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ANNUAL PROGRESS REPORT
GAMMA-RAY SPECTROMETRY OF NEUTRON-DEFICIENT ISOTOPES

IDAHO NUCLEAR CORPORATION
NATIONAL REACTOR TESTING STATION
IDAHO FALLS, IDAHO

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ANNUAL PROGRESS REPORT GAMMA-RAY SPECTROMETRY OF NEUTRON-DEFICIENT ISOTOPES

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ANNUAL PROGRESS REPORT
GAMMA-RAY SPECTROMETRY OF NEUTRON-DEFICIENT ISOTOPES

A B S T R A C T

The primary objective of this program has been to produce neutron-deficient nuclides to obtain high-resolution gamma-ray spectra and basic information on gamma-ray branching ratios, gamma-ray energies, and intensities for the Gamma-ray Spectrum Catalogue. The emphasis in this effort is to provide nuclear laboratories and experimenters with these data obtained with state-of-the-art gamma-ray spectrometers. To make this information most useful, standard methods for obtaining and analyzing data obtained with Ge(Li) spectrometers are being developed.

During the past year, neutron-deficient nuclides have been produced primarily by proton bombardment of target materials using (p,xn) reactions and by (n,p) and (n, α) reactions using fast neutrons. Spectra have been obtained for approximately 30 nuclides. Data on these nuclides include precise energies and intensities for the primary gamma rays. Considerable effort has also been made in the study of the operating characteristics of standard laboratory spectrometers. Systematic studies have been made of the detection efficiency of Ge(Li) detectors for gamma rays up to 10 MeV. Such data are designed to provide criteria for the selection of detectors to fill particular experimental needs.

As an extension of these studies, a number of specialized detector systems have been investigated. Preliminary measurements of the operating characteristics of a two-crystal Compton summing spectrometer have been completed. Data obtained indicate that such systems offer considerable promise in the reduction of the unwanted Compton continuum in pulse-height spectra. In the interest of improving the performance of high-resolution Ge(Li) spectrometers, pulse rise-time systems for rejecting unwanted pulses resulting from charge collection problems in these detectors have been evaluated. The development of electronic circuitry and study of problems in spectrometers which lead to degradation in performance at high counting rates have also received considerable attention. A laboratory system has been successfully operated

which exhibits essentially no measurable baseline shift and less than 10% peak broadening (for ^{60}Co gamma rays) at counting rates up to 80,000 pulses/sec. This system is entirely D.C. coupled from detector to ADC which greatly simplifies D.C. restoration problems.

An investigation of parameters to improve the performance of Si(Li) spectrometers for x-ray fluorescence measurements have been continued. Detection efficiencies and response functions for a 30-mm² x 3-mm detector have been obtained for x-rays from 3 keV to 2000 keV. Investigations have included the optimization of source-detector configuration, the use of different types of excitation sources (e.g., α , β , γ , and bremsstrahlung) for different applications.

The status of continuing work on the Gamma-ray Spectrum Catalogue is as follows: the third volume of the NaI Scintillation Catalogue is presently going to press and will be issued by the end of 1968. Due to improvements in technique which can result in improved precision in the measurement of gamma-ray energies using Ge(Li) spectrometers, the preliminary Ge Catalogue will now be issued by January 1969. Work during the past year has contributed to the publication of 12 journal articles and 5 papers presented at meetings.

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ANNUAL PROGRESS REPORT
GAMMA-RAY SPECTROMETRY OF NEUTRON-DEFICIENT ISOTOPES

I. Program Summary

The continuing objective of this program is directed at the measurement and compilation of gamma-ray spectra of neutron-deficient isotopes in support of isotope technology. The major emphasis of this effort is to provide the applied nuclear laboratory with a compilation of working data representing the instrumental response of lithium-ion drifted germanium gamma-ray spectrometers. Secondary objectives include the development of criteria for experimental design and techniques for data acquisition and analysis to provide the laboratory analyst with usable qualitative and quantitative techniques. A parallel objective is to develop the necessary technology for the application of high-resolution Si(Li) detectors to x-ray fluorescence techniques. This effort is aimed at optimizing systems for effective laboratory applications. Applications which require information of this character include the use of neutron generators, the expanding use of accelerator-produced isotopes in biology and medicine, and the support of reactor developments in the area of high-flux and fast reactors.

The emphasis during the past year has been on the production of catalogue spectra for Ge(Li) spectrometers for isotopes formed by proton, He³, and electron bombardment. During this past year Ge(Li) spectra of over 100 nuclides have been analyzed, including (in most cases) the measurement of precision energies for major gamma rays. Instrumental techniques have recently been refined to make it possible to measure gamma-ray energies to 3 MeV with an accuracy of better than 100 eV.

Work on low-noise electronics has resulted in improved performance of Si(Li) spectrometers for x-ray analyses. A resolution of 400 eV (FWHM) has been attained for the Fe K_α x-ray line. Studies of Ge(Li) and Si(Li) detector systems have been completed to provide the user with useful criteria for purchase of detectors from commercial sources.

Work on the publication of Volume 3 of the NaI Scintillation Catalogue and the First Edition of the Ge(Li) Spectrum Catalogue is in

progress. Present plans are to publish the 3rd Volume of the NaI compilation by late 1968. The first preliminary edition of the Ge(Li) Catalogue will be issued early in 1969 with a formal edition, including text, to follow in approximately six months. The present estimate for completion of the Ge compilation is 2 to 3 years at the present level of activity. The present press run on the NaI Catalogue is in excess of 5000. Work during the past year has resulted in the publication of 12 formal papers and 5 papers presented at technical meetings. Consultation in the areas of x-ray and gamma-ray spectrometry has been provided to a large number of laboratories involved in various areas of isotope technology.

II. Development, Study, and Use of Semi-conductor Spectrometers

A. Ge(Li) Detectors

One of the more exciting and useful advances in the field of nuclear spectroscopy in recent years has been the development of semi-conductor detectors. In particular, the lithium-ion drifted germanium [Ge(Li)] detector has completely re-oriented the field of gamma-ray spectroscopy. The superior resolution of the peaks in a pulse-height spectrum from these detectors enables not only the determination of the presence of many more gamma rays in a given spectrum, but the determination of the energies and intensities of these gamma rays with previously unattainable precisions.

To fully realize the potential of these systems, it has been necessary to investigate fully each component of a Ge(Li) spectrometer and to obtain the ultimate in stability, linearity and resolution. Preamplifiers have been developed at this laboratory¹⁾ which yield the presently obtainable limit in resolution. These preamplifiers employ cooled field-effect transistors in the first two stages which are contained in the cryostat along with the detector. Detectors which are manufactured both commercially and in individual laboratories cover a very large range of sizes, shapes and geometrical configurations. No

1. K. F. Smith and J. E. Cline, IEEE Transactions on Nuclear Science, Vol. NS-13, No. 3 (June 1966) p. 468.

"standard" shapes or sizes have yet evolved. It is, therefore, often difficult for an experimenter to decide upon detectors with which to equip a laboratory or to perform a given experiment. Each of the detectors has different operating characteristics which should be known before the "optimum" device can be chosen. Among these characteristics are: 1) charge collection efficiency, which can give rise to both symmetric and asymmetric peak broadening, 2) energy resolution, 3) gamma-ray detection efficiency, both absolute and relative, and 4) timing characteristics, for application in coincidence or lifetime studies. It is thus of value to provide information on the quantitative and systematic behavior of these parameters for detectors of different shapes and configurations. Such information should enable experimentors to best determine the shape, volume, and operating characteristics which will best satisfy their own particular needs.

The capability for fabrication of Ge(Li) detectors was developed at this laboratory for a variety of reasons. Primary purposes were to provide high-resolution devices for use in obtaining high quality Ge(Li) spectra and for studies of operating characteristics of Ge(Li) spectrometers and other special applications. Another advantage of achieving this capability is a requirement for maintaining the ability to repair cryogenic systems which have suffered some damage such as a non-operating FET in the internal preamplifier or detectors which have suffered neutron damage.

The effort during this past year has been concentrated on the construction of reasonably large-volume planar devices. Techniques used at this laboratory in the fabrication differ from those used in other laboratories only in detail.

There are two major suppliers of single-crystal germanium of detector quality. These are Sylvania Electric and Hoboken Metals. During the past year, test samples of approximately twenty ingots of germanium have been obtained from these two firms. Six of these ingots have proved to be of sufficient quality to warrant the purchase of the remainder of the ingot. Of these six, only three have yielded devices which do not show severe charge-collection problems. Samples of new ingots are continually being tested to maintain a stock of good detector material.

