational member of the $[510]$ band.

Gamma ray number 35 populates a state at 682 keV, which is believed to be the $\frac{3}{2}^-$ member of the $[521]$ band. Other gamma rays seen between 4.0 and 4.5 MeV populate states from 1.431 to 1.756 MeV above ground.

The spectrum information on Hf^{179} is tabulated in Table XLIV. Very good agreement is seen between our energy values for the two lowest-energy transitions and the values reported by Namenson, Jackson, and Smither.¹ Six of the peaks previously noted in the 0.06-eV spectrum are seen to be transitions in Hf^{179} .

TABLE XLIV. Transitions in Hf^{179}

Peak No.	Gamma-ray energy (keV)		Excitation energy (keV)	Transition energy (keV)	Namenson, Jackson, and Smither ^a
	$E_n = 0.06 \text{ eV}$	$E_n = 7.8 \text{ eV}$			
19	5723	5722	377	5722	5720
23	5676	5676	423	5676	5676
35	5416	5417	682	5417	
37		4668	1431	4668	
38		4568	1531	4568	
39		4526	1573	4526	
40		4493	1606	4493	
41	4394	4392	1706	4393	
42	4373	4372	1727	4372	
43	4345	4342	1756	4343	

^aReference 1.

The three resonances leading to states in Hf^{178} that we studied are at energies of 1.1, 2.4, and 5.9 eV. Spins have been assigned to these resonances by two different groups, one using a resonance scattering method and the other using a coincidence capture gamma-ray technique. Both groups assigned 3^- to the 1.1- and 5.9-eV resonances and 4^- to the one at 2.4 eV. Our spectrum from the 1.1-eV irradiation is shown in Fig. 279. Peak 1 corresponds to a gamma ray populating the 93-keV 2^+ rotational state in Hf^{178} . Gamma rays 3 and 4 go to states of spin 2^+ with excitation energies of 1.174 and 1.267 MeV. Several other lower-energy transitions are also seen.

Figure 280 shows the spectrum obtained at 5.9 eV. This 3^- resonance de-excites with a similar pattern except that the 308-keV 4^+ member of the ground-state rotational band receives primary population as indicated by the presence of peak number 2 corresponding to this transition. Less population of states by transitions near 6 MeV is also noted.

Fig. 279. Spectrum from capture in the 1.1-eV resonance of $\text{Hf}^{177} + n$.

Fig. 280. Spectrum from capture in the 5.9-eV resonance of $\text{Hf}^{177} + n$.

Figure 281 shows the spectrum associated with the 2.4-eV resonance. This was the resonance assigned as 4^- . Indeed, its pattern of de-excitation is different. No transitions are seen with energies greater than 6.4 MeV, which would be the primary transition to the ground-state band. The state at 1.174 MeV, which is probably a 2^+ state, is also not populated. This would be consistent with the 4^- assignment. Peak 4, a gamma ray of 6.355 MeV, however, populates

Fig. 281. Spectrum from capture in the 2.4-eV resonance of $\text{Hf}^{177} + n$.

a state at 1.267 MeV which is well known from reaction and decay-scheme studies and has spin and parity 2^+ , assigned with a very high degree of certainty. Since primary M2 transitions can be ruled out with great certainty, we must suggest that the 4^- assignment is in error and that this resonance must rather have a spin of 3, the same as the other two resonances studied.

Table XLV lists our data on Hf^{178} . Also shown are the data of Namenson et al.¹ The agreement in energies is surprisingly good between the two studies.

As a summary of the Hf^{178} data, Fig. 282 shows the transition patterns from the three states plus the transitions seen at 0.06 eV. Short bars on the right-hand side indicate states that we did not see, but that were assigned to this isotope by Namenson et al. States seen by us and not previously reported are indicated by asterisks.

TABLE XLV. Transitions in Hf^{178} .

Peak No.	Gamma-ray energy (keV)				Excitation energy (keV)	Transition energy (keV)	Namenson, Jackson & Smither ^a
	$E_n = 0.06 \text{ eV}$	$E_n = 1.1 \text{ eV}$	$E_n = 2.4 \text{ eV}$	$E_n = 5.9 \text{ eV}$			
1		7530		7528	93	7529	7530
2				7314	308	7314	7317
3	6449	6448		6447	1174	6448	6445
4	6356	6349	6355	6354	1267	6355	6354
5		6241	6240	6237	1382	6240	6240
6		6214			1408	6214	6214
7	6110	6111			1512	6110	6110
8			6091		1531	6091	6091
9	6060	6061			1561	6061	6063
10			6029		1593	6029	
11	5988		5989		1634	5988	5985
12			5982		1640	5982	
13			5819		1803	5819	
14	5805	5806		5809	1816	5806	5802
15				5775	1848	5775	
16	5763		5762	5763	1859	5763	5759
17	5754	5753	5748		1870	5752	5751
18		5733			1889	5733	
20		5711			1911	5711	5707
22		5680			1942	5680	5679
24		5669			1953	5669	5666
26		5637			1985	5637	5635
27			5627		1995	5627	5623
28		5612			2010	5612	5610
30		5583			2039	5583	
31	5573	5574			2048	5574	5574
32	5504	5505	5508		2116	5506	
33	5473	5470			2151	5471	
34	5416		5419		2204	5418	
37			5352		2270	5352	

^aReference 1.

Fig. 282. States in Hf^{178} . Bars show states reported by Namenson *et al.* (Ref. 1) but not seen by us. Asterisks show states not previously reported.

* * *

L. M. BOLLINGER, Argonne National Laboratory: In my opinion, the assignment of Jackson and Coté (paper I-1) is so certain that you have to look for some other explanation for your result on the 1268-keV state in Hf^{178} .

FALER: This morning we saw the data they had used, and the assignment is very convincing. There are, of course, other explanations. This peak may be from a background contaminant, although it is very unlikely that such a contaminant would have exactly that gamma-ray energy and also a resonance at 2.4 eV. I think we can probably eliminate that possibility. Another possibility is that the spin of that state might possibly have been incorrectly assigned from decay-scheme work. However, it is rather clearly seen to decay to the 0^+ , 2^+ , and 4^+ members of the ground-state rotational band; and this indicates very strongly that it has to be a 2^+ state. One might also invoke the possibility of having a doublet at that energy. If so, the doublet would have a separation of only a few keV. (Our energy agrees with that of the decay-scheme

people within 1 keV.) Also, its spin would have to be something other than 2^+ . There is certainly some worry here, but on examination these other possibilities do not look any more attractive than disagreeing with Coté's assignment. So I am afraid we will have to stick by that opinion for now.*

SPENCER: I would like to ask Dr. Bollinger if there is any other evidence that this is a 4^- level? That is, are there scattering data or data from other people? From Coté's data alone, the lack of the transition to the first excited state, which is 2^+ , is not enough to assign the spin unambiguously. Isn't that correct?

BOLLINGER: No, it is not correct. The data that Coté presented this morning, and similar data obtained for a wide class of other nuclides, are of two-step cascades having the very special property of averaging over a large number of intermediate states. Thus for a nuclide that behaves properly, as this one seems to, the intensity of two-step cascades does not fluctuate all over the map. Rather, it is a quantity that is constant to within the accuracy with which we have been able to measure it.

SPENCER: Were you looking at the total spectrum or just at the high-energy end?

BOLLINGER: The assignment was based on the high-energy end of the two-step-cascade spectrum. This is a special kind of coincidence spectrum that has very special properties.

* Since the meeting, at least three groups (including the authors) have shown that this 1268-keV state in Hf^{178} is a doublet.

MEASUREMENT OF RESONANCE-CAPTURE GAMMA-RAY SPECTRA WITH A $1/E$ NEUTRON SPECTRUM*

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In this paper I want to tell you about the use of the internal-target facility at CP-5 for the study of resonance capture. First, let me remind you what the facility is. It was described in some detail by Thomas (paper B-1) the day before yesterday. Figure 283 shows the facility. The target is mounted in the center of the straight-through hole in the reactor CP-5. The collimation is arranged so that the only source of radiation viewed by the detector is the target itself. Now, of course, with an ordinary target most of the neutrons that are captured in the target are thermal neutrons. However, because we are in a high-flux region of the reactor, some resonance-energy neutrons are also detected. And if we could somehow separate out these resonance-capture events, we might have something of interest.

In these measurements our first idea was to try to look at capture in individual resonances, principally in light nuclides. These

Fig. 283. Internal-target facility at CP-5.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

TABLE XLVI. Uses of average-resonance-capture spectra.

-
1. Study of capture mechanisms, including dependence on
a) γ -ray energy
b) character of final state
c) character of initial state
d) multipolarity
e) parity change
2. Spectroscopic information about low-energy states
a) energy
b) parity
c) spin
-

would have been experiments similar to those described earlier by Slaughter (paper E-4). Because of the lack of time, I won't tell you anything about these experiments, although there are many interesting aspects to them. I can quickly summarize the results, however, by saying that

there aren't any. We have failed completely in this endeavor. This is not to say that the experiment is impossible; it is merely difficult. What I do want to tell you about is our effort to study the average spectrum that results from capture of neutrons in many resonances. And I think you will appreciate, from all that has been said in the last 24 hours, that this is a subject of considerable interest.

The basic idea in these experiments is to select capture in a relatively narrow band of neutron energy by, on the one hand, limiting the contribution from low-energy neutrons by using an absorber and, on the other hand, depending on the $1/E$ spectrum of the incident neutrons to limit the effect of high-energy capture. The general motivation behind experiments of this sort is to try to measure partial radiation widths that are free of the Porter-Thomas fluctuations that plague the study of high-energy transitions.

More specifically, Table XLVI shows some of the things that one might hope to learn by measuring average-resonance-capture spectra of good quality. There are two rather different points of view that might be adopted. The first would be to focus attention on the study of capture mechanisms; in particular, one might be interested in studying

how the average radiation widths depend on the multipolarity, on the gamma-ray energy, on the character of the final state, or on the character of the initial state. Then once the dependence on these quantities became well understood, one might hope to use the spectra to obtain spectroscopic information—in particular, to obtain information about the energies, parities, and spins of the final states, and possibly to learn something about the average characteristics of the initial states.

In our first measurement we wanted to work with a nuclide that is relatively well understood. For this purpose we chose to study capture in Pt^{195} , a material that has been widely studied. As shown in Fig. 284, the Pt sample is surrounded by a blanket of B^{10} and the B^{10} is enveloped in a graphite container, which serves only to hold things together. The thickness of the B^{10} was one absorption mean free path at an energy of about 200 eV.

The detector views this sample along the axis and the collimation is arranged so that only the central portion of the sample is seen by the detector.

Figure 285 shows the spectrum that was obtained. It has a great many interesting features. First, notice that there are transitions to all of the known low-energy states in Pt^{196} —to the ground state, the first excited state, and so on. These peaks march right along. Second, the intensities of all these transitions are roughly equal; this is to be contrasted with the great fluctuations that one observes in the spectrum of a single resonance. Third, the spectrum becomes quite complex rather suddenly at energies less than about 6.2 MeV. This is partly because at this point the density of states in Pt^{196} increases rapidly, and partly because at this point we begin to have contributions

Fig. 284. A B^{10} -surrounded platinum sample used in an average-resonance-capture measurement.

Fig. 285. Average-resonance-capture spectrum for the reaction $\text{Pt}^{195}(n, \gamma)\text{Pt}^{196}$ in comparison with the spectrum for a single resonance. The energies associated with the peaks are the energies of the final states for the high-energy transitions.

from the even-odd target nuclides which are present in the normal-Pt target that is being studied.

There are also some interesting technological features to the spectrum. Notice first the high counting rates—counting rates measured in thousands of counts per day. This again is to be contrasted with the rather miserable situation when a single resonance is studied. Second, notice the low background. Our main source of background comes from materials that are present in the sample itself, namely the boron (which shows up in the form of two strong lines) and the carbon (which has strong lines off scale).

Now let us examine these data more quantitatively in Table XLVII. Here we have the relative intensities of transitions to the various final states listed; and these intensities are compared with the results obtained by Jackson et al. at Saclay. The agreement seems to be excellent.

TABLE XLVII. Average intensities measured with a thin (0.30 g/cm²) B¹⁰ absorber. The data are normalized at the ground-state transition.

Gamma-ray energy (MeV)	Final-state energy (keV)	Relative intensity	
		Jackson <u>et al.</u>	This experiment ^a
7.920	0	2.0	2.0
7.564	356	1.2	1.25
7.231	689	1.4	1.24
6.777	1143	0.7	0.75
6.560	1360	...	0.70
6.516	1404	1.1	0.79
6.310	1610	...	0.66
6.237	1683	...	0.77

^aAll values $\pm 20\%$.