Details of detector construction are illustrated in Figures 1-3. Slices are cut from the ingot with a diamond-impregnated wire saw as shown in Figure 1. The wire in this saw contains no joints yielding a

Figure 1 - Wire saw used to slice single-crystal ingots of germanium.

much smoother cut with less crystal damage than would be possible with a wire containing a weld. A circular cut (as shown in Figure 2) is made in the ingot following lithium diffusion to remove the material from the corners and edges. This material has been observed by many experimentors to contain a higher density of trapping centers than the material from the center of the ingot. The circular saw can also be used to cut the center out of the slice for special detectors. A coaxial detector has been constructed using this technique so that the lithium could be deposited on the inside of the center hole and drifted outward. This construction technique yields better coaxial detectors from material which shows preferential trapping for holes than does the conventional construction technique. This results from the $\frac{1}{r}$ nature of the electric field in these devices so that on the average

Figure 2 - Circular saw used to shape diffused germanium slices.

Figure 3 - Constant temperature drifting vats used in drifting lithium ions into germanium.

most of the pulse resulting from the detection of a photon results from electron collection whereas in conventional units, most of the pulse is from the collection of holes. Drifting is performed in constant temperature baths (boiling liquids) as shown in Figure 3. Some work has been initiated in investigating AC drift techniques for the construction of deep-drift planar detectors. In this technique, lithium is diffused into both surfaces and drifted toward the center by the application of an AC voltage applied between the surfaces. When the two drift regions join, one of the lithium surfaces is ground away and a p-type contact established by a deposition of gold on a clean lapped surface. The drifting is then completed in the normal manner. AC drifting has produced detectors 12- to 16-mm thick which show considerably less charge-collection problems than those made from conventional DC drifting. Even these diodes, however, still show evidence of charge trapping, particularly of holes.

Most of the Ge(Li) spectrometers constructed at this laboratory utilize internal cooled FET preamplifiers. The detectors are DC coupled to the input FET which requires that they be electrically isolated from the cryostat. Figures 4 and 5 show the cryostat and the loading of a

Figure 4 - Typical vacuum cryostat used for Ge(Li) detectors. The cryostat contains a cooled FET preamplifier.

Figure 5 - Ge(Li) detector being installed in the vacuum cryostat.

device in place, respectively. The electrical insulator for the detector mount in Figure 4 is, in this case, a wafer of sapphire which is an excellent heat conductor and is also an excellent insulator. Detector current and capacity measurements are made on most completed devices. These data are correlated with the performance of the diode as a gamma-ray detector. Current values of 1×10^{-10} amperes are commonly obtained for a 2000-V bias when the detector is shielded from the black-body radiation from the cap. These measurements usually indicate those units which will be potentially good spectrometers. They do not, however, yield any information on charge-collection properties. These properties are discussed in the following sections.

Detection efficiencies which have been investigated are absolute full-energy peak and double-escape peak efficiencies. Absolute full-energy peak efficiencies, ϵ_{fep} , are defined as the fraction of the emitted gamma rays which are detected and recorded in the peak of the pulse-height distribution corresponding to the full energy of the gamma ray. Absolute double-escape peak efficiencies, ϵ_{dep} , are similarly

defined as the fraction of gamma rays emitted from the source which are detected and recorded in the peak corresponding to the full energy of the gamma rays less $2 m_0 c^2$. Events which are recorded in the full-energy peak arise from one of the three primary gamma-ray interaction processes. For an event to be recorded in the peak following an initial Compton or pair-production process, secondary absorption must occur within the depletion region of the detector. Thus, the behavior of the full-energy peak efficiency as a function of initial gamma-ray energy is dependent, for gamma-ray energies above ~ 400 keV, upon the magnitude of the secondary absorption processes. An additional effect which influences the dependence on energy is that of electrons leaving the depletion region without depositing all of their energy. This effect removes events from the full-energy peak.

The energy dependence of the double-escape peak efficiency is also influenced by electrons (and positrons) escaping from the depletion volume. Events are removed from the double-escape peak by the detection of one or both of the annihilation quanta. This effect is essentially independent of gamma-ray energy. The reason is as follows: Although, on the average, the point of origin of the annihilation quanta moves deeper into the depletion region as the gamma-ray energy increases, the average flux of annihilation photons over the sensitive region does not change. Therefore, the energy dependence of the double-escape peak efficiency should not be influenced by this process.

Detector edge effects can influence energy dependence of the full-energy peak efficiency at lower energies. These are caused by gamma rays entering the detector near the edge of the front surface at other than normal incidence (i.e., from a source located near the crystal). The average path length traversed by a gamma ray is therefore reduced at the edge of the detector causing a decrease in the relative efficiency for detection of high-energy (i.e., $E_\gamma \gtrsim 200$ keV) gamma rays.

The effects of random and real coincidence summing can often significantly contribute to inaccuracies in the measurement of gamma-ray intensities and detection efficiencies. Real coincidence summing effects, although often ignored, can nevertheless readily be taken into account. The amount removed from a peak through this effect can be

calculated if the absolute detection efficiencies for the two coincident gamma rays are known. These can be obtained through a knowledge of the peak detection efficiencies and the peak-to-total ratios. The solution to the problem of random coincidence summing, however, is more elusive. If a pulse, normally stored in the pulse-height distribution corresponding to a peak, occurs randomly coincident with another pulse (within the width of the two pulses), the pulses will, in part, sum and the event will not be recorded in the peak.

Detectors constructed in the normal manner by diffusing lithium into the "front" surface prior to the drift have an insensitive region on the face of the detector. This layer varies in thickness from a few hundred microns to a millimeter or more and can severely reduce the detection efficiency of the device for gamma rays having energies less than ~ 200 keV.

Systematic studies have been made of the energy dependence of efficiencies for planar detectors as a function of detector area, at constant drift depth, and of drift, at constant area. Studies were also made of an open-ended coaxial detector and a large volume 5-sided drift detector. From these studies, the systematic trends in the factors which influence the energy dependence of detector efficiencies could be observed. The detectors used in this study are listed in Table I. Most of the units were fabricated at this laboratory and their dimensions could be measured directly. The drift depth was determined by Cu staining. Location of the detector within the cryostat was accomplished with x-ray photography.

Efficiency measurements for gamma-ray energies up to 2.76 MeV were made using radioactive sources. A full-energy peak efficiency curve for the 2.5-cm x 8-mm detector was obtained from sources calibrated with a 3" x 3" NaI(Tl) detector. Sources of ^{241}Am , ^{153}Gd , ^{57}Co , ^{141}Ce , ^{139}Ce , ^{203}Hg , ^{51}Cr , ^{198}Au , ^7Be , ^{85}Sr , ^{137}Cs , ^{54}Mn , ^{88}Y , ^{65}Zn , ^{60}Co , and ^{24}Na were used for this measurement. The accuracy of source calibration using this method²⁾ is considered to be about 2%. Such accuracy has been obtained in measurements of IAEA and NBS standards. The accuracy

2. R. L. Heath, Scintillation Spectrometry Gamma-Ray Spectrum Catalogue, 2nd Edition, IDO-16880 (August 1964).

Table I

List of Detectors Studied in Efficiency Measurements

Detector	Dimensions	Volume	Type
1	2.5 cm ² x4 mm	1.0 cc	planar
2	5.8 cm ² x4 mm	2.3 cc	planar
3	2.5 cm ² x8 mm	2.0 cc	planar
4	4.9 cm ² x8 mm	3.9 cc	planar
5	6.4 cm ² x8 mm	5.1 cc	planar
6	10.2 cm ² x8 mm	8.2 cc	planar
7	6.6 cm ² x12 mm	7.9 cc	planar
8	3-cm long x 2.6-cm diam, 8.5-mm drift open-ended	12 cc	coaxial
9	2.8-cm long x 4-cm diam. 12-mm, 5-sided drifted	~35 cc	coaxial

of the detection efficiencies obtained from the calibrated sources is considered to be about 5% for relative measurements. The uncertainties in the location of the surface of the sensitive volume of the detector. Efficiency curves for the other detectors studied were obtained through the use of a mixed source of ¹⁸²Ta, ¹⁹²Ir, ¹³⁷Cs and ⁸⁸Y. This source was prepared so that detection efficiencies could be determined simultaneously over a wide range of gamma-ray energies. The absolute intensities of the gamma rays emitted by this source were measured with the 2.5-cm² x 8-mm detector calibrated as mentioned above.

Gamma rays having energies greater than 2.8 MeV were obtained for efficiency measurements from neutron capture gamma-ray sources. The primary source used in these measurements was melamine (C₃H₆N₆). A study of the gamma rays resulting from the capture of thermal neutrons by ¹⁴N has been made by Motz et al.³⁾ using a Compton spectrometer.

3. H. T. Motz, R. E. Carter and W. D. Barfield, Proceedings of the Symposium on Pile Neutron Research in Physics, Vienna, 1960. Published by IAEA (1962) 225.