A key question that people will want to ask now is this: Is there any evidence at all that the average intensities of transitions to the various low-lying states differ significantly? That question is considered in the last column, where we have listed the reduced radiation width—the width divided by the third power of the energy. One notices that there are variations, but qualitatively one feels that these variations are what would be expected for a sample of resonances such as the one responsible for the measured spectrum.

Let us consider that question a little more quantitatively, as follows. From the observed fluctuations we calculate that the amount of fluctuation in the intensities would be consistent with a χ^2 distribution with 70 degrees of freedom. That is, the fluctuations indicate that in effect we are averaging over something like 70 resonances. This is to be compared with our rather crude estimate that we are averaging over about 30 resonances. Therefore, there is a slight anomaly; but the anomaly is in such a direction that we can with certainty say that there is no evidence whatever for differences in the average radiation widths of transitions to various states.

Fig. 286. Gamma-ray line shapes in an average-resonance-capture spectrum.

capture in boron. There is a distinct difference; and this difference can be explained qualitatively, at least, in terms of the wider spectrum of neutrons involved in capture in platinum.

We can say with certainty, then, that all of the high-energy transitions observed in Pt^{196} are primary transitions. There was no doubt of this, I suppose, but it is nice to have it tied down.

Now that we have tested our new method of measurement, we are ready to do some physics with it. Naturally, the first case we have chosen to study has been capture in W^{182} which was discussed at length in an earlier paper (paper I-4). The results obtained are shown in Fig. 287. Here there are some technological problems caused by background. Nevertheless, we are able to see very clearly some of the lines that are of interest, namely the lines that result from the primary transitions to three low-energy states in W^{183} .

There is one amusing feature of these spectra that you might not have been able to observe in the measured spectrum (Fig. 285); it has to do with the line widths. Because our spectrum is formed by contributions from a range of neutron energy, in principle one would expect the line shape to reflect this averaging process. It turns out that it is surprisingly easy to observe this effect.

In Fig. 286, the line shape from capture in Pt is compared with the line shape obtained from

Fig. 287. Average-resonance-capture spectrum for the reaction $W^{182}(n, \gamma)W^{183}$.

The average intensities of the high-energy W^{183} lines are shown in the inset on the figure. One sees that there is no difference whatever between the average intensities of the transitions to the first two states. And although the measured intensity of the transition to the state at 210 keV is somewhat smaller, it is certainly not smaller than can be accounted for by statistical fluctuations. As a result, we feel that we have demolished whatever evidence there might have been that there are differences among the average widths for radiative transitions to the various low-energy states of W^{183} .

* * *

R. E. CHRIEN, Brookhaven National Laboratory: I really don't understand what meaning can be given to these average intensities. The contribution of each resonance presumably would be weighted by a factor something like Γ_n/E_0^2 , where Γ_n is the neutron width of the resonance and E_0 is the resonance energy. This is to take account of the $1/E$ spectrum. Therefore you have a highly distorted average, it seems to me, rather than a straight average over resonances. How do you interpret this highly distorted average?

BOLLINGER: What you say is undoubtedly true; things are highly distorted. In answer to your question about the interpretation, Fig. 288

Fig. 288. Spectrum of neutrons captured in a Pt^{195} sample surrounded by B^{10} . The vertical lines give the energies of known $J=1$ resonances in Pt^{195} .

gives a qualitative indication of what we think is the spectrum of neutrons captured in the boron-surrounded sample. The known resonances with $J = 1$ are indicated by the vertical lines. This capture spectrum undoubtedly has the unfortunate effect of emphasizing the resonances in one energy region in comparison with those at another energy. Nevertheless, if the energy range of the spectrum is adjusted (by adjusting the absorber) so that contributions come from a large

number of resonances, then the measurement gives a meaningful average—even though one cannot understand in detail which resonances contribute to the average. That is the basic philosophy of the measurement.

CHRIEN: Are you saying that by using different absorbers and thereby varying the weighting function you can hope to unravel the contributions of all the resonances?

BOLLINGER: No. What I am saying is that it is not necessary to understand how individual resonances contribute to the average. With a sufficiently thick absorber, one is in effect averaging over a very large number of resonances—even though some of them will be contributing more than others. The basic assumption of the measurement is that one has contributions from resonances that are all of effectively the same character, namely s-wave resonances.

CHRIEN: One other comment: You called this resonance capture, but there may also be an off-resonance component. If so, it would influence your results. Would you care to comment on that?

BOLLINGER: What you say is undoubtedly true. In fact, it might turn out to be one of the more interesting things to try in the future. It may or may not be possible to look for a difference between the spectra that result from capture at all neutron energies and the spectra formed when capture at resonances is somehow inhibited.

G. G. SLAUGHTER, Oak Ridge National Laboratory: Do I correctly assume that these transitions that showed such a uniform average over resonances were all of the same multipolarity and involved the same parity change?

BOLLINGER: There still is not enough independent evidence to answer your question with complete certainty. If one had a good understanding of the characteristics of the high-energy transitions in a particular nucleus, such as Pt^{196} , then an observed line of unknown character could be used to gain spectroscopic information about the low-lying state.

SESSION J

4 NOVEMBER 1966

PANEL DISCUSSION SUMMARIZING THE MEETING

L. M. BOLLINGER, CHAIRMAN

R. E. CHRIEN

J. A. HARVEY

O. W. B. SCHULT

J. VERVIER

J. PANEL DISCUSSION SUMMARIZING THE MEETING

Members of the panel:

L. M. Bollinger, Argonne National Laboratory (chairman)
R. E. Chrien, Brookhaven National Laboratory
J. A. Harvey, Oak Ridge National Laboratory
O. W. B. Schult, Technical University, Munich, and
Brookhaven National Laboratory
J. Vervier, C.E.N.-S.C.K., Mol, Belgium

BOLLINGER: The purpose of the discussion this afternoon is to summarize the conference in a meaningful way by asking the panel members to answer questions that will encourage them to comment on significant or controversial matters considered during the conference. The panelists have been urged to state their opinions in fairly categorical terms, in the hope that this will stimulate discussion. Whether this will work or not remains to be seen.

To provide a framework within which to conduct this session, a series of about twelve questions has been submitted to the panel members in advance. Each panel member has been asked to take the primary responsibility for answering a particular small set of questions. The first response will be of moderate length, something like five minutes; then other panel members will either quarrel with this response or add to it—and you in the audience will also be invited to contribute to the discussion.

We will start off on primarily technological matters—on a class of questions that you might label as being germanium-diode technology. Next we will go on to some questions that have to do with the technology of determining decay schemes and, intermixed with this, the technology of various experimental facilities as a whole. And finally, we will consider a set of questions having to do with the physics of capture gamma-ray spectra.

Let's start off with a very basic technological question. I will ask Jack Harvey to give us a reliable set of reference lines for use in determining the energies of capture gamma-ray lines and to indicate how accurately the energies and intensities of neutron-capture gamma rays can be measured.

HARVEY: First let me say how pleased I was with yesterday afternoon's session (Session F) on precise determinations of gamma-ray energies. For the past year or so, we have been using gamma rays from neutron capture in chlorine for calibration; but the energies of the high-energy gamma rays were known to an accuracy of only 5 keV. I was gratified to see that the energies of high-energy capture gamma rays are now measured to about an order of magnitude higher accuracy.

Let me first consider the low-energy region below ~ 3 MeV. The accurate determination of the energies of gamma rays in this region has in general presented no problems for experimenters using germanium detectors. The energies of many gamma rays in this energy range have been measured very accurately in the past few years. Some of the precise values obtained recently at Livermore by White and Groves (paper F-4) are listed in Table XLVIII. To show the kind of agreement attained in this energy region, I have also included some results of Black and Heath¹ at the Materials Testing Reactor, Murray *et al.*² at Chalk River and others. The agreement between values from the different experimenters is very good, ~ 0.1 keV. There are several other gamma rays up to 3 MeV (not included in Table XLVIII) whose energies are also measured to an accuracy of ~ 0.1 keV. What I think was a significant contribution at this meeting was the precise determination of the energies of the several gamma rays which often occur as

¹W. W. Black and R. L. Heath, Nucl. Phys. A90, 650 (1967).

²G. Murray, R. L. Graham, and J. S. Geiger, Nucl. Phys. 63, 353 (1965).

TABLE XLVIII. Examples of accurate standards of low-energy gamma rays (in keV).

Element or isotope	LRL White and Groves ^a	NRTS	Chalk River	ORNL Robinson et al. ^b	Others
¹⁴¹ Ce	145.41 ± 0.03	145.44 ± 0.05 ^c			
⁵¹ Cr	320.11 ± 0.03	320.07 ± 0.05 ^c		319.8 ± 0.3	
⁸⁸ Y		898.01 ± 0.07 ^c		898.2 ± 0.4	
⁶⁰ Co	1173.25 ± 0.08		1173.23 ± 0.04 ^d		
²² Na	1274.58 ± 0.10	1274.52 ± 0.07 ^c		1274.6 ± 0.3	
⁴¹ Ar	1293.76 ± 0.14				
⁶⁰ Co	1332.56 ± 0.05		1332.48 ± 0.05 ^d		
²⁴ Na			1368.53 ± 0.04 ^d		
²⁸ Al	1778.70 ± 0.17				{ 1778.7 ± 0.7 ^e 1777.8 ± 0.6 ^f
⁸⁸ Y	1836.17 ± 0.12	1836.08 ± 0.07 ^c		1836.2 ± 0.3	
H(n, γ)		2223.29 ± 0.07 ^g	2223.18 ± 0.20 ^h		2223.2 ± 0.1 ⁱ
²⁰⁸ Tl			2614.47 ± 0.10 ^d		
²⁴ Na			2753.92 ± 0.12 ^d		

^aD. H. White and D. J. Groves, paper F-4, this conference. These values were based on an annihilation gamma energy of 511.003 ± 0.005 keV, and ¹⁸²Ta, ¹⁹²Ir, ¹⁹⁸Au, and ¹³⁷Cs.

^bR. L. Robinson, P. H. Stelson, F. K. McGowan, J. L. C. Ford, and W. T. Milner, Nucl. Phys. 74, 281 (1965).

^cW. W. Black and R. L. Heath, Nucl. Phys. A90, 650 (1967).

^dG. Murray, R. L. Graham, and J. S. Geiger, Nucl. Phys. 63, 353 (1965). These values were calibrated with the (411.795 ± 0.009) -keV gamma ray in ¹⁹⁸Hg.

^eE. Bieber, paper E-1, this conference.

^fD. E. Alburger and K. W. Jones, Phys. Rev. 149, 743 (1966).

^gR. C. Greenwood and W. W. Black, Phys. Letters 21, 702 (1966).

^hJ. W. Knowles, Can. J. Phys. 40, 257 (1962).

ⁱJ. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. 67, 32 (1965).

background lines in neutron-capture gamma-ray spectra. For example, the energies of the gamma rays from ^{41}Ar and ^{28}Al were previously known only to ~ 2 keV, but they have now been measured to an order of magnitude higher accuracy.

Now let me consider the high-energy region above ~ 3 MeV. The accuracy of the energies of high-energy gamma rays has recently been greatly improved. The technique employed in the impressive work of Greenwood (paper F-1) was to look for gamma-ray cascades whose double-escape peaks are at < 3 MeV and to use these to build up to the neutron binding energy by a bootstrap method. From this binding energy and precise energies of the low-energy gamma rays, he obtained the energies of the high-energy primary gamma rays. In addition, double-escape peaks can be compared with the full-energy peaks of gamma rays whose energies are about 1 MeV lower and known accurately. Greenwood has listed values to an accuracy of 0.5 keV. Judging from the effort he has devoted to the problem, I am willing to believe that they are accurate to 0.5 keV. Some of Greenwood's results are listed in Table XLIX and are compared with values obtained at CR, ANL, BNL, and LASL. In general the agreement is very good. The only possible disagreement is for ^{16}N . The unpublished data of Jones *et al.*³ used gamma rays from ^{56}Co , ^{60}Co , and ^{24}Na as calibrations. Their values are preliminary, which I interpret to mean that their errors are meaningful but they reserve the right to make small changes in their values.

I would like to draw your attention to the value for $^{12}\text{C}(n,\gamma)$ determined by Prestwich *et al.*⁴ at ANL to an accuracy of 0.2 keV. This value given in Table XLIX agrees well with the value obtained from

³K. W. Jones (private communication). The work is now published with minor changes [C. Chasman, K. W. Jones, R. A. Ristinen, and D. E. Alburger, *Phys. Rev.* **159**, 830 (1967)].

⁴W. V. Prestwich (private communication). This has now been published [W. V. Prestwich, R. E. Coté, and G. E. Thomas, *Phys. Rev.* **161**, 1080 (1967)].

TABLE XLIX. Examples of accurate standards of high-energy gamma rays (in keV) from (n, γ) reactions on the indicated elements or separated isotopes.

Element or isotope	NRTS Greenwood ^a	CR Bartholomew <i>et al.</i> ^b	ANL	BNL Jones <i>et al.</i> ^c	LASL Carter and Motz ^d
C		4944.5 $\pm$ 1.4	4945.5 $\pm$ 0.2 ^e		4944.0
N	5269.6 $\pm$ 0.35	5270.5 $\pm$ 1.5		5270.4 $\pm$ 0.6	5267.8
N	5298.3 $\pm$ 0.35	5298.2 $\pm$ 1.5		5298.8 $\pm$ 0.6	5296.8
N	5533.5 $\pm$ 0.4	5532.7 $\pm$ 1.5			5532.7
N	5562.6 $\pm$ 0.4	5562.9 $\pm$ 1.5			5561.5
¹⁶ N	6128.9 $\pm$ 0.4		6128.9 $\pm$ 0.4 ^f	6130.0 $\pm$ 0.4	
Na	6395.1 $\pm$ 0.4				
Be	6809.4 $\pm$ 0.4		6811 $\pm$ 1 ^g		6808.0
Fe		7645 $\pm$ 2	7646 $\pm$ 1 ^g		
Al		7725 $\pm$ 2	7722 $\pm$ 1 ^g		
N	10829.7 $\pm$ 0.7	10830.1 $\pm$ 1.8	10830.6 $\pm$ 0.9 ^h		10828.1

^aR. C. Greenwood, paper F-1 of this conference.

^bG. A. Bartholomew, E. D. Earle, and M. R. Gunye, Can. J. Phys. **44**, 2111 (1966).

^cK. W. Jones (private communication to this conference via W. R. Kane). (These are preliminary values and do not include the error in the ⁵⁸Co used as standard.) This has now been published [C. Chasman, K. W. Jones, R. A. Ristinen, and D. E. Alburger, Phys. Rev. **159**, 830 (1967)].

^dR. E. Carter and H. T. Motz, in *International Conference on Nuclear Physics with Reactor Neutrons* (Argonne National Laboratory, Argonne, Illinois, 1963), Report No. ANL-6797, p. 179. The errors in these results are 1—2 keV [private communication, this conference].

^eW. V. Prestwich (private communication, this conference). This has now been published [W. V. Prestwich, R. E. Coté, and G. E. Thomas, Phys. Rev. **161**, 1080 (1967)].

^fR. E. Coté (private communication, this conference).

^gH. E. Jackson, A. I. Namenson, and G. E. Thomas, Phys. Letters **17**, 324 (1965).

^hJ. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. **67**, 32 (1965).

masses. Note that all the high-energy gamma rays listed in Table XLIX are from neutron capture except for the ¹⁶N beta decay. During this conference we also heard a paper from McMaster University on the silicon isotopes (paper F-3) where consistencies of ~ 0.5 keV were obtained and the energies of high-energy capture gamma rays were quoted to 1 keV. Similarly, in the (n, γ) work on chromium from Brookhaven (paper F-2), the energies of the high-energy gamma rays were quoted to an accuracy of ~ 1 keV. Thus, I conclude that we now

have many high-energy gamma rays whose energies are now known to better than 1 keV and several are known to ~ 0.5 keV.

However, I would like to point out that there are other gamma rays whose energies we would very much like to know accurately. These gamma rays are the ones which often occur as background lines and can be very useful for energy calibrations. For example, the intense high-energy gamma rays from neutron capture in Al, Pb, Fe, Cl, etc. would be very valuable secondary standards. At present, I would estimate that these are probably known to only a few keV. There are also a few other nuclides which would be valuable as secondary standards. However, since highly accurate energy measurements require a lot of effort, it will be necessary for experimenters to agree on a few most valuable nuclides and perhaps someone can be induced to measure the energies of their gamma rays very accurately.

H. T. MOTZ, Los Alamos Scientific Laboratory: With reference to the γ -ray energies in Harvey's Table XLIX, I would like to point out that the Los Alamos values were calibrated relative to the sodium line at 2.7 MeV. Thus our energy scale was completely independent of any mass measurement.

BOLLINGER: Jack, would you want to come back to the mike and make a summary statement as to how this is supposed to be?

HARVEY: I believe that the energy of gamma rays in the 5—8- and even 10-MeV region can be measured to an accuracy of $\lesssim 1$ keV. I think the 3-year-old LASL data are accurate to 1—2 keV.

MOTZ: Oh, yes. These discrepancies are within the absolute errors of those measurements. There is no doubt about that; 2 keV would be a reasonable estimate of the error.

BOLLINGER: Then unless there is some quarrel with it, let's go on to the second part of this question, which was concerned with how much we know about techniques of measuring intensities of gamma-ray lines.

In this connection, I would be particularly interested in the question of whether we need a much more comprehensive calculation of the response function for germanium diodes.

HARVEY: Again let me divide my answer into a low-energy and a high-energy gamma-ray region. For the low-energy gamma rays, below ~ 3 MeV, things are in good shape. Here we can measure absolute intensities to an accuracy of $\sim 5\%$.

For higher-energy gamma rays things are somewhat poorer. Kane (paper F-2) stated that the intensities of high-energy gamma rays measured with magnetic spectrometers may be accurate to 15% but are often accurate only to 30%. These measurements can be used to determine the efficiency of a Ge detector to an accuracy of $\sim 15\%$.

The only Monte Carlo calculation that I am familiar with is that done at the University of Montreal.⁵ With a Ge crystal 7 or 8 mm thick, these calculations showed that above ~ 3 MeV the efficiency was constant. However, the experimental efficiency curve showed by Carpenter (Fig. 198, paper G-3), for a detector of comparable size, dropped off by a factor of three or four in this high-energy region—in marked conflict with the calculations. At present, Monte Carlo calculations, with the assumptions that have been made, are not accurate for the thicker detectors. If other effects such as bremsstrahlung production (which is important for high-energy gamma rays) were included, the calculations might give better agreement. However, I won't venture a comment on just how accurately the efficiency might be calculated in the future.

V. J. ORPHAN, Massachusetts Institute of Technology: I think that the accuracy of a Monte Carlo calculation of detector efficiency

⁵N. V. deCastro Faria and R. J. A. Levesque, IEEE Trans. Nucl. Sci. NS-13, 363 (June 1966).

might be limited by the accuracy with which the gamma-ray attenuation coefficients are presently known. I feel that you still have to carry out calibration experiments to obtain a reliable efficiency curve for the detector.

HARVEY: I am surprised. I would have thought the cross sections for all processes were well known.

ORPHAN: The pair cross sections, for example, are not well known.

R. C. GREENWOOD, Idaho Nuclear Corporation: Only the total cross section is well known.

HARVEY: To what accuracy would you say the pair cross section is known?

ORPHAN: About 3%, so perhaps the uncertainty in the cross section is not as important as I first thought. Nevertheless, I believe that since you have to correct for bremsstrahlung in the calculation, you still would have to measure the efficiency experimentally—at least at a few points—before you could believe the efficiency curve.

G. T. EMERY, Indiana University: I think the curve that Kane presented in his report on the $\text{Cr}^{53}(n,\gamma)$ reaction (paper F-2) is a step in the right direction. It is only a partial curve with a few points on it in the high-energy region. But, if one can use that same technique on several isotopes (two or three isotopes, I think, would be enough), then I think one can tie down the high-energy intensity curve to something of the order of 10%. I think it will be a long time before the Monte Carlo calculations will approach that accuracy, or at least that believability.

ORPHAN: We have used the capture gamma rays from several elements to determine the efficiency curve for a Ge(Li) pair spectrometer from about 1 MeV to 9 MeV. The agreement between efficiency curves obtained with strong gamma rays from different elements is quite good.

HARVEY: Which elements? Do you need to know the absolute intensities of these gamma rays, or are you making relative intensity determinations?

ORPHAN: We used Groshev's magnetic Compton spectrometer data⁶ for Hg, Fe, and Ni. We obtained a relative-efficiency curve which was then normalized to a measurement of the absolute efficiency at several energy points. (We used decay gamma rays from several calibrated sources for the absolute efficiency determination.)

HARVEY: How accurate do you think Groshev's intensity values are?

ORPHAN: Groshev claims an accuracy of 15—20% for the most intense gamma rays. We observe a scatter of experimental points when we use Groshev's data to determine an efficiency curve. By taking the average of efficiency curves obtained from several different elements, we feel we have a more reliable curve than could be determined by using the data from only a single element—such as chlorine. The accuracy of our curve has been independently checked by using it to determine the intensities of capture gamma rays from Be, which has a simple decay scheme. The intensities obtained are consistent with the known Be decay scheme within less than 10%.

HARVEY: We also have tried chlorine and the points scatter by about 50%.

MOTZ: The technique of assuming a decay scheme and balancing the input and output intensities is a unique one, when you know that

⁶For Hg: L. V. Groshev, A. M. Demidov, V. A. Ivanov, V. N. Lutsenko, and V. I. Pelekhov, *Izv. Akad. Nauk SSSR, Ser. Fiz.* 27, 1377-1391 (November 1963) [English transl.: *Bull. Acad. Sci. USSR* 27, 1353 (1964)]. For Fe: L. V. Groshev, A. M. Demidov, G. A. Kotelnikov, and V. N. Lutsenko, *Nucl. Phys.* 58, 465 (1964). For Ni: L. V. Groshev, A. M. Demidov, V. N. Lutsenko, and V. I. Pelekhov, Atlas of γ -Ray Spectra from Radiative Capture of Thermal Neutrons, translated by J. B. Sykes (Pergamon Press, London, 1959).

decay scheme. This was presented (Kane and Mariscotti, paper F-2) for chromium, and was the technique used for nitrogen, for actually getting the sensitivity of the Compton spectrometer. In the case of N^{15} , I think there are something like 18 or 19 gamma rays in the thermal capture. At the time we took the data, within the accuracies of a few keV there was a possible dual placement of only one of these gamma rays, and it was a very weak one. All the other ones fitted uniquely into the decay schemes so there is no doubt about the feeding and the decay. One can balance these things very well.

If, similarly, people can determine decay schemes (e.g., for chlorine) with high reliability so all the gamma rays are placed, then the same technique could be extended to other energies. That method gives unique values of the relative intensities. The total cross section of nitrogen was determined from the capture-gamma-ray spectra.

BOLLINGER: I think we'd better move on to the second question, which is very closely related to the first. This question is to be put to Otto Schult. To what accuracy should we measure the capture-gamma-ray energies and in what form should the data be reported in order to preserve whatever accuracy is inherent in the data?

SCHULT: Answering the first part of your question, I would think that a precision of about 0.5 keV for the energies of primary gamma transitions should be sufficient in order to establish a considerable part of the low-lying levels between which low-energy transitions should be fitted. The chance for accidental combinations can be reduced as the precision of the primary (n, γ) rays is improved. However, it might be difficult to obtain much more precise absolute energy values E_γ (in keV). It is fairly easy to measure relative γ -ray energies $E_{\gamma,rel}$ which satisfy the numerical condition $|E_\gamma - E_{\gamma,rel}|/E_\gamma < 10^{-4}$. If the energy differences $E_{\gamma,rel(1)} - E_{\gamma,rel(2)}$ are determined with high accuracy for all pairs of indices (1) and (2), these differences will be more useful during the application of the energy combination principle.

At this point I should answer the second question of Dr. Bollinger. May I suggest that the data should be reported as relative γ -ray energies $E_{\gamma,rel}$ given in such a way that they agree with the absolute energy values E_{γ} (keV) computed with the use of a standard E_{γ}^0 (keV) whose absolute error dE_{γ}^0 (keV) has not been included in the errors of the relative γ -ray energies. These errors $dE_{\gamma,rel}$ can (for obvious reasons) be given in keV. This form of reporting the experimental data will preserve the maximum accuracy and it will be most useful for energy combinations. The energies of low-energy (n,γ) transitions may also be given as relative energies. Here it will usually be possible to achieve $|E_{\gamma} - E_{\gamma,rel}|/E_{\gamma} < 3 \times 10^{-5}$, so that it will not cause trouble to match the high-energy and low-energy data. The relative energies should be measured with the maximum accuracy that can be obtained. At the present time, the limit seems to be $dE_{\gamma,rel}/E_{\gamma,rel} \approx 10^{-5}$ for $E_{\gamma} < 150$ keV. A considerable improvement would be valuable.

BOLLINGER: Do you see any steps that ought to be taken now to improve the precision by another factor of 5 — 10, or whatever it might be?