These data provide accurate values for the absolute intensities of the reaction gamma rays. A list of these gamma-ray energies and intensities is given in Table II. Since the sample also contained a known amount

Table II

Table of High-energy Gamma Rays used in Efficiency Measurements

Reaction	E_{γ} (MeV)	I_{γ} ($\gamma/100$ captures)	Reaction	E_{γ} (MeV)
$^{14}\text{N}(n,\gamma)$	3.53	9	$\text{Fe}(n,\gamma)$	5.92
	3.68	23		6.02
	4.51	16		7.28
	5.27	32		7.63
	5.30	21		7.64
	5.53	21		8.89
	5.56	11	$^9\text{Be}(n,\gamma)$	3.37
	6.32	18		3.44
	7.30	9		6.81
	8.31	4	$^{27}\text{Al}(n,\gamma)$	7.72
	9.15	1.4		
	10.83	14		
$^1\text{H}(n,\gamma)$	2.223	441	$\text{Ni}(n,\gamma)$	5.31
$^{23}\text{Na}(n,\gamma)$	3.59			5.82
	3.98			6.84
	6.40			7.54
$\text{S}(n,\gamma)$				7.82
	2.38			8.53
	2.93			9.00
	3.22			
	4.87			
	5.42			

of hydrogen, the 2.223-MeV gamma ray resulting from the capture of a neutron by the hydrogen could be included in the analysis. Spectra of gamma rays with energies above a few MeV show the double-escape peaks as the most prominent feature. This was generally the case in the gamma-ray spectra resulting from capture by the melamine source, where the full-energy peaks were often indistinguishable from the background. For this reason only relative double-escape peak efficiencies were obtained with the spectra from this source. Absolute double-escape peak efficiencies were obtained by normalizing these data to the lower energy

data obtained from sources. The ratio of full-energy peak efficiency to double-escape peak efficiency as a function of energy was obtained above 2.8 MeV by measuring this ratio for the prominent gamma rays in the neutron capture spectra from samples of Be, Al, S, Fe, Na and Ni. Full-energy peak efficiencies were then obtained from the value of this ratio and from the value of the normalized double-escape peak efficiency at the appropriate gamma-ray energy.

Studies were made of the effects of random coincidence summing. The probability of such summing should be proportional to the square of the counting rate. To verify this relationship and to determine the constant of proportionality a series of efficiency measurements was made at several different counting rates using accurately calibrated ^{137}Cs sources of different strengths. A straight-line fit could easily be made to the data, verifying the relationship and yielding a constant of proportionality of 13.6 μsec or a value of 6.8 μsec for the effective resolving time of the system. This value is consistent with the observed pulse shape. The spectrometer used in these measurements incorporated "pole-zero" pulse shaping⁴⁾ and base-line restoration which greatly reduced counting rate effects.

The depth of the insensitive lithium-diffused region on the face of the detectors varied but was less than 1 mm in all cases. The presence of this "dead-layer" severely reduced the detection efficiency of these devices for gamma-ray energies less than 100 keV. One of the detectors which was studied had a thin "dead-layer", constructed by lapping off the undepleted p region and depositing a thin Au layer. The window thickness of this detector is $< 50 \mu$. Details of the technique have been reported by Janarek *et al.*⁵⁾

Full-energy peak efficiencies are shown in Figure 6 for gamma-ray energies up to 11 MeV for three different detectors having constant drift depths but different cross-sectional areas. Figure 7 shows the double-escape peak efficiencies for these same detectors. Full-energy

4. C. H. Nowlin and J. L. Blankenship, Rev. Scient. Instr. 36 (1963) 1830.

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

Figure 6 - Full-energy peak efficiencies for three detectors having 8-mm drift depths, but different cross-sectional areas.

Figure 7 - Double-escape peak efficiencies for three detectors having 8-mm drift depths, but different cross-sectional areas.

peak efficiencies at essentially constant area but for different drift depths are given in Figure 8. Double-escape peak efficiencies for

Figure 8 - Full-energy peak efficiencies for three detectors having nearly equal cross-sectional areas, but different drift depths.

these detectors are shown in Figure 9. Absolute full-energy peak and absolute double-escape peak efficiencies are shown in Figures 10 and 11, respectively, for two large-volume (~ 8 cc) planar detectors and for the two coaxial detectors. Figure 12 is a plot of the full-energy peak efficiency of the thin window device compared to that of a detector with a "normal" window.

From an inspection of the double-escape peak efficiency curves of Figures 7, 9, and 11, it is apparent that the double-escape peak efficiency eventually decreases with increasing gamma-ray energy. This effect is caused almost entirely by electrons and positrons escaping from the detection region, as has been discussed above. The effects from bremsstrahlung are considered to be minor for the gamma-ray

Figure 9 - Double-escape peak efficiencies for three detectors having nearly equal cross-sectional areas, but different drift depths.

Figure 10 - Comparison of full-energy peak efficiencies of two coaxial detectors with those of two planar detectors having nearly equal volumes but different drift depths and cross-sectional areas.

Figure 11 - Comparison of double-escape peak efficiencies of two coaxial detectors with those of two planar detectors having nearly equal volumes but different drift depths and cross-sectional areas.

Figure 12 - Comparison of full-energy peak efficiencies of a thin-window detector with a detector having a "normal" window.

energies in these studies. The three curves of Figure 7 are essentially parallel, showing that, in general, the relative double-escape peak efficiency at higher energies does not increase with increasing surface area. Figure 9, however, shows that as the depletion depth is increased, the relative double-escape peak efficiency increases at higher energies.

Events which are recorded in the full-energy peaks of pulse-height distributions result from three processes. The photoelectric effect dominates at low energies but is essentially negligible above 500 keV where an event in the peak results either from the absorption of the Compton scattered gamma ray or from the full-energy absorption of both annihilation quanta following pair production. The relative amount of secondary absorption may be compared for the various detectors through an examination of the ratio of full-energy peak to double-escape peak efficiency as a function of gamma-ray energy. Some of these data are given in Figure 13. This ratio is representative of secondary Compton absorption to pair-production probabilities. To first approximation, values of this ratio are not affected by electron escape. At lower energies, the magnitude of the ratio is nearly proportional to

Figure 13 - Ratio of full-energy peak to double-escape peak efficiencies for several detectors.

the volume of the detector. The divergence of the curves at higher energies shows the increased relative probability of complete secondary absorption at these energies for the larger volume detectors. As would be expected, the ratio of single-escape to double-escape peak efficiencies is not a function of energy. It is proportional to the probability for full-energy absorption of a 511-keV gamma ray which is emitted isotropically from within the volume of the detector. Thus, the value of this ratio is also indicative of the effectiveness for the detection of secondary processes. Full-energy peak efficiency curves show the combined effects of secondary processes and electron escape. The energy dependence of these efficiencies should demonstrate even more than that for the double-escape efficiencies the effect of increased average path length traversed by secondary gamma rays and electrons. The curves of Figure 6, constant thickness and varying area, are much more parallel than those of Figure 8, constant area and varying thickness.

A comparison of full-energy peak efficiencies and double-escape peak efficiencies was presented in Figures 10 and 11, respectively, for planar and coaxial detectors. The differences in the energy dependence of these curves result from the different relative effects from electron escape and secondary Compton absorption in the two quite different configurations. Since the electrons from the pair process are directed in a forward direction ($\theta_0 = m_0c^2/E_\gamma$, where θ_0 = average angle between electron and initial gamma ray) and the gamma rays enter the crystal from the open end, the 3-cm long channel of the coaxial detector reduces the effects of electron escape over that for the 10.2-cm² x 8-mm detector. The relative shape of the curves for the ratio of full-energy peak to double-escape peak efficiencies shows that the coaxial detector is relatively more efficient for secondary processes at higher energies. The coaxial device of equivalent surface area is probably relatively less efficient for secondary processes at the lower energies due to the dead core in the center.

There appear to be two categories of charge-collection problems which affect energy resolution in Ge(Li) spectrometers. One of these gives rise to the asymmetric broadening of peaks and the other gives rise to a symmetric broadening. One might speculate as to the differences in the charge-collection process which can give rise to these

two effects as opposed to "normal" charge collection. If there are regions within the crystal which trap some of the charge from only a few of the events occurring within the detector, these particular pulses will be smaller than most of the pulses and will give rise to the familiar "low-energy tailing" which is observed in many gamma-ray spectra. Furthermore, if the fraction of events which are affected is proportional to the total number of events, then the amount of tailing will increase with increasing gamma-ray energy, as observed. These asymmetric peaks are particularly annoying when a function is fit to these peaks for the determination of peak position, to be used for energy determinations. Since a Gaussian function is usually used, inaccuracies can be introduced. The height of the peak above the background or Compton distribution is also reduced. Figure 14 shows a series of peaks giving the relationship of width at half-maximum to width at 1/10 maximum for peaks with varying amounts of tailing. These peaks have been normalized to constant area. This asymmetric type of peak broadening is often associated with the material from which the detector was constructed but can be induced by neutron damage in a detector which did not previously exhibit tailing.

Figure 14 - Peak shapes, normalized to constant area, showing effects of tailing.

Symmetric broadening effects produce an anomalous increase in peak widths with increasing gamma-ray energy. They could be caused by a charge trapping phenomenon in which a small fraction of the charge from each event is trapped or not collected within the integrating time constant of the amplifier. This problem is usually not so serious a problem as that of the asymmetric broadening, at least in gamma-ray "singles" spectroscopy. It seems to be associated with regions of low electric field such as occur in large five-sided coaxial detectors. An example of this phenomenon is shown in Figure 15 which presents energy resolution as a function of energy for two detectors having "normal" charge collection and one detector showing this anomalous increase in the width of peaks with energy. A curve showing the resolution as a function of energy calculated for a Fano factor of 0.15 is included for comparison.

Figure 15 - Plot of measured energy resolution (FWHM) for three detectors showing anomalous energy-broadening effects. Included is a curve of theoretical resolution calculated assuming a Fano factor of 0.15.

The peak-to-total ratio, defined as the ratio of the number of events in the full-energy peak to the number of events in the entire pulse-height distribution of a single gamma-ray energy, can often be indicative of the performance of a detector. This quantity can serve as an indication of the efficiency for secondary processes in the detector and as an indicator of possible charge collection problems. Experimental values of peak-to-total ratios for ^{137}Cs and ^{54}Mn for the detectors studied are presented in Table III. The larger ratios are given by the thicker units showing the effects of the longer average path length presented to higher-energy forward Compton scattered gamma rays. Coaxial detectors contain a region of germanium which is insensitive to the collection of charge. This region can influence the peak-to-total ratio in two ways. First, the secondary Compton gamma rays created in the depletion region can interact in this dead core and be lost to collection in the outer detector regions, and second, secondary Compton gamma rays can be created in this core and be detected in the outer region, adding to the lower-energy distribution of the pulse-height spectrum. Fowler has reported⁶⁾ an experiment in which this core was removed resulting in an increase of 50% in the peak-to-total ratio for 0.66-MeV gamma rays.

Of primary interest to detector users is the ability of a detector to cause a peak to rise above the continuous Compton distribution so that it can be readily observed and analyzed. This characteristic, which might be termed a signal-to-noise ratio, is related to both resolution and peak-to-total ratio. A "figure-of-merit" at a given energy could be defined as the peak-to-total ratio divided by the resolution (FWHM). Table III presents (column 2) the capacitance of the detector and (column 3) the resolution which could be expected using the best currently available preamplifiers. Values for the resolution from both cooled and room-temperature operated preamplifiers are shown. The last column gives the "figure-of-merit" at two gamma-ray energies for both types of preamplifiers.

The advantages of large volume devices are somewhat more obvious than the disadvantages. One practical advantage can be seen in the data of Figure 16, which shows spectra of ^{142}La taken with a 2.5-cm² x 8-mm planar detector and the large 5-sided drift coaxial detector.

Table III

Table of Peak/Total Ratios, Energy Resolution (FWHM), and (Peak/Total)/
(FWHM) at 662 and 835 keV for the Detectors Studied

Detector	Detector Capacitance pf	Peak/total ratio ($\times 10^{-2}$)		Resolution (FWHM) (keV)*				(Peak/total)/(FWHM) ($\times 10^{-2}$)			
		^{137}Cs	^{54}Mn	Cooled ^{137}Cs	P.A. ^{54}Mn	Room Temp ^{137}Cs	P.A. ^{54}Mn	Cooled ^{137}Cs	P.A. ^{54}Mn	Room Temp ^{137}Cs	P.A. ^{54}Mn
2.5 cm ² x 8 mm (2.0 cc)	4.4	4.9	3.5	1.41	1.56	1.73	1.85	3.5	2.2	2.8	1.9
4.9 cm ² x 4 mm (2.0 cc)	17.2	3.3	2.5	1.58	1.72	1.98	2.09	2.1	1.5	1.7	1.2
4.9 cm ² x 8 mm (3.9 cc)	8.6	4.3	3.5	1.48	1.63	1.81	1.93	2.9	2.1	2.4	1.8
6.4 cm ² x 8 mm (5.1 cc)	11.3	5.3	4.1	1.53	1.67	1.88	2.00	3.5	2.5	2.8	2.0
10.2 cm ² x 8 mm (8.2 cc)	18.0	5.7	4.6	1.59	1.73	2.00	2.11	3.6	2.7	2.8	2.2
6.6 cm ² x 12mm (7.9 cc)	7.8	7.1	5.5	1.46	1.61	1.80	1.92	4.9	3.4	3.9	2.9
3-cm long; 2.6-cm diam. ~8.5-mm drift open-ended coax (12 cc)	~3C	8.3	6.3	1.72	1.85	2.21	2.28	4.8	3.4	3.7	2.8
2.8-cm long, 4-cm diam, 12-mm 5-sided drift, coax (~35 cc)	~2C	9.1	7.0	1.61	1.75	2.04	2.14	5.6	4.0	4.5	3.3

* Resolution as calculated using data presented in paper by K. F. Smith et al., IEEE Transactions on Nuclear Science, Volume NS-13, No. 3, 468 (1966). The assumptions were made that the Fano factor for Ge is 0.15 and that internal preamplifiers have an additional 3 pf and external preamplifiers have an additional 10 pf stray capacitance due to the detector lead wire.

^{142}La emits gamma rays having energies up to about 4 MeV and the advantages of the increased relative efficiency of the larger detector for higher-energy gamma rays are apparent in the figure. The heights above the base line of the peaks at 641, 862 and 894 keV are enhanced in the spectrum from the larger detector relative to the heights in the spectrum from the smaller detector by about the ratio of the "figure-of-merit" for these two detectors. Small detectors, however, usually have the advantage of better resolution. This superior resolution can result in energy measurements with higher precision and in the unravelling of highly complex gamma-ray spectra in which resolving closely-spaced gamma rays requires the best resolution attainable. An example of this is given in Figure 17, a spectrum of gamma rays from the decay of ^{239}Pu ,

in which over 125 transitions having energies less than 700 keV have been resolved.

Figure 18 - Spectra of gamma rays from the $^{14}\text{N}(n,\gamma)^{15}\text{N}$ reaction taken with a large (~ 35 cc) coaxial detector and with a $4.9\text{-cm}^2 \times 4\text{-mm}$ planar detector.

It appears, from the efficiency, resolution, and timing characteristics of the various types of detectors, that for the same detector volume, a deep-drift planar detector has the more desirable operating characteristics for most applications in gamma-ray spectrometry. This, however, presumes that germanium ingots of sufficient quality can be obtained to make such devices. Currently, even the best material available appears to give rise to serious charge-collection difficulties when detectors are fabricated which have drift depths greater than 10-14 mm. Spectra from the deeper-drifted detectors generally exhibit tailing on the peaks. These detectors generally give rise to a high proportion of long rise-time pulses. Thus, it appears that at present the better detectors having volumes greater than about 12 cc are generally coaxially drifted. Some reasons why the coaxial detectors are better are as follows. First, the drift depths are generally less than 10 mm. Secondly, for coaxial detectors made from material in which the dominant trapping centers trap electrons, and where the lithium is drifted in from the

outside, most of the pulse results from hole collection, since the holes travel on the average through a larger potential than do the electrons. Good coaxial detectors have been successfully made from material which was unsuitable for good planar devices. In material that evidences hole trapping, it should be possible to accomplish the same thing by coring out the center and drifting outward. Larger depletion volumes can be achieved with less initial material by using the technique of five-sided drift. Some excellent detectors, such as that studied in the present experiments, have been made using this technique. Often, however, five-sided coaxial detectors show the undesirable properties of anomalous increase in peak widths with increasing energy and have very bad timing characteristics.

From the discussions presented above, it becomes apparent that it is difficult to describe detector performance characteristics in a quantitative manner. The experimenter is generally faced with the availability of a wide variety of detector sizes, shapes and quality of performance. The following comments are offered to assist in selecting devices for a given application.

For any given experiment, one should consider the desired set of characteristics to realize the objectives of the experiment. Important considerations include: (1) energy resolution, (2) energy range to be investigated, (3) absolute detection efficiency in the range of interest, (4) desired energy dependence of detection efficiency, (5) timing, and (6) system considerations (e.g., cost, maintenance, etc.). If low-energy measurements are a major emphasis, energy resolution and the thickness of the "dead layer" on the entrance window of the detector may be of prime importance. If the ultimate in energy resolution is required, it can be attained only with low-capacity detectors combined with cryogenic FET preamplifiers. Equipment of this type is costly and difficult to fabricate and is mechanically delicate, making shipment of such systems a problem. Charge collection problems in detectors are usually magnified by the increased resolution.

Sufficient knowledge of detector operating characteristics requires information in the following categories: (1) detector and system resolution as a function of gamma-ray energy, (2) absolute efficiency for

at least one energy, and (3) some indication of charge collection efficiency. Such information, when obtained for a detector having "known" volume, shape, drift depth, and capacitance can be compared with reported characteristics of other, similar devices.