SCHULT: I have the feeling that an accuracy of 0.5 keV for the absolute energies of primary (n,γ) transitions is sufficient at the present time. This is even a fair precision for the relative energies of primary γ rays. The utmost precision is, however, fundamental during the measurement of low-energy transitions.

BOLLINGER: Does anyone want to quarrel with this conclusion which, as I understand it, is that an accuracy of roughly 0.5 keV is as much as we need at this time?

GREENWOOD: I would like to say, with regard to the errors I have quoted on my data (paper F-1), that you can't reduce the error values much more without first improving the precision of the standards on which the data are based. The 2.75-MeV gamma ray which is emitted in the

15-h beta decay of Na^{24} was primarily used as the standard in my work. Since there is an uncertainty of ± 0.12 keV associated with the energy of this gamma ray, the contribution that this error in the standard will make to the error assignment on a 7-MeV gamma ray measured with the "boot-strap" technique will be ± 0.24 keV. Thus, I feel that any major improvement in the energy precision of high-energy gamma rays would first have to start with an improvement in the energy precision of some of the lower-energy gamma rays, especially the gamma rays in the 2—3-MeV region.

BOLLINGER: Any further comment?

BOLOTIN, Argonne National Laboratory: If people report their energy values as relative, I should hope that in the various energy regions everyone might standardize on what lines would be used as references; that is, possibly the carbon line can be used at 5 MeV and possibly the nitrogen line at 10 MeV. If people use different standards when they quote relative values, then it would be very difficult to up-date all the data once these standards are known much more accurately.

SCHULT: Which lines would you then propose for use as standards?

BOLOTIN: Naturally, the ones I would normally find are my background lines.

SCHULT: The trouble with this is that these lines may not be useful or that they simply cannot be used as standards if the low-energy (n, γ) spectrum is measured with a curved-crystal spectrometer which gives much more accurate energies than a $\text{Ge}(\text{Li})$ spectrometer for $E_{\gamma} < 500$ keV. Secondly, I can imagine that the experimentalist will arrange his experiment in such a manner that the background lines are as weak as possible. This will naturally imply that the positions of the standard lines are obtained with lower precision than the positions of the majority of the observed lines from the reaction under study. A background line with an energy greater than the binding energy of a neutron in the target nucleus will increase the background of the whole

spectrum and, therefore, impair the sensitivity of the Ge(Li) spectrometer. In addition, a serious systematic error may be introduced when background lines are used as standards: a weak (n, γ) line might have an energy so close to that of the standard that the Ge(Li) spectrometer cannot resolve these two lines. As a result, the centroid of the peak will differ from that of the standard.

For these reasons I would recommend that background lines should not be used as standards. I am convinced that the experimentalist may use any other standard that suits his experiment best. He must, of course, give E_{γ}^0 (keV) in his paper and he should also quote dE_{γ}^0 (keV).

MOTZ: With regard to references, the carbon and nitrogen, for example, and the beryllium are excellent primary standards. But, they have very low cross sections. The sensitivity of many of the single spectra we have seen here are adequate to use those, and in most cases the time consumed is not so great. But, there are setups like Jack Harvey's where he couldn't see the carbon and nitrogen. His background is higher. He would prefer to use chlorine. So chlorine should be a secondary standard. Another similar requirement would be for coincidence measurements. These are terrible standards for coincidence measurements. I would suggest not only the chlorine, and perhaps the iron, but also titanium for that purpose.

R. K. SMITHER, Argonne National Laboratory: I should like to make one further request in recording errors. Sometimes it is difficult in reading the article to determine what kind of an error is being quoted—whether it is the relative error, the root-mean-square error, the maximum probable error, or whatever. Some people tend to quote errors twice what the statistics imply. It would be nice to have everybody quote errors in the same terms, but that isn't a matter it is possible to legislate. It would be very convenient, however, if the publications would include some discussion of the errors.

One other thing about errors is important for many of us who are putting level schemes together. In using someone else's high-energy gamma rays, we are not too sensitive to their absolute errors, but very sensitive to the errors in the energy differences. If the error in the differences between the energies of high-energy gammas can be kept less than 0.5 keV, it makes the development of the level scheme much easier. In some cases, it should be possible to obtain even smaller errors in the relative energies of gammas—say, 0.2 keV for gammas differing in energy by 1 MeV. If pairs of such gammas are used to define level differences in the level scheme, then the chance of misplacing the lower-energy gammas obtained from the bent-crystal-spectrometer work is greatly reduced.

One more comment: The limit on the relative error in the spacing of two gamma rays is in many cases dependent upon their channel separation in the multichannel analyzer. I think that in many cases the relative errors in an expanded spectrum, obtained with a biased amplifier, could be lower than 0.5 keV without much trouble. I have compared a couple of high-energy and low-energy spectra, and I would say that the ease in putting the spectra together goes at least with the square of the energy precision.

BOLLINGER: Let's move on to another topic—another question addressed to Mr. Harvey. The question is: Should a major effort be mounted to develop an all-inclusive program for the analysis of germanium-diode data? If so, what features should be incorporated in it? Or are the relatively crude programs that people are now using good enough?

HARVEY: I think the relatively crude programs now being used are almost sufficient because the resolution of germanium detectors is very good. For such narrow peaks there is almost no reason for taking the elaborate approach of considering the whole spectrum as is necessary in analyzing sodium iodide spectra. In general, one has

to work with only the narrow individual peaks. The three fine papers in Session D on this subject were all based on this principle.

There is a question of how far one should make the analysis program automatic. Some prefer, and I am on that team, to look at the spectrum and do a little bit of analysis by eye (such as locating peaks) rather than asking the program to find them as in paper D-1. I certainly would not object to feeding the raw data into a computer, and have it tell me where it thinks the peaks are; but then I want to look at the spectrum and say "Yes, I agree," or "No, I know that this is a double peak," etc. If you have double peaks, or triples, it is much harder for the computer to determine this than for the experimenter and computer working together. I think there has to be some combination of the computer and experimenter in order to get the maximum out of your data. Obviously, it depends on how complicated the spectrum is. In conclusion, I think the present level of analysis of the germanium detector data is almost sufficient.

CHRIEN: I would like to disagree somewhat, because I feel that when thicker detectors are used, the spectra become considerably more complex. It is very important to know, say, the relative ratios of the single-escape peak to the double-escape peak. We find it fairly difficult to unravel a complicated spectrum. It is inefficient to rely on hand computational methods to calculate backgrounds or peak positions, and to make corrections for the multiply-peaked response of Ge detectors. Automation of much of this procedure is necessary to keep pace with the flow of data from the existing facilities. Effort put into programming automated procedures saves time and cuts down on error.

SLAUGHTER, Oak Ridge National Laboratory: I disagree with Jack (Harvey) with some trepidation, since he is my boss. If you have a very complicated spectrum in which even a germanium crystal will resolve only a few lines, then using the total response function to

unfold the data might tell you where the extra area lies; and you could perhaps make a meaningful comparison between the contribution of your lines and the total spectrum. Do you see what I mean?

HARVEY: Yes. But I don't think it is worth the effort.

SLAUGHTER: Neither do I.

HARVEY: With regard to Bob Chrien's comment, are not the double-escape peaks still five times as strong as the single-escape peaks are, even with a 30-cc detector?

CHRIEN: Yes, but the chance superimposition of these extra peaks on other peaks makes the analysis quite complicated. I am not sure that in a finite amount of time a human looking at all this can unravel the scheme and still keep his sanity.

BOLLINGER: On that cheerful note, we finish the first group of questions. We will now pass on to those that have to do with the technology of determining decay schemes and the technology of experimental facilities.

The first of these questions is addressed to Chrien. The way I have it phrased here is: With existing sources of neutrons, is it important to study both thermal capture and resonance capture to obtain information about the characteristics of low-energy states? In view of the excellent resonance-capture spectra we have seen at this meeting, I think I would like to rephrase the question. Is it really worth while to bother with thermal capture?

CHRIEN: Well, I think I would be taking my life in my hands if I said it is not worth while. It would certainly not be the correct answer anyway. It certainly is worth while to bother with thermal-capture spectra, if you want to put it that way. Let me make a few remarks.

Since the thermal-capture spectrum represents capture into an undefined mixture of initial states, it cannot give the maximum amount of information about the character of the final states populated

in the reaction. In order to interpret the data of (n,γ) reactions, it is important to know unambiguously the spin and parity of the initial state. Because of the random character of partial radiative widths, the most probable value in the width distribution (the Porter-Thomas distribution) is zero. Therefore, it frequently happens that a low-lying final state will fail to be directly fed in thermal capture, or only weakly fed. Furthermore, more level-level interference effects are very strong in the partial cross sections, and these effects influence the thermal spectra. For example, in $^{169}\text{Tm}(n,\gamma)^{170}\text{Tm}$ the ground-state transition is virtually absent in thermal capture but reasonably strong in the resonances. Conclusions regarding, for example, the correlation of (n,γ) and (d,p) strengths would be erroneous or misleading if based solely on thermal-capture data.

Such remarks apply as well to the suggestions raised by Bolotin (paper G-1) regarding the relative populating of the [512] and [510] Nilsson orbitals in the Hf and W region. Both resonance data from BNL (paper I-4) and average epithermal capture measurements from Argonne (paper I-11) show no systematic differences in the populating of these states from epithermal capture.

In addition to the above comments, it might be pointed out that p-wave capture can be important in the resonance region.

Nevertheless, the high intensities available from thermal capture are decisive in many experiments involving low-abundance isotopes and low cross sections. The thermal capture can provide calibration points for partial-width determinations, as in the case of Wasson's $^{59}\text{Co}(n,\gamma)^{60}\text{Co}$ experiment (paper I-6). It seems certain that the main usefulness of thermal-capture work lies in the accurate determination of γ -ray energies, in the study of γ - γ coincidences and angular correlations, and in related experiments requiring high neutron intensities.

BOLLINGER: Now, as I understand it, you are saying that even for the high-energy gamma rays, both kinds of measurements are still highly valuable.

CHRIEN: Yes.

BOLLINGER: Does anyone feel otherwise on the basis of what you have seen here? I personally am a little skeptical about the thermal business.

I think that finishes off your question, Bob, and we can go to the next one, which will be addressed to Otto Schult. Is the bent-crystal gamma-ray spectrometer made obsolete by the germanium diode? In particular, is it not likely that coincidence measurements with germanium diodes will displace the bent-crystal spectrometer?

SCHULT: The germanium diode is indeed the most powerful tool for a general and universal investigation of (n, γ) spectra. Therefore, it is not unexpected that people may wonder whether this modern device will not displace an old-fashioned instrument like a curved-crystal spectrometer. My answer is a definite "yes" as long as we are discussing γ -ray energies greater than about 600 keV. Experts know that a curved-crystal spectrometer is in general not a good spectrometer for such energies and, therefore, we cannot talk about a displacement in the strict sense of the word. For this reason, we should ask more specifically whether the present-day Ge(Li) spectrometer will replace a present-day curved-crystal spectrometer in the γ -energy region up to 600 keV. The answer is still "yes" if the target has a cross section less than a few barns. For neutron-capture cross sections greater than about 10 barns, my answer is "no". Although the Ge(Li) detector is useful for the measurement of singles spectra, it is the curved-crystal spectrometer that gives much more precise γ energies, better resolution, and a larger dynamic range (detection of weak lines in the vicinity of intense transitions).

Coincidence measurements with two germanium diodes do provide us with extremely valuable information, and such data are essential for the construction of a nuclear level scheme. It is known, on the other hand, that very precise curved-crystal-spectrometer data permit the application of the energy combination principle which serves the same purpose. However, accidental combinations put a natural limit on the latter method. Such limitations are not experienced during coincidence studies—a fact that speaks in favor of the germanium diode. The dynamic range of the Ge(Li) spectrometer is, however, considerably smaller than that of a curved-crystal spectrometer for energies between 80 keV and about 300 keV. Here the crystal spectrometer permits the observation of very weak γ transitions which are essential for the investigation of the nuclear levels of the isotope under study. These weak transitions have not been observed so far with germanium diodes—neither in singles spectra nor during coincidence studies. For these reasons I would rather conclude that coincidence measurements with germanium diodes complement the study of the low-energy (n,γ) spectrum with a curved-crystal spectrometer.

BOLOTIN: You quote a large dynamic range for the bent-crystal spectrometer. Let's take what you yourself might consider the strongest lines you see between 30 keV and several hundred keV. How many of those do you actually wind up fitting into a decay scheme?