Since system energy resolution results from both detector and system contributions, it is necessary to measure system resolution for at least two gamma-ray energies, one high and one low energy. Convenient radioactive sources for such measurements are 240-day ^{153}Gd (97 and 103 keV) or 138-day ^{139}Ce (166 keV) and 1.9-yr ^{228}Th in equilibrium with its daughters (spectrum contains a major transition at 2.62 MeV). A quantitative measure of the peak shape (tailing) would be given by the resolution (FWHM in keV) and the ratio of the width at 1/10 maximum to that at 1/2 maximum for the higher-energy full-energy peak.

Absolute detection efficiency should be measured at some agreed upon geometry and gamma-ray energy using calibrated sources. Convenient calibrated sources of ^{60}Co and ^{137}Cs are commercially available for this purpose.

Combined with the determination of detector peak efficiency, the peak-to-total ratio or figure-of-merit (described above) should be measured. These values, when compared to published values for other detectors of similar volume and configurations, would be quite indicative of the charge-collection efficiency of a detector. It should be stressed that all such measurements are subject to influence by problems in the electronic systems used (e.g., moderate counting rates should be used to minimize base-line difficulties at high rates).

B. Si(Li) Detectors

Recent developments in fabrication techniques for lithium-ion drifted silicon detectors have resulted in improved performance for x-ray and gamma-ray spectrometers employing these devices. A general discussion of the characteristics of detectors and associated electronic systems for use in x-ray spectrometry is presented. This will include a description of the optimum operating parameters for detectors, considerations in the design of low-noise preamplifiers employing field-effect transistors, instrumental requirements for high-resolution

systems, and methods which can be applied for data analysis. Practical laboratory x-ray spectrometer systems using commercially available equipment are described.

Data were obtained on a system which exhibits an energy resolution of 420 eV (FWHM) for 6-keV photons. Examples of the application of this system to x-ray spectrometry are presented. Fluorescent excited x-ray spectra are shown for the elements from chlorine to lead.

The measured width of a peak in a pulse-height spectrum resulting from interaction of a primary photon by the photoelectric effect is used as a measure of the resolution. This width is related to the statistical spread in the number of electron-hole pairs created in the detector following an ionizing event. In addition to this fundamental limitation, the observed peak width also includes contributions from a number of "noisesources" arising from other elements of the electronic system. These may be attributed to problems in the detector and the characteristics of the preamplifier, amplifier, and the pulse-height analyzer.

In silicon, on the average, 3.76 eV of energy is required to produce an electron-hole pair (2.96 eV for germanium). Following the production of an electron in the detector by the Compton process or by the photoelectric effect, energy is lost either by the production of electron-hole pairs or processes which result in the emission of phonons. The resolution may be given by

$$\text{FWHM (keV)} = 2.355 \sqrt{FE\epsilon}$$

where

E = the energy of the electron in keV,

ϵ = the average energy to create an electron-hole pair, and

F = the Fano factor, a semi-empirical factor which reflects the fact that the width of the distribution deviates from that of a purely Poisson distribution.

Other sources of noise which can be attributed to a practical detector configuration include (a) fluctuations in detector leakage current, (b) charge collection problems resulting from trapping of charge carriers or variation in charge collection time which will

produce a variation in pulse rise-time, and (c) shunt resistance noise sources in the preamplifier input circuit.

It is of interest to determine a value for the Fano factor, F , to obtain an estimate of the ultimate limit in energy resolution to be expected from a detector. Figure 19 shows the results of recent measurements made in our laboratory to obtain an experimental value for the Fano factor in lithium-ion drifted silicon devices. This figure indicates experimental values for the energy resolution of a silicon spectrometer system as a function of energy in the x-ray region. To obtain an estimate of the detector line width, the contribution from all other factors can be assumed to be given by the observed width of a mercury-switch tail pulse generator measured simultaneously with the x-ray source. The resulting line width for the detector, after removal of the contribution from system noise is shown by the triangles. Also plotted for comparison are two solid curves representing the expected line width for Fano factor values of 0.2 and 0.15 for silicon. The experimental points are seen to agree quite well with a value of 0.15

Figure 19 - Resolution vs energy for Si(Li) system indicating experimental determination of the Fano factor for Si.

for the Fano factor in silicon. Also indicated for comparison by the dashed line is the expected resolution for lithium-drifted germanium detectors for $F = 0.15$ ⁷⁾.

From an examination of these data one may conclude that (1) in the x-ray region, the experimental values for energy resolution are limited largely by preamplifier noise, and (2) that improved resolution could be obtained by using germanium devices because of the lower values for the energy required to create an electron-hole pair in germanium.

The performance of lithium-ion drifted silicon devices is quite sensitive to operating temperature. In view of the advantages of using silicon in the x-ray energy region: (1) availability with thin entrance windows, and (2) lower sensitivity to high-energy gamma rays, studies were conducted to determine an optimum operating temperature for these devices for the detection of electrons and low-energy photons. These studies have been summarized previously.⁸⁾

To illustrate the resolution which can presently be attained with Si(Li) detectors under the best laboratory conditions, Figure 20 is a pulse-height spectrum of radiation emitted in the decay of ⁵⁷Co. This nuclide decays by electron capture, emitting Fe x-rays (6.4 keV) and a major gamma ray at 14.4 keV. As indicated in the figure, the Fe K_{α} and K_{β} x-rays are clearly resolved with a resolution for the K_{α} line of ~ 420 eV. The noise contribution from the electronic system (370 eV) was measured by inserting pulses from a mercury relay tail pulser into the input of the preamplifier. These data were obtained with a TMC photon spectrometer using selected components. In this case, the detector used was a 30-mm² area by 3-mm planar Si(Li) device. Photons entered the vacuum cryostat through 20-mil Be window. It should be stressed that these results represent the present limit in FET noise performance, although there are indications that further improvement may be expected as FET fabrication techniques improve.

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7. R. L. Heath, W. W. Black and J. E. Cline, IEEE Transactions on Nuclear Science, Vol. NS-13, No. 3 (June 1966) p. 445.
 8. J. E. Cline and R. L. Heath, Annual Progress Report, Gamma-Ray Spectrometry of Neutron Deficient Isotopes, IDO-17222 (March 1967).

Figure 20 - Low-energy x-ray spectrum of ^{57}Co obtained with 30-mm² TMC detector system.

A more practical demonstration of the performance of a Si(Li) x-ray spectrometer is given in Figure 21. This figure shows a series of spectra of characteristic x-rays for elements from vanadium to lanthanum. Examination of these data indicates that, for elements in this range of Z , adjacent elements are easily resolved.

As an indication of the performance of these devices for low- Z elements, we have successfully observed Cl x-radiation produced by fluorescence excitation.

The data presented above should serve to adequately demonstrate that the solid-state spectrometer is capable of energy resolution which compares favorably with dispersive instruments. Inherently, these devices lend themselves to applications where the availability of simple portable instrumentation might permit the use of x-ray fluorescence techniques. To establish the feasibility of applying Si(Li) spectrometers for non-destructive assay employing x-ray fluorescence techniques several experiments have been performed.

Figure 21 - Series of x-ray spectra for elements from vanadium to lanthanum obtained with 80-mm² x 3-mm TMC Si(Li) detector in laboratory cryostat.

Using a "source-target" assembly such as that described by Rhoades⁹⁾, x-ray fluorescent studies of mineral and stainless steel samples have been conducted. The physical arrangement of the source, target, and detector are shown in Figure 22. 60-keV gamma rays from a 14-mc ²⁴¹Am source excited the K_α and K_β x-rays in tellurium (from 27.2 to 31.7 keV) which in turn excited the x-rays from the various elements in the samples. Typical data taken with this system are presented in Figure 23. This shows the x-ray spectrum excited in a typical silver-bearing ore. In this case, silver was used as an exciting source. Thus, the silver x-rays in the sample were not excited. The silver x-rays which were observed were exciting x-rays scattered by the sample into the detector. The presence of Fe, Ni, Cu, Sr, and Pb in the samples are indicated by their characteristic x-rays.

9. J. R. Rhoades, T. G. Ahier and I. S. Boyce, Symposium on Radiochemical Methods of Analysis, Salzburg, October 1964, Paper SM-55/20 (Vienna, IAEA).

Figure 22 - Geometry used for x-ray fluorescence excitation studies.

Figure 23 - X-ray spectrum of ore sample excited by Ag x-rays.

Figure 24 shows x-ray spectra from three different samples of stainless steel. The spectra have been displaced vertically from one

Figure 24 - X-ray spectra of stainless steel samples.

another to avoid confusion. At the top of the figure are shown the pulse-height positions of the K_{α} and K_{β} x-rays for the various elements present in the samples. The table on the figure shows the composition listed by the manufacturers for these varieties of stainless steel. Examination of this figure clearly demonstrates the ability to differentiate between different types of stainless steels by non-destructive methods by exciting minor constituents.

C. Electronic Components

The preamplifier presently in use was developed at this laboratory. Its basic properties were described previously.⁸⁾ Minor improvements have been made which include almost exclusive use of D.C. coupling to the detector (eliminating some stray capacitance) and the addition of

"pole-zero" cancellation networks. First order "pole-zero" cancellation is also now employed in all main amplifiers. With these improvements, counting rates up to 20,000 c/s have been used with little broadening of the peaks. Figure 25 shows typical results obtained from such a system. These data were taken using a source of ^{60}Co . The broadening of the peaks with increased counting rate is accompanied by an asymmetry on the high side.