SCHULT: In cases where we are a little lucky, as for example in Dy^{163} , we find that about 60% of all transitions up to about 400 keV can be successfully placed into the level scheme. These transitions make up $\sim 95\%$ of the total γ intensity observed up to 400 keV. These lines cover the full dynamic range. They include transitions which belong to the weakest lines we have recorded; their intensity is only $1/7000$ of the intensity of the strongest line in that energy region. There do not exist any reasons that reduce the dynamic range.

BOLOTIN: How often are you lucky? You said in the most favorable cases you fit in $\sim 95\%$ of the intensity.

SCHULT: It depends on our effort! We can achieve such results in most cases if the cross section is 100 b or greater.

MOTZ: To quote an example, this refers back to the holmium data which I put on the board yesterday. We could not see, with our germanium detector, the 111-keV line in Ho^{166} . This was absolutely crucial in determining the level scheme. It happened to locate a band head which was quite important in a 4^+ band. We held up the holmium work for approximately six months because we had contradictory data on that one loop. We had to clear this up before we could go ahead. Coincidence data surely simplify the spectra you see in germanium to some extent. But, I doubt that it will do it—at least to the extent that you see lines which are 0.1% in abundance—when it is only a few keV away from a line as strong as 16%, e.g., the 116-keV line. You have to do both experiments, I think.

BOLLINGER: Are there any further comments?

SMITHER: I have two comments. It has been mentioned that the dynamic range of the crystal spectrometer is very large. This is important not only for finding the levels in the scheme but also for getting some nuclear physics out of the level scheme. For example, among the important experimental results of a typical (n, γ) experiment are the branching ratios of the gamma rays. But these ratios are often very difficult to measure because the intensities of the gamma rays may differ by factors of 50—100 just because the transition probability varies as the third or fifth power of the gamma energy E_γ . Once this E_γ^3 or E_γ^5 energy dependence is taken out, the two values of $B(E2)$ may be very close together—and these may be just the quantities you are trying to measure. Therefore, even after taking coincidence data and developing the complete level scheme, you will ask what is the

branching ratio between the 2^+ and the 4^+ levels. For a long time it seems this will only come from the crystal-spectrometer data.

BOLOTIN: I think you probably have to keep both instruments, but when you refer to the coincidence data you have to realize that eventually the resolution widths at the high-energy end will be reduced to possibly 4.5 keV and at the low-energy end to possibly 1 keV. We are going to have larger detectors, and we are going to be able to do germanium-germanium coincidence work. So when you consider the coincidence data that you have seen, you must anticipate a greatly improved situation when we go to two Ge(Li) detectors that have close to optimum (theoretically realizable) limits.

SCHULT: I completely agree. Personally, I would wish that we had several groups studying coincidences with two germanium diodes with very good resolution. In the case of Ho^{166} , for instance, several questions have come up. They can only be solved through such coincidence studies or through measurements with much better curved-crystal spectrometers than we have now. It is clear that very complex coincidence spectra are difficult to unravel and they might even lead to erroneous conclusions.

BOLOTIN: I am familiar with the work to which you allude. However, that experiment was done with sodium iodide detectors. Similar coincidence studies with two Ge(Li) detectors should improve the situation dramatically.

SCHULT: I agree. The germanium diode will improve the situation drastically, but it will not remove such difficulties completely.

MOTZ: I would like to strengthen the argument that Bob Smither gave about the dynamic range as follows. Sometimes it is quite crucial to show that a gamma ray does not occur with an intensity as great as a certain given limit—even though no one has observed it. You want to show that a crossover does not exist. This very often strengthens the spin assignments. So the highest accuracy (i.e., the smallest

upper limit you can give) demands the highest dynamic ratio. So, if you can state a crossover as, say, 10^{-3} , this is important to know. So the dynamic range comes in here even when you don't see a line.

BOLLINGER: I would like to pass on now to another aspect of this question. This was answered yesterday but I did not feel it was answered entirely satisfactorily. It will at least be good to hear somebody else's point of view. The question is whether the DuMond or the Cauchois geometry is preferable in a curved-crystal spectrometer used to study capture gamma rays.

SCHULT: Either system has its advantages and disadvantages. The Cauchois geometry is clearly superior in cases in which the target is rather extended—as, for example, in the possibly unique case of the $H(n, \gamma)$ experiment—and if low-energy lines from neutron capture in gases should be measured. It is also an interesting device if the detector is rather small. Its main advantage is that part of the spectrum can be recorded simultaneously instead of line by line. It is a rather simple device, but its luminosity (the intensity in the reflex divided by the source strength) is roughly two orders of magnitude less than that of a DuMond-type spectrometer. This latter system is more complicated and requires larger detectors, but it is very useful for studies of separated isotopes. Quantities of 10—100 mg are sufficient as a source for a DuMond-type spectrometer.

Both geometries should be useful in connection with a germanium diode. The DuMond geometry seems to be favorable if the amount of target material is small. If large targets are used, then the germanium diode can be used in conjunction with a Cauchois spectrometer. A simple flat crystal might be as useful in this case, where the resolution is determined by the solid-state detector. The flat crystal could be smaller in area but larger in thickness than the curved crystal. Therefore, the source could be made smaller and still the higher reflectivity of the thicker crystal would prevent reduction of the counting rate.

BOLLINGER: Does anyone wish to respond to this comment?

SMITHER: The first point which I think Dr. Schult made, is that when you want to use small separated isotopes, the DuMond spectrometer is usually the easiest spectrometer to use. This is essential in complicated spectra in heavy nuclei, for which there are many isotopes in the naturally-abundant sample, and they would double, triple, and even quadruple the number of lines that would have to be resolved in any one case. Without enriched isotopes in most of these investigations (and when I say enriched isotopes, I don't mean that one runs just one isotope; you might run all four or all five), you just cannot solve the problem. There are a number of possible combinations of crystal spectrometers and germanium diodes that may be useful as I mentioned briefly before (paper C-2). I think that both types of spectrometer (DuMond and Cauchois) have advantages when used in combination with a Ge(Li) detector. The DuMond geometry has the advantage when you are trying to resolve a close doublet; the Cauchois geometry or a flat-crystal geometry is preferable when you are looking at a region of a spectrum that covers many lines but still covers few enough lines that you don't sit on the Compton background of the lines under investigation.

SCHULT: If you already have a spectrometer, then you may, of course, use it in conjunction with a Ge(Li) diode. You would not build a new flat-crystal spectrometer for this purpose. However, if you consider building a new Cauchois spectrometer for use in connection with a germanium diode, then it seems to me easier to consider a flat-crystal spectrometer instead.

SMITHER: Only when you are doing groups of spectra, but not with close doublets. When using the combined system, the advantage of the DuMond geometry is that you are able to enhance the weaker member of the close doublet, and therefore improve the resolution.

SCHULT: That is right, yes.

BOLLINGER: I think perhaps we should pass to the next question. This one I will address to Bob Chrien. The question is: Does an internal-beam facility have any important advantages over an external-beam facility for the study of singles thermal-neutron-capture gamma rays?

CHRIEN: It seems to me the answer to that question is rather obvious. As Thomas showed in his talk (paper B-1) on the first day of this conference, an internal-beam facility has an intensity advantage because its intensity depends on only one solid angle whereas a product of two solid angles is involved in getting the gamma rays out to the detector in an external-sample facility. We have seen some beautiful data, as I mentioned before, from internal facilities—both from thermal capture and epithermal capture. There is an intensity factor of up to 3 orders of magnitude in favor of the internal-sample facility. This factor allows the use of a 3-crystal pair spectrometer to improve the signal-to-background ratio by reducing the Compton contribution to the recorded spectrum.

To start an argument, perhaps I ought to list some disadvantages that do not necessarily pertain to thermal-neutron-capture gamma-ray work. It is really comparing apples and oranges. There are different kinds of experiments that can be done with each facility. Let's concentrate on what the internal-beam facility cannot do. It cannot do such things as angular-correlation work, gamma-gamma coincidences, and that whole class of experiments. The internal-beam facility has relative inflexibility in sample handling, although I must admit that in the case of the Los Alamos group this does not seem to be a particular problem. You are, as I said before, limited to singles spectra. You do have sample problems in that the sample becomes heated and, of course, it becomes radioactive. This means you must purchase your samples from Oak Ridge. This leads to monetary difficulties, I would imagine; but this perhaps is not a fundamental objection.

BOLLINGER: That is a fundamental objection!

CHRIEN: Going on to a consideration of resonance capture, it appears to me that there is a serious disadvantage in the measurements with an internal-target facility in that you do not have any precise energy selection on the neutrons initiating the reaction. Therefore such a facility cannot be used in assigning the parity and spin of the capturing states. You are, furthermore, dealing in many cases with isotopic mixtures which could complicate the spectra that you observed, and various background lines might also be present.

Now, if you are doing resonance capture, the Porter-Thomas distribution means that in any particular resonance you look at, you would not see all of the lines. By combining a series of resonances, one can effectively overcome the problem of unresolved transitions. You don't have all the transitions piled up one on top of the other. So, by doing resonance capture, you do have the advantage of improving your resolution and cutting down on the probability of missing a transition.

This is perhaps enough of a rebuttal on this basis.

BOLLINGER: We seem to have two different discussions going on here, one after the other. Perhaps I should make it clear why I asked the question about the thermal capture in the first place. Even at a relatively low-flux reactor such as CP-5, with an internal-beam facility we have more flux than we know what to do with. Therefore, as far as the flux is concerned, it would seem that we ought to be able to extract the beam and measure the thermal-capture gamma rays perfectly well with the target outside the reactor. The thing that is not entirely clear, however, is whether the background can be made as low as it should be in an external-beam facility. Perhaps Harvey has some opinion on that question.

HARVEY: I don't think there is any problem handling the background if you get a good clean thermal beam free from fast neutrons

and gamma rays. However, if you look right at the reactor to get a resonance neutron beam as we have done at the ORR, then you have terrific background problems with fast neutrons and gamma rays.

BOLLINGER: Even with this good clean thermal beam, how do you make out when you are trying to look for a weak line such as that from capture in C^{13} in a normal sample of graphite? Do you actually have that kind of sensitivity?

HARVEY: Let me ask Grimes Slaughter about the carbon and beryllium data with the deflected beam. Was there any background problem?

SLAUGHTER: Not that I remember.

HARVEY: Years ago we tried to measure the gamma rays from beryllium and carbon with a large sodium iodide crystal with a reactor beam, but it was hopeless because of the background of fast neutrons. Once we obtained the totally reflected thermal beam which eliminated the fast neutrons and gamma rays, we were able to use beryllium, carbon, and even heavy water as calibrations to obtain line shapes with the large sodium iodide crystal.

BOLLINGER: But, it was the C^{13} that I explicitly asked about.

HARVEY: I don't think we have seen the C^{13} line from natural graphite.

BOLLINGER: But you see, that is an easily detected line in our spectrum.

HARVEY: I am not sure whether we don't see it because of the background, or just because of the lack of intensity.

W. R. KANE, Brookhaven National Laboratory: If it is still appropriate to discuss the relative merits of nuclear-structure studies with either thermal or resonance capture, I think one important point has not yet been made. This is that many types of experiments (angular-correlation and coincidence experiments, studies of internal-conversion electrons, and so forth) require long counting times.

There the basic limitation is not usually the source strength, but such things as pile-up in detectors or accidental coincidence rates. And the point is that the resonance-capture work is being done almost exclusively with time-of-flight devices with very short duty cycles, with the exception of the Bragg-diffracted neutron-beam experiments, which are good only up to about 15 or 20 eV.

Thus, if you have an experiment that would require, for example, 2 weeks of continuous counting time with the permissible source strength, and you have a duty cycle of 1/200 or 1/500, the experiment is completely out of the question at a time-of-flight facility.

ORPHAN: I would like to say a word in defense of external-beam facilities. We are using a Ge(Li) pair spectrometer in conjunction with an external-neutron-beam facility at the MIT reactor to study thermal-capture gamma rays. The spectrometer can be effectively shielded against background from the external-beam facility. The thermal-neutron flux (about 6×10^8 neutrons/cm²/sec) at the sample is quite adequate for studying fairly-low-cross-section elements — such as Zr, Be, and C. Furthermore, the neutron beam has a very favorable thermal-to-fast-neutron ratio (the cadmium ratio is about 2000). Also, sample changing is much simpler with an external-beam facility. At our facility, samples may be changed in a few minutes with the reactor at power.

HARVEY: Have you seen C¹³ capture from a natural graphite sample?

ORPHAN: No, we have not seen C¹³ lines.

MOTZ: If one has a very low-power reactor and doesn't have any of the disadvantages you mentioned about temperature, irradiating separated isotopes, and things of this sort, then I think it is clear-cut. The internal target is definitely preferable, especially if a clean source is available.