Figure 25 - Count-rate performance of amplifier system with pole-zero correction. The figure shows 1.33-MeV peak from ^{60}Co for four different counting rates.

D. Measurements of New Energy Standards

The use of 4096-channel multichannel analyzers permits one to take advantage of the superior resolution characteristics of Ge(Li) detectors to determine energies with precisions heretofore obtainable only with crystal diffraction spectrometers. To utilize this ability, however,

it is necessary for the experimenter to have available precise energies which can be used as primary standards. Consequently, a program to measure some of these standards was undertaken at this laboratory. The energies of these standards were measured relative to the energies of the transitions in ^{192}Ir and ^{182}Ta . These latter transitions have been studied with crystal spectrometers. Table IV presents a list of transition energies which have been measured for some primary standards.

Table IV

Transition Energies Determined for Use as Primary Standards

Nuclide	Gamma-ray Energies	Nuclide	Gamma-ray Energies
^7Be	477.575 ± 0.020	^{137}Cs	661.630 ± 0.030
^{85}Sr	513.998 ± 0.020	^{54}Mn	834.795 ± 0.040
^{207}Bi	569.674 ± 0.020 1063.614 ± 0.040	^{160}Tb	879.329 ± 0.030
^{124}Sb	602.712 ± 0.025 1690.991 ± 0.050	^{88}Y	897.996 ± 0.030 1836.075 ± 0.050

III. Experimental Measurements of Catalogue Spectra

A. Samples Irradiated

As during previous years, measurements were made using the variable-energy cyclotron operated by the University of Colorado and the electron linear accelerator operated by the General Atomic Division of General Dynamics Corporation. Table V shows a list of samples which were irradiated during the past year.

Table V

Samples Irradiated during FY 1967

Nuclide Produced	Target Nuclide	T _{1/2}	Reaction	Sept 66	Jan 67	March 67
^{44m} Sc	⁴⁵ Sc	2.4 d	(γ ,n)	x		
⁴⁷ Sc	⁴⁸ Ti	3.4 d	(γ ,p)	x		
⁴⁸ Sc	⁴⁹ Ti	1.8 d	(γ ,p)	x		
⁴⁸ V	⁴⁹ Ti	16 d	(p,2n)		x	
⁶⁰ Cu	⁶¹ Ni	24 m	(p,2n)		x	
⁶¹ Cu	⁶³ Cu	3.3 h	(γ ,2n)	x		
⁶² Cu	⁶³ Cu	9.8 m	(γ ,n)	x		
⁶⁷ Cu	⁶⁸ Zn	59 h	(γ ,p)	x		
⁶² Zn	⁶³ Cu	9.3 h	(p,2n)		x	
⁶⁵ Ga	⁶⁶ Zn	15 m	(p,2n)		x	
⁶⁶ Ga	⁶⁶ Zn	9 h	(p,n)		x	
⁷³ Ga	⁶⁴ Ge	4.9 h	(γ ,p)	x		
⁶⁷ Ge	⁶⁹ Ga	19 m	(p,2n)		x	
⁶⁹ As	⁷⁰ Ge	15 m	(p,2n)			x
⁷⁰ As	⁷² Ge	52 m	(p,3n)		x	
⁷⁰ As	⁷⁰ Ge	50 m	(p,n)			x
⁷¹ As	⁷¹ Ge	62 h	(p,2n)		x	
⁷² As	⁷³ Ge	26 h	(p,2n)		x	
⁷⁴ Br	⁷⁶ Se	42 m	(p,3n)			x
⁷⁵ Br	⁷⁶ Se	1.6 h	(p,2n)		x	
⁷⁵ Br	⁷⁶ Se	1.6 h	(p,2n)			x
⁷⁶ Br	⁷⁷ Se	17 h	(p,2n)		x	
⁷⁷ Br	⁷⁹ Br	58 h	(γ ,2n)	x		
⁸³ Sr	⁸⁴ Sr	36 h	(γ ,n)	x		
^{85m} Sr	⁸⁶ Sr	70 m	(γ ,n)	x		
⁸⁴ Y	⁸⁶ Sr	50 m	(p,3n)			x
⁸⁵ Y	⁸⁶ Sr	3.3 h	(p,2n)			x
⁸⁶ Y	⁸⁶ Sr	14 h	(p,n)			x
^{86m} Y	⁸⁶ Sr	49 m	(p,n)			x
⁸⁷ Y	⁸⁸ Sr	80 h	(p,2n)			x
^{87m} Y	⁸⁸ Sr	14 h	(p,2n)			x

Table V (Cont.)

Nuclide Produced	Target Nuclide	T _{1/2}	Reaction	Sept 66	Jan 67	March 67
⁸⁷ Zr	⁸⁹ Y	1.6 h	(p,3n)			x
⁸⁹ Nb	⁹⁰ Zr	1.9 h	(p,2n)			x
^{89m} Nb	⁹⁰ Zr	1 h	(p,2n)			x
⁹⁰ Nb	⁹⁰ Zr	14.6 h	(p,n)			x
⁹⁶ Nb	⁹⁷ Mo	23 h	(γ,p)	x		
^{99m} Rh	¹⁰⁰ Ru	4.7 h	(p,2n)			x
⁹⁹ Rh	¹⁰⁰ Ru	16 d	(p,2n)			x
¹⁰⁰ Rh	¹⁰¹ Ru	21 h	(p,2n)			x
¹⁰¹ Rh	¹⁰¹ Ru	3.1 y	(p,n)			x
¹⁰¹ Rh	¹⁰¹ Ru	4.7 d	(p,n)			x
¹⁰² Rh	¹⁰⁴ Ru	206 d	(p,3n)		x	
¹⁰¹ Pd	¹⁰³ Rh	8.5 h	(p,3n)			x
¹¹² Ag	¹¹³ Cd	3.2 h	(γ,p)	x		
¹¹² Cd	¹¹¹ Cd	49 m	(γ,n)	x		
^{117m} In	¹¹⁸ Sn	1.9 h	(γ,p)	x		
^{119m} In	¹²⁰ Sn	18 m	(γ,p)	x		
¹⁴³ Eu	¹⁴⁴ Sm		(p,2n)			x
¹⁴⁴ Eu	¹⁴⁴ Sm	18 m?	(p,n)			x
¹⁴⁵ Eu	¹⁴⁷ Sm	5.9 d	(p,3n)		x	
¹⁴⁶ Eu	¹⁴⁷ Sm	4.6 d	(p,2n)		x	
¹⁴⁷ Eu	¹⁴⁸ Sm	24 d	(p,2n)		x	
¹⁵⁰ Eu	¹⁵² Sm	5 y	(p,3n)		x	
^{150m} Eu	¹⁵² Sm	12.8 h	(p,3n)		x	
¹⁵⁵ Tb	¹⁵⁶ Gd	5.6 d	(p,2n)		x	
¹⁶¹ Tb	¹⁶² Dy	7 d	(γ,p)	x		
¹⁶² Dy	¹⁶³ Dy	14 m	(γ,p)	x		
¹⁵⁹ Ho	¹⁶¹ Dy	33 m	(p,3n)			x
¹⁶⁰ Ho	¹⁶¹ Dy	28 m	(p,2n)			x
^{160m} Ho	¹⁶¹ Dy	2.5 h	(p,2n)			x
¹⁶¹ Ho	¹⁶² Dy	2.5 h	(p,2n)			x
¹⁶² Ho	¹⁶³ Dy	12 m	(p,2n)			x
^{162m} Ho	¹⁶³ Dy	68 m	(p,2n)			x

Table V (Cont.)