One of the situations that has developed with high-power reactors is that people can't get the clean beam facilities. So they brought beams out from the reactor (even refracted them from lead crystals and things of this sort) in an effort to get the ratio of thermal neutrons to fast neutrons and γ rays up higher—and then did external-beam measurements. I think that some of these facilities end up using 20-MW, perhaps even 40-MW reactors in some cases, and having a less clean beam facility than is possible with a good internal-source arrangement. So there are cases in which it is clear that the internal target is definitely preferable.

On the other hand, if you want to go to very low cross sections (with such nuclides as C^{13} , for example) I think the volume of the target comes in. You can extend this volume almost indefinitely with an internal target, especially with light elements, but you can't do that with an external beam.

BOLLINGER: That was our international statesman speaking in favor of "Atoms for Peace", in case you didn't recognize it.

Let's get back to the second part of Chrien's statement, in which he wanted to argue with me about how much nicer it is to look at individual resonances instead of measuring average spectra. I don't want to engage in this argument because I agree with him completely. If it is possible, then by all means one should study individual resonances. But there are many things one cannot measure with present pulsed-neutron sources, and our average-resonance-capture technique does provide a solution for some of these problems.

So let us go on to our next question. It will be addressed to Otto Schult again. If germanium-diode data are assumed to be available, which is the more useful source of information, the bent-crystal gamma-ray spectrometer or the internal-conversion-electron spectrometer? This is a question, by the way, that we here—and perhaps others at some other laboratories—will be facing in connection

with the use of the new high-flux reactors. Suppose one cannot afford two expensive pieces of apparatus of this sort. You have to make a choice. Which does one choose?

SCHULT: It was quite interesting that you said "high-flux reactor". We have heard just before that you prefer the internal-target geometry for germanium-diode spectroscopy. Do I correctly assume that you will use the internal-target geometry to obtain germanium-diode data at a high-flux reactor.

BOLLINGER: No. We expect to continue to use CP-5 for the germanium-diode work that we are doing there now.

SCHULT: Well, if we identify germanium-diode data with the measurement of the whole (n,γ) spectrum, using one (or preferably several) present-day germanium counters, then at first glance it seems to be advantageous to combine the information on the gamma spectrum with that which can be obtained from the measurement of the conversion-electron spectrum from neutron capture.

It must be emphasized, however, that the detailed knowledge of the (n,γ) spectrum, in particular in the low-energy region below 500 keV, is necessary for the analysis of the (n,e^-) spectrum. The low-energy (n,γ) spectrum, as obtained with a germanium spectrometer, is not sufficiently detailed. The resolution and the dynamic range of a germanium counter will permit a good analysis of the (n,e^-) spectrum only for those transitions that appear as strong lines. An unambiguous characterization of the weak (n,e^-) lines close to strong conversion-electron transitions will, in general, not be possible. Nor can one expect the energies for transitions below 500 keV to be obtained with high accuracy. Thus, it seems that little could be accomplished with the low-energy (n,γ) or (n,e^-) data.

A combination of high-energy (n,γ) data (measured with one germanium diode) and low-energy (n,γ) data (obtained with a curved-crystal spectrometer) allows the use of the energy combination

principle and, thus, the construction of part of the nuclear level scheme. However, spins and parities cannot be determined in this way.

In reply to the question about which source of information is more useful for the study of nuclear structure, we would favor the crystal spectrometer. We think it is more useful to first establish a level and then ask for its spin and parity than it is to know the multipolarities of several intense transitions whose locations in the level diagram are more or less speculative. In fact, it is largely a matter of taste which kind of information is considered to be more useful. Therefore, I can imagine that other people may arrive at the opposite answer.

I am convinced that the experiments to be performed in the future are getting more and more expensive, and it seems to me to be less and less probable that all experiments related to (n, γ) studies can be performed at a single laboratory. This situation does not worry me at all as long as there is someone who has an instrument that can supply me with the special data I may need. Therefore, the problem hidden in Dr. Bollinger's question does not arise for me, since both types of instruments exist at several different spots on our globe. Apart from this, I do not think that a bent-crystal spectrometer or a conversion-electron spectrometer is an expensive piece of apparatus if we compare the expenses with those for a germanium diode plus electronics. Furthermore, I am convinced that both instruments could be installed at fairly low cost at a high-flux reactor if this facility has been well designed (i. e., designed for physics rather than for prestige).

BOLLINGER: Thank you. We will pass on to the next question. This one is addressed to Chrien: Is the chopper in any way competitive with the pulsed accelerator for the study of gamma-ray spectra resulting from capture in resonances?

CHRIEN: Yes, it is competitive in some ways. A properly designed chopper can compete with a linac in the energy regions in

which the lack of good resolution is not a dominating factor; that is, when the ratio of the resolution width to the average level spacing is much smaller than unity, or reasonably smaller than unity.

For many nuclides this region extends to several hundred electron volts. What I feel makes the chopper competitive is that, when it is coupled to a high-flux reactor, its relatively high duty cycle enables it to achieve an intensity higher than that of all the modern linac systems of which I am aware.

For weak resonances, the reliability and steady output of the chopper/reactor combination make it compare favorably with the linacs. I believe extended runs are much more practical with the chopper. The higher intensity of the chopper will make possible angular-distribution measurements (for example, in p-wave resonances) and, if necessary, gamma-gamma coincidence experiments.

The lack of the gamma flash, and the ability to do thermal runs under precisely the same experimental conditions as the resonance runs (and therefore to use the thermal spectra as calibration points) are additional advantages of the reactor/chopper combination.

At this point I would like to remind the audience that although most of the discussion and the experimental results of this conference have been devoted to using the (n,γ) process to populate the low-lying states in the residual nucleus and therefore to investigate nuclear structure, nevertheless the theory of the (n,γ) reaction—the reaction mechanism—is perhaps one of the most interesting aspects of this work. And we certainly heard that in the theory discussion (paper H-3) yesterday.

For this study of the reaction mechanism, we must examine the energy dependence of the capture cross sections and of the partial cross sections. For interference studies with weak interfering amplitudes, good resolution is not important since the maximum

interference effects occur where the resonance and background amplitudes are equal; and this is many widths away from the center of the resonance. Here again, intensity rather than resolution is of the greatest importance.

The comparison of intensity factors for several choppers and linacs is as follows. The BNL fast chopper coupled to the HFBR yields $8000/E \text{ neut/cm}^2/\text{eV/sec}$ at 22 meters.

The Yale linac operating at 8 kW and 0.5 μsec burst yields $1000/E \text{ neut/cm}^2/\text{eV/sec}$ at 20 meters.

The Argonne fast chopper (Mark I rotor) coupled to CP-5 yields $11.4/E \text{ neut/cm}^2/\text{eV/sec}$ at 25 meters (according to the 2nd Geneva Conference Report).

Analysis of the recent Saclay linac experiment on $^{195}\text{Pt}(n,\gamma)^{196}\text{Pt}$ leads to an estimate of about 1/30 or 1/40 of the intensity of the BNL fast chopper. It must be admitted, however, that the Saclay experiment may have been run under less than optimum conditions.

BOLLINGER: I suspect if we had somebody like Julien present, he would give you a run for your money on this factor of 40. I find it somewhat anomalous because H. E. Jackson, who has worked both at Saclay and at the chopper here at Argonne, has informed me that the Saclay linac gives 30 times the neutron flux at our chopper. Combining this with your numbers implies that your flux is 1000 times ours. This is an inference I would have a little trouble swallowing.

HARVEY: Even accepting Bob Chrien's numbers, it is always a battle between resolution and intensity. The Saclay linac data on ^{195}Pt were taken at 30 meters with a factor of ~ 50 better resolution than the BNL chopper data. A decrease of a factor of 5 in distance would result in a gain in intensity of 25 or even more, depending upon assumptions. I don't think the gamma flash would give trouble at this shorter flight path for the low-energy resonances, which is where I suppose you made the comparison.

CHRIEN: The counting-rate comparison was made at the 11.9-eV resonance in ¹⁹⁵Pt. I do not know the exact experimental conditions, so the counting-rate comparison is inexact. Further work at Saclay has indeed been carried out with a shorter flight path.

BOLLINGER: I would like to make a comment that is closely related to something you said, but in slightly more blunt terms. It seems to me clear that if one is primarily interested in the spectroscopy of low-energy states, then the chopper probably has a number of advantages over existing or, perhaps, even planned electron linacs. But, on the other hand, if one is interested in the study of capture mechanisms, in which one usually has to look at many neutron resonances, then the chopper is in a bad way.

The second part of the question was: At what value of the ratio of event rate to repetition rate does random adding significantly reduce the quality of germanium-diode spectra. Let me rephrase that in a slightly different form. With any of the pulsed sources, the events arrive in a pulsed fashion. Consequently, even though the average rate may be low, the instantaneous rates may be high and one is in trouble. The question is to give a quantitative statement on that.

CHRIEN: In a time-of-flight experiment, of course, as Dr. Bollinger mentioned, the instantaneous counting rates can be much higher than the average rates. The instantaneous rates in a resonance are high in that portion of the beam burst during which the neutrons having the appropriate velocity to excite that resonance are passing through the sample. The compression of the high-energy portion of the spectrum into relatively few time channels also affects the instantaneous rate.

In order to assess the importance of the instantaneous counting rate in determining the quality of the capture γ -ray spectrum, it is convenient to consider first the extreme case of a black sample—one that captures all the neutrons. We further assume a $1/E$ spectrum.

It can be shown that the instantaneous rate dn/dt at a time t corresponding to energy E is given by the relation

$$\frac{dn}{dt} = \frac{k'}{L^3} T \sqrt{E},$$

where T^{-1} is the repetition rate and L is the flight path. For the BNL fast-chopper facility, we get an instantaneous rate of about $500\sqrt{E}$ per second for $L = 22$ m, $T = 10^{-3}$ sec, sample area 50 cm^2 , and detector solid angle $\sim 10^{-3}$ sr. From this number, one sees that instantaneous counting rates are not a problem for neutron energies below 1 keV, even for a totally black sample. In this limiting case, the burst width plays no part at all, and the chopper has no advantage over the linac. The repetition rate should be kept high to achieve a high average intensity with low instantaneous burst rates.

I feel that the planned facilities, even the Oak Ridge machine, would then probably not be in trouble until they get up to perhaps the keV region, according to this calculation. This is my interpretation of the question, as posed.

SMITHER: It was my impression that the neutrons coming out of the chopper facility were fairly directional. Is that right? Does the intensity really vary as the cube of the distance?

CHRIEN: No, if the sample is smaller than the beam, then the cube factor is not far from correct. If it were larger than the beam, it wouldn't go with the cube at all. It would be more nearly linear. If you can make a sample big enough, I think we can make this simpler and make it a linear factor. You get one factor of L from the relationship between energy and time, anyway. From the wording of the question it seems to be based on the premise that the chopper might have an advantage due to its relatively long burst width. It can be seen from the argument just presented that any such advantage

would be limited to the higher neutron energies where the poor resolution of the chopper seriously degrades its performance. Therefore, such an advantage does not exist for practical applications.

BOLLINGER: I feel that the chopper may have an advantage under some circumstances. It is always difficult to follow this kind of arithmetic on the board. That is why I was not going to argue with you in public. Since you have drawn me out, I feel that under the circumstances in which the natural resonance width is much narrower than your resolution width, the narrow burst of the linac necessarily means that its instantaneous rate will be higher. Whether this will be bothersome or not is not obvious because I am not sure that the concept of instantaneous rate has much meaning when one has the circumstance that you have a burst of a high rate and then it is followed by a rather quiet period until you get to the next resonance, and you have another burst at the high rate.

CHRIEN: This calculation was on the assumption that the resonance was black and just as wide as it possibly could be. In other words, it assumed total capture in the sample. This is, therefore, the maximum you could ever possibly get.

HARVEY: In comparing the quality of the spectra from a chopper and a linac, isn't it necessary to know how the recovery time of the electronics compares with the observed width of the resonance? Strauss's curves (paper C-6) showed counting rates of $\sim 10^5$ counts/sec indicating that the recovery time must be less than 10 μ sec. If the recovery time were (say) 2 μ sec, then for the same spectral distortion of an isolated resonance whose width is $\ll 2 \mu$ sec, a chopper with a 10- μ sec resolving time could tolerate several times the average counting rate that could be tolerated by a linac with the same pulse repetition rate. Under these conditions, the instantaneous counting rate with the linac is much higher, but the average rate is a little

lower, than with a wide-burst chopper. The distortion in the spectrum for a given pulse repetition rate and average counting rate for an isolated resonance is independent of the instantaneous rate as long as the resonance width is less than the recovery time.

CHRIEN: One other point. You will notice in the extreme limit—talking about nuclear detonations, for which the repetition rate is very, very low—if you maintain the same average intensity as for a chopper or a linac, your intensity goes pretty high.