Nuclide Produced	Target Nuclide	$T_{1/2}$	Reaction	Sept 66	Jan 67	March 67
^{168}Tm	^{170}Er	85 d	(p,3n)		x	
^{172}Lu	^{173}Yb	6 d	(p,2n)		x	
^{183}Re	^{184}W	70 d	(p,2n)			x
^{184}Re	^{185}Re	2.2 d	(γ ,n)	x		
^{184}Re	^{186}W	38 d	(p,3n)			x
$^{185\text{m}}\text{Re}$	^{185}Re	50 d	(p,3n)	x		
^{203}Pb	^{204}Pb	52 h	(γ ,n)	x		
$^{204\text{m}}\text{Pb}$	^{206}Pb	64 m	(γ ,2n)	x		

B. Index of Spectra Taken with NaI(Tl) Spectrometers

<u>Nuclide</u>	<u>Half-Life</u>	<u>Energy Scale (keV/channel)</u>	<u>Producing Reaction</u>	<u>Plate Number</u>
^{73}Ga	4.8 h	10	(γ ,p)	31-73-1
^{96}Nb	23 h	10	(γ ,p)	41-96-1
^{112}Ag	3.2 h	20	(γ ,p)	47-112-1
$^{117\text{m}}\text{In}$	1.9 h	10	(γ ,p)	49-117m-1
$^{118\text{m}}\text{In}$	4.4 m	10	(γ ,p)	49-118m-1
$^{162\text{m}}\text{Tb}$	8 m	10	(γ ,p)	65-162m-1
^{184}Re	38 d	10	(γ ,n)	75-184-1

C. Index of Spectra Taken with Ge(Li) Spectrometers

<u>Nuclide</u>	<u>Half-Life</u>	<u>Energy Scale (keV/channel)</u>	<u>Producing Reaction</u>	<u>Plate Number</u>
^7Be	54 d	0.244	(p,n)	4-7-1
$^{44\text{m}}\text{Sc}, ^{44}\text{Sc}$	2.4d, 4h	0.707	(γ ,n)	21-44,44m-1
^{47}Sc	3.4 d	0.242	(γ ,p)	21-47-1
^{48}Sc	1.8 d	0.556	(γ ,p)	21-48-1
^{48}V	16 d	0.713	(p,n)	23-48-1
^{51}Cr	28 d	0.437	(γ ,n)	24-51-1
^{60}Cu	24 m	4.106	(p,n)	29-60-1

<u>Nuclide</u>	<u>Half-Life</u>	<u>Energy Scale (keV/channel)</u>	<u>Producing Reaction</u>	<u>Plate Number</u>
⁶¹ Cu	3.3 h	1.434	(p,2n)	29-61-1
⁶² Cu	9.8 m	2.203	(γ,n)	29-62-1
⁶⁷ Cu	59 h	0.242	(γ,p)	29-67-1
⁶² Zn	9.3 h	0.895	(p,2n)	30-62-1
⁶⁵ Zn	245 d	0.366	(n,γ)	30-65-1
⁶⁵ Ga	15 m	2.77	(p,2n)	31-65-1
⁷³ Ga	4.9 h	1.258	(γ,p)	31-73-1
⁷⁰ As	52 m	0.616	(p,n)	33-70-1
⁷¹ As	62 h	0.519	(p,2n)	33-71-1
⁷² As	26 h	1.046	(p,2n)	33-72-1
⁷⁵ Se	127 d	0.175	(γ,n)	34-75-1
⁷⁵ Br	1.6 h	0.615	(p,2n)	35-75-1
⁷⁶ Br	17 h	1.226	(p,2n)	35-76-1
^{85m} Sr	70 m	0.719	(n,γ)	38-85m-1
^{87m} Sr	2.8 h	0.536	(n,γ)	38-87m-1
^{87m} Y, ⁸⁷ Y	14.6h, 80d	0.615	(p,2n)	39-87, 87m-1
^{91m} Y	50 m	0.239	(γ,p)	39-91m-1
⁸⁹ Zr	79 h	2.260	(γ,n)	40-89-1
⁹⁰ Nb	14.7 h	2.476	(p,2n)	41-90-1
^{110m} Ag	260 d	0.484	(n,γ)	47-110m-1
¹¹² Ag	3.2 h	3.16	(γ,p)	47-112-1
¹¹³ Ag	5.3 h	1.435	(γ,p)	47-113-1
^{117m} In, ¹¹⁷ In	1.9h, 66m	1.434	(γ,p)	49-117m, 117-1
^{154m} Tb, ¹⁵⁴ Tb	8.5h, 21h	0.952	(p,2n)	65-154m, 154-1
¹⁵⁵ Tb	5.6 d	0.224	(p,2n)	65-155-1
^{162m} Tb		1.435	(γ,p)	65-162m-1
²⁰³ Pb	52 h	0.350	(γ,n)	82-203-1

D. Table of Energies of Gamma Rays Assigned to Nuclide Decays

Nuclide	E_γ	Nuclide	E_γ	Nuclide	E_γ
^7Be	477.63±0.12	^{62}Zn	507.35±0.18	^{72}As	765.7 ±0.3
$^{44\text{m}}\text{Sc}$ IT	271.19±0.08		548.38±0.20		786.4 ±0.3
^{44}Sc	1001.99±0.20		596.76±0.20		834.03±0.13
	1126.16±0.15	^{65}Zn	511.006 ann.		894.17±0.15
	1157.02±0.10		rad.		1050.65±0.16
	1499.63±0.25		1115.51±0.07		1215.3 ±0.5
^{47}Sc	159.38±0.08	^{65}Ga	53.9 ±0.6		1379.2 ±0.4
			61.2 ±0.6		1390.3 ±0.3
^{48}Sc	175.4 ±0.2		90.0 ±1.0		1464.08±0.18
	983.4 ±0.2		115.2 ±0.5		1475.8 ±0.2
	1037.5 ±0.2		153.2 ±0.4		1710.7 ±0.3
	1312.1 ±0.2		207.1 ±0.4		1917.8 ±0.3
^{48}V	290.1 ±0.4		751.3 ±0.4		1991.1 ±0.4
	928.3 ±0.3		932.4 ±0.4		2071.7 ±0.4
	944.1 ±0.2	^{71}As	174.70±0.2		2090.6 ±0.5
	983.46±0.15		247.1 ±0.5		2105.6 ±0.5
	1311.9 ±0.2		279.2 ±0.5		2109.4 ±0.5
	1437.6 ±0.4		326.5 ±0.3		2201.6 ±0.1
	2240.1 ±0.2		349.9 ±0.4		2248.3 ±0.3
			373.6 ±0.5		2507.68±0.16
^{51}Cr	320.07±0.07		391.2 ±0.3		2620.9 ±0.4
^{61}Cu	23.20±0.35		465.0 ±0.6	^{73}Ga	53.39±0.20
	44.8 ±0.5		499.85±0.17		68.66±0.30
	55.4 ±0.5		526.6 ±0.2		285.00±0.30
	67.60±0.25		572.2 ±0.3		297.37±0.20
	283.00±0.25		615.3 ±0.3		325.74±0.25
	373.6 ±0.3		622.7 ±0.5		379.28±0.40
	405.2 ±0.3		679.7 ±0.5		739.37±0.25
	529.3 ±0.3		685.4 ±0.8		767.87±0.35
	588.6 ±0.3		707.7 ±0.3		833.30±0.35
	656.01±0.25		712.5 ±0.3	^{75}Se	66.10±0.15
	1185.0 ±0.3		747.0 ±0.3		96.73±0.10
^{67}Cu	91.34±0.08		851.2 ±0.3		121.11±0.08
	93.36±0.08		920.6 ±0.2		136.02±0.08
	184.54±0.10		1026.7 ±0.2		198.68±0.10
	208.92±0.12		1033.5 ±0.2		264.69±0.07
	300.13±0.10		1037.9 ±1.0		279.57±0.07
	393.5 ±0.15		1095.48±0.15		303.93±0.10
^{62}Zn	243.47±0.25		1139.3 ±0.2		400.71±0.10
	246.99±0.25		1212.8 ±0.3	^{75}Br	112.51±0.5
	260.36±0.25		1231.3 ±0.4		141.50±0.25
	305.2 ±0.3		1298.4 ±0.2		236.0 ±0.2
	349.7 ±0.7	^{72}As	1331.5 ±1.5		286.7 ±0.18
	393.94±0.25		600.88±0.17		293.1 ±0.2
			629.80±0.13		316.0 ±0.4
			756.7 ±0.3		377.6 ±0.3