BOLLINGER: The last was a nice comparison. I feel, however, that this is almost too technical a subject to be handled in this way—without stating what the assumptions are and so on. So unless someone is extremely eager to pursue it, let's go on to the next topic.

This concludes our questions on purely technological matters; we now pass on to those that have to do with the physics of the capture-gamma-ray spectra. The first question of this sort is addressed to Mr. Vervier. How reliable is the usual assumption that strong high-energy lines are E1 primary transitions?

VERVIER: First, I would like to recall the usual way to get some indication as to whether a transition is E1 or M1. The Weisskopf estimate for the width of a primary gamma ray of the E1 type is given in eV by the expression

$$\Gamma_{\gamma}^{\prime}(E1) = 0.11 E^3 A^{2/3} D/D_0 ,$$

where D is the spacing (at the separation energy) of levels with the same spin and parity as the capturing state, D_0 is the single-particle value of D , E is the γ -ray energy, and A is the mass number.

Similarly, the width for an M1 primary γ ray is $0.021 E^3 D/D_0$ and that for an E2 is $1.2 \times 10^{-7} E^5 A^{4/3} D/D_0$. The quantities D , D_0 , and E are expressed in MeV. In order to determine the experimental value of this width $\Gamma_{\gamma}^{\prime}$ for a case in which the thermal capture is

dominated by a single resonance, one takes the total radiation width for this resonance multiplied by the number of gamma rays (of the type studied) per capture. If the thermal capture is not dominated by one single resonance, one has to take some estimate of the mean total radiation width of nearby resonances—although this is, of course, much less reliable. If there are not enough of these, it is necessary to use a theoretical estimate such as that proposed by Cameron.

I would like to present some empirical data of this kind which were summarized in 1961 by Bartholomew⁷ (Fig. 289). What is

Fig. 289. Reduced radiation widths of primary neutron-capture γ rays. All known E1 and M1 primary γ rays are included (solid circles). The ordinates of the two diagrams have been shifted by an amount corresponding to the $A^{2/3}$ factor with $A = 130$ so that energy-reduced radiation widths for E1 and M1 γ rays may be directly compared from one graph to the other. The open circles represent γ rays of unknown multipolarity whose reduced widths are exceptionally large, in most cases exceeding those of known E1 gamma rays in the same spectrum. The resonance fluorescence results of Reibel and Mann [K. Reibel and A. K. Mann, Phys. Rev. 118, 701 (1960)] are included for comparison (crosses). The Weisskopf prediction [J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, New York, 1952)] for $D_0 = 15 \text{ MeV}$ and Cameron's average width $\langle k_{E1} \rangle$ [A. G. W. Cameron, Can. J. Phys. 37, 322 (1959)] are also shown.

⁷G. A. Bartholomew, Ann. Rev. Nucl. Sci. 11, 275 (1961).

plotted on the graph is the quantity k_{E1} which is the width of the E1 transition divided by $E^3 A^{2/3} D$. If this Weisskopf estimate were realized in nature, we should obtain $k_{E1} = 0.11/D_0$. In the M1 case, k_{M1} is the width of the M1 transition divided by $E^3 D$. Again in the case of a completely accurate Weisskopf estimate, k_{M1} would be $0.021/D_0$. In this plot D has been determined from experiment as much as possible; when D was not available from experiments, it was taken from Cameron's theoretical formula. On the left in this figure is Bartholomew's compilation of E1 transitions, and on the right are the M1 cases. Of course, as we have seen from the formula, we have an A dependence for E1, and no A dependence in the case of M1 transitions; so these curves have been normalized with respect to each other at a mass value of $A = 130$. You see that there is a general grouping of these data, showing that the average width for E1 transitions is larger than that for M1 radiation; at first sight it is roughly in agreement with the single-particle estimates. Still, there is a large region of overlap: weak E1 and strong M1 transitions cannot be distinguished on this graph.

In other words, it is not always possible, just on the basis of the strengths of capture γ -ray transitions, to make a clear-cut distinction between E1 and M1, except for the cases of very strong E1 and very weak M1 transitions. Since there is a large range of overlap, I think that in more than 50% of the cases this comparison does not give a very clear-cut answer. In some cases—for nuclei in which there are both M1 and E1 transitions and their parity assignments can be made from other data with certainty—the ratio of E1 to M1 strengths usually is roughly of the order of magnitude predicted by the theory. For the case of E2 transitions, which I have not mentioned, I must add that there are very few well established cases of primary E2 transitions, and in every case they are at least between 10 and 100 times weaker than the competing M1 transitions. There are, of course, some outstanding exceptions—for instance, the M1 ground-state transition

in Al^{28} , M1 transitions in Cl^{36} , and also some transitions in the zirconium region. Also, the Oak Ridge Group (paper I-9) has reported very strong M1 transitions in the tin isotopes.

The second part of the question was: Is there any need to determine the parity of the final states experimentally? In view of the large number of overlapping strengths of M1 and E1 transitions seen in Bartholomew's compilation, the answer is: Yes, there is such a need. But the only ways I know to distinguish between M1 and E1 primary transitions are usually very difficult. One way is by linear polarization experiments, which have been carried out at Chalk River for the case of mercury. However, these linear polarization experiments have a rather low counting rate even with the use of NaI(Tl) detectors; it is of course, completely out of the question to think of using Ge(Li) detectors for linear polarization experiments in the foreseeable future. With NaI(Tl) detectors, of course, there is a serious difficulty with the lack of good enough resolution. The other conceivable method for determining the parity is to study the angular correlation of the pairs produced by internal pair formation. This has been attempted at Chalk River with a magnetic spectrograph but, as far as I know, unsuccessfully. In summary, there is a need to make measurements of multipolarities, but the ways available to measure them are extremely difficult.

BOLLINGER: I would like to ask you to extend your subject a little by answering the question: To what extent are these high-energy transitions primary transitions? And this leads to the even more practical question: Is it worth while to make the effort to identify those transitions that are primary transitions? As we have seen several times in this conference, observation of small shifts in energy or differences in line shape now make it technically possible to identify a number of primary transitions; but it is not at all obvious that it is worth the effort. Do you have an opinion on that?

VERVIER: I think it is worth the effort in the region where it is possible, i. e., in the light nuclei. There the resonances are spaced far enough apart that it is technically feasible to measure the energy shift of a line when you go from capture in one resonance to capture in another resonance. This is also the only region of the nuclide chart where I think there is serious doubt, in some cases, as to whether the transition is primary or not. In the heavier nuclei, the same technique is not available and I think that there is very little doubt about the primary nature of the high-energy capture γ rays.

BOLLINGER: Is there anybody in the audience that wants to quarrel with that?

EMERY: I would like to suggest the matter should not be considered completely closed, even for heavier nuclei. The natural frequency of quadrupole oscillations of nuclei corresponds to an energy of only 2 MeV, sometimes less. There is the very faint possibility that quadrupole vibrational transitions up around that region might have sufficient strength to compete with primary dipole transitions. There is even the possibility that one might find deformed states in some nuclei in that energy range, particularly in nuclei that are close to the edge of a region of deformation. It is a minor comment.

I should also like to make a comment on the original question as to the reliability of the assumption that strong high-energy lines are E1 primary transitions. This is that the Bartholomew-Weisskopf estimates rely on the single-particle level spacing D_0 . In principle, if you are investigating transitions to a single-particle state, you should consider transitions not only from single-particle states but from other states from which you can have single-particle transitions. Those states are two-particle one-hole states, for example. There are more two-particle one-hole states in the region of the neutron binding energy than there are single-particle states—by a factor of 30 or 40.

In the E1 case, that is probably not important, because the strength of the E1 particle-hole transition is pushed up to a higher energy region, so one probably gets back to something of the same order of magnitude. Some fraction of that strength is left in the original region. In the M1 case, however, there are more two-particle one-hole states and there is no evidence that the strengths of those M1 transitions are pushed away to a very different energy region. One might get a slightly more reliable estimate for M1 single-particle strengths if the value of D_0 is obtained by adding the density of one-particle states to that of two-particle one-hole states.

SMITHER: I would like to mention the particular case of Cd^{114} , for which we have made some effort to distinguish the parity of about the lowest 30—35 states, using both the (n, γ) and (d, p) reactions. When we compare the average strength of the M1 radiation versus the average strength of the E1 radiation, the M1 radiation is stronger and contains the few lines that are much stronger than the rest; the E1 transitions were always among the weaker half to the lowest third of the strength. In other words, all the individual E1 strengths in this one case were noticeably smaller than the average M1 strength—at least for the lower energy states. However, the low-lying positive-parity states corresponding to M1 radiation were much more numerous than negative-parity states. Therefore the distribution may reflect the fact that we had many more candidates for the M1 transitions and therefore we had a few strong ones as well as many moderately weak ones. I just wanted to say that in this one case, the M1 transitions appear to be stronger on the average than the E1's. There are no absolute values for the strengths of these gamma rays. All of the gamma rays may be relatively slow, and therefore not unusual for M1 transitions. But to assign a transition as an E1 multipole just on the basis that it is one of the stronger ones in the level scheme seems very dangerous.

W. V. PRESTWICH, Argonne National Laboratory: If you are going to restrict yourself to dipole radiation, the most clear-cut evidence for E or M is simply the (d,p) work. I think there is a crying need for more l values from (d,p) reactions. When they are even or odd, you know what you are doing. You also know that they are primary transitions if the (d,p) level is populated in the (n, γ) work.

BOLLINGER: Let us now move to another question for Vervier. The question is: Does the gamma-ray reaction have any special role in nuclear spectroscopy in comparison with charged-particle reactions? If not, why bother to study the (n, γ) reactions?

VERVIER: I think that this question has been partially answered by Otto Schult (paper G-5) yesterday, but I would like to emphasize some points. For instance, if you compare the neutron-capture gamma-ray reaction with any charged-particle reaction, it is obvious that the precision of the energy level positions obtained from capture gamma rays is much better in almost every case than that obtained from charged-particle reactions. As far as I know, the precision obtained in charged-particle work up to now is at best a few keV; but in thermal-neutron-capture gamma-ray work, we have seen precision down to 1 keV, or perhaps 0.5 keV, and to even much better accuracy in the low-energy region.

As an example, in V^{52} , which we have studied recently, there are two doublets—one at 17 and 22 keV and a second at 141 and 147 keV. Neither of the doublets was resolved in the (d,p) work, but each one is very easily resolved in the gamma-ray work. Also, not only does the capture-gamma-ray experiment give better precision for the level energies, but it also completes the level scheme. For instance, the (d,p) reaction has some selection rules (e.g., it does not populate the proton excited states); the capture gamma-ray reaction can do it if the spin selection rules are fulfilled. Also in the capture-gamma-ray reaction, levels that cannot be populated by

(d,p) or other charged-particle reactions, can nevertheless be reached by cascades of low-energy capture gamma rays. If one wants to determine the decay scheme only by the (d,p) reaction, I think that the resolution is definitely not sufficient. On the other hand, (d,py) experiments are barely possible and only, as far as I know, with NaI(Tl) detectors. I don't think that it is possible, or that it will be possible in the near future, to make (d,py) measurements with Ge(Li) detectors. Consequently, for the decay of the levels seen in the (d,p) reaction, we have to rely on the capture-gamma-ray work.

Let me conclude by saying that the (n, γ) and (d,p) reactions are indeed very complementary for obtaining complete decay schemes. I think I demonstrated this point in the case of Sc^{46} yesterday (paper H-1). The (d,p) data give you the ℓ_n values, the parity and, in addition, the spectroscopic factor which gives some indication about the spin and the nature of the levels. This is extremely useful and, in some cases, indispensable for completing the capture-gamma-ray data.

BOLLINGER: Does anyone want to comment on this? Herb (Bolotin), you have had some limited experience on the (d,py) reaction. Is this a true analysis of the situation?

BOLOTIN: We did not do (d,py); but we did (α ,py) experiments and we have had some success. Everyone warns us that in (d,py) the fast neutrons might give a lot of trouble. I think there are some people trying it, and I don't think I would categorically agree that (d,py) in the near future is going to be impossible. I think probably it will be possible.

VERVIER: With germanium?

BOLOTIN: With germanium. We did these (α ,py) experiments with Ge(Li) detectors. If the backgrounds aren't much different, I don't see why you can't do (d,py) if you can do (α ,py).

BOLLINGER: As I understand the experience in the Argonne attempts to do (d,py), it is technically feasible; but with the limited

running time available to any one experimenter here, it is generally found not to be as fruitful as other kinds of experiments, and therefore people don't do it. However, this situation might change somewhat as bigger and bigger germanium diodes become available.

VERVIER: Also, in these (d,py) experiments, you have to detect the proton in a counter, not with a magnetic spectrograph. This gives you a much worse resolution than can be attained with the high-energy capture γ rays. You cannot pick out a single level if the proton groups are too close together.

BOLLINGER: The next topic is addressed to Harvey. Perhaps some others will want to add to it. The primary question is: Is there any conclusive experimental evidence for a failure of the simple statistical description of the primary capture gamma radiation? What I am trying to draw out here is a summary of anything at all that shows rather special nuclear effects, as contrasted with the general mess that one expects from a statistical picture. Hence you should feel free to broaden the question to any extent that is useful.

HARVEY: No, I don't think there is any conclusive evidence. A statistical picture, which means the capturing states are very complicated, would give the Porter-Thomas distribution of partial radiation widths, i.e., a χ^2 distribution with $\nu = 1$. Several years ago there were data that indicated that maybe ν wasn't quite as low as unity. This implied that perhaps the statistical picture was not exactly valid. Also there was evidence that there were correlation effects between high-energy gamma rays from resonance capture in ^{183}W . However, these effects have gradually disappeared. I would not claim that there is any experimental evidence which proves that the distribution of partial radiation widths is not in agreement with a $\nu = 1$ distribution or that any correlations definitely exist.

BOLLINGER: Now, let's go into some of the other things that people have been talking about—such as, first of all, the question

whether or not correlations between (d,p) strengths and (n, γ) strengths have really been observed.

HARVEY: I would answer both yes and no. It depends on the nuclide and how the data are compared. For the region of the periodic table where strong E1 transitions are possible from thermal capture to low-lying p states, there is a fairly good correlation with the $l_n = 1$ strengths from the (d,p) reaction. This part of the thermal capture has been interpreted as direct capture similar to the direct-process nature of the (d,p) reaction.

Others have argued that it isn't meaningful to compare the intensity of thermal capture data with the (d,p) data but that resonance capture data should be used. Bob Chrien pointed out in paper I-4 that one should measure the spectra for many resonances in order to average over the Porter-Thomas fluctuations. In the measurements on ^{55}Mn and ^{59}Co (paper I-7), a correlation was observed between the (n, γ) strengths for two resonances in ^{55}Mn and the (d,p) strengths whereas the 336-eV resonance did not show a correlation. Hence, for a meaningful comparison it is necessary to average the spectra for many resonances.

Another point that Jean Vervier has mentioned is that you do not see excited proton states in the (d,p) reaction. Hence, one should not compare the strengths of all the gamma-ray lines with (d,p) strengths, but a careful selection should be made before comparison. Also for nuclides where the strong high-energy gamma rays are M1 transitions, there may be little correlation between the (d,p) and the (n, γ) strengths. I would like to ask Dr. Clement to comment on this point.

C. F. CLEMENT, Florida State University, Tallahassee:
Direct M1 transitions from the initial $s_{1/2}$ state are weak in the tin isotopes. The observed M1 strength in this region probably arises from the decay of a two-particle one-hole state to a single-particle

state. This ties in with what Dr. Emery said earlier about primary M1 transitions; they can go from a single-particle state to a single-particle state or from a two-particle one-hole state to a single-particle state. The second class of transition probably dominates in the tin region and the (d,p) strengths are then mostly uncorrelated with the (n, γ) strengths.

I would like to comment on the manganese and cobalt experiments of Prestwich and Coté (paper I-7). It did seem to me that there was correlation over resonances between the capture widths.

HARVEY: Yes, that was true for ^{55}Mn .

CLEMENT: The comparisons made so far between (d,p) strengths and capture strengths from a resonance in these nuclei are not adequate. The reason is that resonances in these nuclei have two different spins. When capture goes from a resonance of given spin, there is an additional spin factor in the matrix element which has not yet been inserted. The (d,p) is some average over two possible spin values and cannot be compared with the (n, γ) without taking this factor into account. When the (n, γ) strengths are averaged over several resonances of different spins, the spin factors average out to some extent, thus restoring a greater correlation between the averaged (n, γ) strengths and the (d,p) strengths. This appears to show up in the data presented.

HARVEY: There is one other comment I would like to make. Groshev and Demidov⁸ have considered the region of the periodic table from $A = 25$ to 67 and compared (d,p) and thermal-capture (n, γ) strengths. They have concluded that although there are correlations for most nuclides, three nuclides (^{57}Fe , ^{63}Ni , and ^{65}Zn) show a

⁸L. V. Groshev and A. M. Demidov, *Yadern. Fiz.* 4, 785—790 (October 1966). In Russian. A computer translation into English has been made at Oak Ridge National Laboratory and is designated ORNL Translation 1259.

strong anticorrelation. This observation is similar to that of Ikegami and Emery⁹ for ^{55}Fe and ^{57}Fe . They concluded that for these two nuclides there was a correlation with (d,p) strengths for the high-energy transitions to near-ground states but a strong anticorrelation for gamma rays to states at 2—3 MeV excitation. They discussed this behavior in terms of the 3-quasiparticle model.

VERVIER: This work of Groshev and Demidov⁸ is summarized in Fig. 290. Here you can see, for instance, that there is a correlation for Ni^{59} and Ni^{61} . For Ni^{63} there is an anticorrelation; and I understand L. L. Lee, Jr., and W. R. Kane at Brookhaven have more information on Ni^{65} , which also shows anticorrelation.

SCHULT: Those are thermal-neutron-capture data, as far as I know.

VERVIER: Yes.

SCHULT: It has been pointed out several times during this conference that one should not only consider thermal neutron capture but also resonance neutron capture. Such studies might give results which show no correlation or anticorrelation in the cases of Ni^{59} and Ni^{61} , and correlations might appear for other nuclei. How do we know that the effects you have shown are not purely due to statistics?

VERVIER: I think one would be more confident if all these captures were dominated by one resonance. But as far as I know, no single resonance dominates the thermal-neutron capture in the Ni isotopes.

CHRIEN: It should again be emphasized that correlations or anticorrelations between thermal (n, γ) and (d,p) strengths are meaningless. The only meaningful (n, γ) widths are those obtained in resonances, since level-level interference effects and Porter-Thomas fluctuations can seriously distort the relative transition strengths at thermal energies.

⁹H. Ikegami and G. T. Emery, Phys. Rev. Letters 13, 26 (1964).

Fig. 290. Comparison between the reduced neutron widths of levels (open bars) and the matrix elements $|M^2|$ (solid bars) of γ transitions to these levels from the states formed by thermal-neutron capture. The reduced widths were determined from (d,p) reactions. The diagrams summarize the data for even-Z odd-N nuclei in the range $25 \leq A \leq 67$. [From L. V. Groshev and A. M. Demidov, "On a Peculiarity in the Capture of Thermal Neutrons by Nuclei," I. V. Kurchatov Atomic Energy Institute Report IAE-1037 (State Committee on the Utilization of Atomic Energy in the SSSR, Moscow, 1966).]

BOLLINGER: Clement, do you want to comment further on whether, in your opinion, data of this sort have any meaning or not?

CLEMENT: I would like to repeat that if the single-particle transition from single-particle state to single-particle state is mainly responsible for (n,γ) capture and the final state is a single-particle state relative to the initial nucleus, then correlation with (d,p) is definitely expected. If, on the other hand, the capture goes through a two-particle one-hole state that comes from the dipole state of the target, there may not be this correlation. Thus this depends on how much of the dipole state there is in the thermal region. The dipole strength is not thought to be large in this region but it may be enough to make the $2p1h \rightarrow 1p$ and $1p \rightarrow 1p$ transitions comparable. There would thus be some correlation but it would be by no means perfect; this appears to reflect the experimental situation. In individual cases in which correlation does not exist, you are learning about the dipole state of the target.

All this assumes that the final state is just a single particle plus the target. If it contains components that are not so simple, say mixtures of $2p1h$ states based on the target, then the situation gets more complicated; so that what one would expect in general is that if the single-particle strength is a considerable fraction of the total possible, as measured in stripping, there would be more correlation than if it is weaker. This may be rather obvious because the uncorrelated parts would then be weaker.

VERVIER: For the Ni isotopes, in the cases in which there was anticorrelation, there was also a large single-particle contribution to the level.

CLEMENT: I can't explain that except to say that there is the possibility of $2p1h$ decay affecting these cases. Why it should affect these cases and not others, I really don't know.

PRESTWICH: As far as I know, Groshev's work included no correction for spin dependence either. Do you have the same objection there?

VERVIER: No, there is no spin correction. However, if the capture is in an even-A target nucleus there is only one possible intermediate spin and there is no spin factor. The latter arises for capture in an odd-A target when there are two possible intermediate spins. Most of the data presented represent capture in even-A targets and need no correction.

BOLLINGER: Let us now move on to a slightly different topic. Jack (Harvey), do you now feel that there is any conclusive evidence that there are any cases in which the average radiation widths for transitions of a given multipolarity are different from final state to final state.

HARVEY: For the target nuclide ^{183}W you have shown that they are the same. However, the thermal capture data from the other three tungsten isotopes suggest that differences may exist, as discussed by Bolotin. But this is not conclusive evidence.

BOLLINGER: How about the case reported by Rae,¹⁰ who studied capture in Hg^{199} and appeared to find a large difference? He looked at two resonances and compared the transitions to states below about 1.1 MeV with those to some unspecified band at a somewhat higher energy. And he found that there is a large difference in average radiation widths taken over these two groups.

HARVEY: Were the selection rules the same?

BOLLINGER: It was assumed that these are E1 transitions, although there was not enough independent information to be sure. But in any case, the transitions to the low-lying states (the ones that turned out to be weaker), are known to be E1. It is the stronger ones for which one doesn't have any information.

HARVEY: I won't comment on the ^{199}Hg data. However, I would like to ask Henry Motz a question related to paper G-2 on

¹⁰E. R. Rae, W. R. Moyer, R. R. Fullwood, and J. L. Andrews, Phys. Rev. 155, 1301 (1967).

holmium capture. Would you not expect a correlation between the intensities of high-energy gamma rays when they go to final states of the same character?

MOTZ: This is a question of whether the Porter-Thomas distribution applies when you have two closely correlated states, namely members of the same rotational band. I would expect that there would be a correlation of the intensities from any given resonance to the members of this band when, say, two E1 and two M1 transitions are involved. Yet the data that we have seen in the resonance capture in Tm shows that one fluctuates relative to the other. One possible reason for this might be mixing—the fact that these are not pure states. I don't think the mixing is that high in the ground-state band for Tm . So, I don't understand this. It really is a separate question.

BOLLINGER: Before we close, I would like to switch away from the scientific matters altogether and ask Jean Vervier to make a statement about his "News Letter", which he has some additional ideas about. It would be useful to get your reactions to his ideas.

VERVIER: Most of you probably received the first two issues of the Slow Neutron Capture Gamma Ray News Letter and any suggestion—and especially any criticisms—on the way it is now presented would be very welcome. The next issue will probably appear at the end of this year, and I should also be grateful for your suggestions concerning the way it is presented.

There is another suggestion that Dr. Bollinger made about a possible extension, in the sense of having compilations of γ -ray energies.

BOLLINGER: Well, Vervier was agreeing to do the work; so under those circumstances it is easy to have ideas.

The idea was that we simply send to him at a fairly early stage (usually before the stage of publication) gamma-ray energies and intensities and rather preliminary decay schemes. Information

of this sort would not be intended to be final in any sense at all, but would merely be to point out in a graphic fashion, to all those who are interested in having such information, what kind of data are being produced, so as to help us in our day-to-day work. The more final compilations we would leave to the professional compilers.

So the idea is that we simply send this information to Vervier, preferably all of it on one page, and just ask him to reproduce it in his News Letter. This would be an entirely voluntary sort of thing. And unless he wishes to do it, he would feel under no compulsion to go out beating the bushes asking people to contribute.

Does anyone care to comment as to whether this is a worth-while thing to be doing or not?

SCHULT: In principle, this is an excellent idea. It would activate the communication of preliminary results and it would make the data available to other people at the earliest possible time. There is, however, one point which we should consider: it may take a year or even longer before the data are interpreted and before the preprint has been completed. What should the other people do in the meantime? Should they refer to the News Letter? If they do so, then the News Letter would become a journal. Or should they consider the data as private communication?

BOLLINGER: Well, I think those would be problems that Vervier would have to work out before any of us could agree to submit data to him.

In order to allow people to meet that bus, I think we'd better conclude this session.

Let me thank you all for coming.

CHRIEN: I would like, on behalf of the the people here at the conference, to thank Drs. Bolotin and Bollinger for running a very fine conference.

BOLLINGER: Thank you.

BOLOTIN: Thank you.

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