Nuclide	E_Y	Nuclide	E_Y	Nuclide	E_Y
^{75}Br	428.2 $\pm$ 0.3	^{76}Br	1568.2 $\pm$ 0.5	$^{110\text{m}}\text{Ag}$	657.78 $\pm$ 0.08
	566.1 $\pm$ 0.3		1578.7 $\pm$ 0.6		677.61 $\pm$ 0.15
	573.1 $\pm$ 0.3		1787.6 $\pm$ 0.5		687.01 $\pm$ 0.10
	598.5 $\pm$ 0.4		2096.2 $\pm$ 0.4		706.66 $\pm$ 0.08
	608.8 $\pm$ 0.3		2110.8 $\pm$ 0.4		744.26 $\pm$ 0.12
	733.6 $\pm$ 0.4		2135.0 $\pm$ 0.4		763.96 $\pm$ 0.08
	771.0 $\pm$ 0.6		2281.2 $\pm$ 0.4		818.07 $\pm$ 0.10
	796.4 $\pm$ 0.8		2329.2 $\pm$ 0.5		884.73 $\pm$ 0.08
	860 $\pm$ 1		2334.0 $\pm$ 0.7		937.50 $\pm$ 0.08
	897.6 $\pm$ 1.0		2348.7 $\pm$ 0.5		1384.19 $\pm$ 0.08
	912.1 $\pm$ 0.6		2390.5 $\pm$ 0.3		1475.70 $\pm$ 0.10
	949.9 $\pm$ 1.5		2439.0 $\pm$ 0.6		1504.94 $\pm$ 0.12
	952.8 $\pm$ 1.0		2510.2 $\pm$ 0.5		1562.49 $\pm$ 0.17
	962.1 $\pm$ 1.0		2600.7 $\pm$ 0.6		
			2617.6 $\pm$ 0.7	^{112}Ag	606.2 $\pm$ 0.35
^{76}Br	358.4 $\pm$ 0.5		2792.15 $\pm$ 0.25		616.8 $\pm$ 0.3
	399.31 $\pm$ 0.5		2900.3 $\pm$ 0.5		694.0 $\pm$ 0.4
	472.7 $\pm$ 0.3		2950.0 $\pm$ 0.25		716.8 $\pm$ 1.0
	490.1 $\pm$ 0.5		2996.8 $\pm$ 0.3		775.7 $\pm$ 0.8
	558.99 $\pm$ 0.25		3023.4 $\pm$ 0.7		797.9 $\pm$ 0.4
	562.4 $\pm$ 0.5		3092.3 $\pm$ 0.7		850.8 $\pm$ 0.4
	598.8 $\pm$ 0.4		3603.5 $\pm$ 0.5		1103.4 $\pm$ 0.5
	604.2 $\pm$ 0.5		3929.5 $\pm$ 0.7		1252.1 $\pm$ 0.6
	657.2 $\pm$ 0.25		4436.7 $\pm$ 0.8		1311.4 $\pm$ 0.6
	665.3 $\pm$ 0.5	$^{87\text{m}}\text{Y}$	381.1 $\pm$ 0.5		1356.8 $\pm$ 1.0
	681.6 $\pm$ 0.5	^{87}Y			1386.6 $\pm$ 0.4
	696.0 $\pm$ 0.5				1468.2 $\pm$ 0.6
	727.1 $\pm$ 0.5	$^{91\text{m}}\text{Y}$	555.59 $\pm$ 0.1		1502.4 $\pm$ 0.8
	737.7 $\pm$ 0.5				1538.9 $\pm$ 1.2
	789.2 $\pm$ 0.5	$^{85\text{m}}\text{Sr}$	151.28 $\pm$ 0.1		1612.8 $\pm$ 0.6
	803.5 $\pm$ 0.5		231.69 $\pm$ 0.1		1798.6 $\pm$ 1.2
	831.1 $\pm$ 0.25		IT 238.65 $\pm$ 0.15		2055.6 $\pm$ 2
	836.6 $\pm$ 0.5	$^{87\text{m}}\text{Sr}$	388.40 $\pm$ 0.08		2105.6 $\pm$ 0.5
	867.7 $\pm$ 0.5				2210.8 $\pm$ 2
	882.2 $\pm$ 0.5	^{89}Zr	713.3 $\pm$ 0.4		2359.6 $\pm$ 3
	886.6 $\pm$ 0.5		909.07 $\pm$ 0.10		2506.2 $\pm$ 1
	901.0 $\pm$ 0.5		1621.4 $\pm$ 0.6		2542.5 $\pm$ 2.5
	942.7 $\pm$ 0.5				2685.7 $\pm$ 1.2
	981.2 $\pm$ 0.5	^{90}Nb	132.5 $\pm$ 0.4		2749.2 $\pm$ 5.0
	1029.7 $\pm$ 0.5		141.5 $\pm$ 0.3		2828.2 $\pm$ 1.2
	1032.2 $\pm$ 0.5		371.5 $\pm$ 1.0	^{113}Ag	3283.7 $\pm$ 2.5
	1129.9 $\pm$ 0.4		890.0 $\pm$ 1.0		97.2 $\pm$ 0.3
	1212.9 $\pm$ 0.5		1128.7 $\pm$ 1.5		258.8 $\pm$ 0.3
	1216.2 $\pm$ 0.3		1269.5 $\pm$ 2.0		298.6 $\pm$ 0.2
	1369.0 $\pm$ 0.4		2186.1 $\pm$ 2.0		316.2 $\pm$ 0.3
	1380.4 $\pm$ 0.4		2318.7 $\pm$ 2.0		333.1 $\pm$ 0.3
	1428.8 $\pm$ 0.6				339.3 $\pm$ 0.3
	1439.2 $\pm$ 0.6				364.6 $\pm$ 0.3
	1453.7 $\pm$ 0.5	$^{110\text{m}}\text{Ag}$	133.29 $\pm$ 0.10		382.0 $\pm$ 0.3
	1470.9 $\pm$ 0.4		446.82 $\pm$ 0.10		583.7 $\pm$ 0.3
	1488.5 $\pm$ 0.4		620.41 $\pm$ 0.13		672.4 $\pm$ 0.3
	1560.1 $\pm$ 0.6				

Nuclide	E_Y	Nuclide	E_Y	Nuclide	E_Y
^{113}Ag	680.9 $\pm$ 0.3	$^{154\text{m}}\text{Tb}$	1004.8 $\pm$ 0.2	^{155}Tb	220.69 $\pm$ 0.10
	884.0 $\pm$ 0.3	^{154}Tb	1060.0 $\pm$ 1.0		226.94 $\pm$ 0.15
	988.7 $\pm$ 0.3		1128.5 $\pm$ 0.6		239.53 $\pm$ 0.15
	1194.8 $\pm$ 0.3		1140.7 $\pm$ 0.8		263.30 $\pm$ 0.10
			1148.9 $\pm$ 1.0		268.56 $\pm$ 0.10
$^{117\text{m}}\text{In}$	158.63 $\pm$ 0.15		1152.4 $\pm$ 1.0		281.03 $\pm$ 0.15
^{117}In IT	315.33 $\pm$ 0.18		1165.3 $\pm$ 1.0		286.93 $\pm$ 0.15
	552.49 $\pm$ 0.15		1258.4 $\pm$ 1.5		321.74 $\pm$ 0.20
			1289.0 $\pm$ 1.5		340.74 $\pm$ 0.15
$^{154\text{m}}\text{Tb}$	123.07 $\pm$ 0.2		1274.9 $\pm$ 1.0		367.32 $\pm$ 0.15
^{154}Tb	180.5 $\pm$ 0.7		1292.0 $\pm$ 1.5		370.70 $\pm$ 0.20
	225.7 $\pm$ 0.3		1410 $\pm$ 2		402.13 $\pm$ 0.25
	231.7 $\pm$ 0.3		1491 $\pm$ 3		422.41 $\pm$ 0.15
	247.7 $\pm$ 0.2		1967 $\pm$ 2		559.09 $\pm$ 0.25
	346.6 $\pm$ 0.2		2186 $\pm$ 1.5		
	381.9 $\pm$ 0.4			$^{162\text{m}}\text{Tb}$	80.90 $\pm$ 0.15
	415.9 $\pm$ 0.3	^{155}Tb	45.35 $\pm$ 0.10		185.43 $\pm$ 0.15
	444.6 $\pm$ 0.4		58.03 $\pm$ 0.15		260.01 $\pm$ 0.15
	517.9 $\pm$ 0.3		60.03 $\pm$ 0.10		697.0 $\pm$ 0.25
	540.10 $\pm$ 0.25		86.60 $\pm$ 0.07		795.8 $\pm$ 0.5
	557.2 $\pm$ 0.5		99.02 $\pm$ 0.20		807.60 $\pm$ 0.15
	598.0 $\pm$ 0.4		101.14 $\pm$ 0.15		882.38 $\pm$ 0.15
	642.4 $\pm$ 0.6		105.36 $\pm$ 0.07		888.16 $\pm$ 0.15
	649.5 $\pm$ 0.3		120.53 $\pm$ 0.20		
	676.4 $\pm$ 0.4		148.63 $\pm$ 0.10	^{203}Pb	279.16 $\pm$ 0.02
	692.3 $\pm$ 0.3		158.38 $\pm$ 0.20		401.28 $\pm$ 0.4
	704.6 $\pm$ 0.5		161.28 $\pm$ 0.10		680.7 $\pm$ 0.6
	714.5 $\pm$ 0.5		163.28 $\pm$ 0.10		
	722.1 $\pm$ 0.5		175.20 $\pm$ 0.20		
	756.9 $\pm$ 0.3		180.06 $\pm$ 0.10		
	815.5 $\pm$ 1.0		181.59 $\pm$ 0.15		
	873.2 $\pm$ 0.2		206.60 $\pm$ 0.20		
	892.7 $\pm$ 0.3		203.04 $\pm$ 0.20		
	925.3 $\pm$ 1.0		208.22 $\pm$ 0.15		
	996.4 $\pm$ 0.2		216.05 $\pm$ 0.15

1.8 day ^{48}Sc
2.5 cm² x 8 mm Ge (Li)
9-23-66
Absorber : 0.5 g/cm² Poly
Source Dist. : 3 cm
Energy Scale : 0.556 keV/channel

29 - 60 - 1

33 - 71 - 1

62 hr As^{71} 2.5 cm² x 8 mm Ge(Li)

1 - 20 - 67

Absorber : None

Source Dist. : 1.8 cm

Energy Scale : 0.5188 keV/ch

38-87m-1

49-117, 117m-1