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April—December 1965

Lowell M. Bollinger, Division Director

Preceding Summary Reports:

ANL-6983, April-December 1964

ANL-7029, January-March 1965

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FOREWORD

The Argonne National Laboratory Physics Division Summary Report is issued from time to time for the information of the members of the Division and a limited number of other persons interested in the progress of the work.

Since reports on any particular research program are written at irregular intervals, the individual issues usually present only a fragmentary picture of the work of the Division. To counteract this, the active projects not reporting are listed in each issue; and an Annual Review issue presents a comprehensive survey.

The articles in the Physics Summary are informal progress reports. The results and data therefore must be understood to be preliminary, tentative, and often incomplete.

The issuance of these reports is not intended to constitute publication in any sense of the word. Final results either will be submitted for publication in regular professional journals or, in special cases, will be presented in ANL Topical Reports.

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I. EXPERIMENTAL NUCLEAR PHYSICS

I-7-8. GAMMA-RAY SPECTRA FROM CAPTURE IN NEUTRON RESONANCES (51313-01)

H. E. Jackson, A. I. Namenson, G. E. Thomas, and R. K. Smither

PRECISION MEASUREMENTS OF SPECTRA FROM THERMAL-NEUTRON-CAPTURE GAMMA RAYS

The development of the lithium-drifted Ge-diode gamma-ray spectrometer has led to a sudden burst of interest in the study of the gamma-ray spectra resulting from the capture of thermal neutrons. As compared with the previous precision instruments used to study high-energy gamma-ray spectra, the Ge detector has a much higher efficiency and better resolution. Consequently, the new spectrometer achieves an order-of-magnitude improvement in the data and has a wider range of applicability. The instruments used previously required heavy samples (such as are available only in naturally-occurring mixtures of isotopes) in order to obtain sufficient gamma-ray intensity for measurement. Isotopic identification of gamma rays was often ambiguous, and it was impossible to measure lines in isotopes whose capture cross section was small or whose abundance in the natural mixture was low. With the Ge diode, on the other hand, it is now practical to measure the gamma-ray spectra resulting from thermal capture in small samples of separated isotopes. Isotopic identification of lines is clear and measurements on rare isotopes are possible. In addition, the high resolution of the Ge detector permits a precision of energy measurement not previously obtainable above 2 MeV.

A facility is being developed at the Argonne research reactor CP-5 to take full advantage of the Ge diode for the study of thermal-neutron-capture gamma rays. Basically, this system consists of a neutron-capturing gamma-ray source mounted in the center of a straight-through beam hole, a gamma-ray beam collimator, and a gamma-ray spectrometer mounted outside of the reactor. This arrangement is believed to be the optimum one for securing a high gamma-ray flux and a high signal-to-background ratio at the detector. The principal drawback is that a relatively complex system is required to handle the gamma-ray source, which may become quite radioactive.

Although a source-handling system with sufficient convenience and versatility for the full intended range of experiments will not be completed before early 1966, a simple temporary system and a detector with a volume of 4 cm^3 have been used in a series of spectral measurements. The over-all resolution width of the detection system is less than 6 keV for 6-MeV gamma rays and about 3 keV for 1-MeV gamma rays. A comparison method that makes use of a precision pulser has been developed for the measurement of relative gamma-ray energies with an uncertainty of only about 0.02% of the gamma-ray energy. The high efficiency of the detector enables the experimenter to obtain all of the data required for a given source in less than one week. Because of the small size of the targets, it has been feasible to change targets quickly and safely and to study several different isotopes in rapid succession.

An especially easy quantity to determine from the neutron-capture gamma-ray spectra is the neutron separation energy. The 1-keV accuracy that is readily achievable with the Ge diode is considerably better than has been obtainable from either mass measurements or studies of alternative nuclear reactions. The neutron-capture spectra have been used to obtain accurate separation energies for several isotopes, including Be^{10} , C^{13} , N^{15} , N , Si , Na^{24} , Mg , Al , Fe , Hf^{178} , Hf^{179} , Hf^{180} , and Hf^{181} .

The neutron-capture gamma-ray spectra observed with a Ge diode are also very useful in the study of nuclear structure. Figure 1 gives a small sampling of the spectra observed for a target of normal hafnium and targets enriched in Hf^{177} and Hf^{179} . The isotopic assignment of a given line was established from its intensity change from sample to sample. The high-energy gamma-ray lines assigned to the various isotopes were combined with the low-energy lines observed with the bent-crystal spectrometer to deduce refined decay schemes for Hf^{178} and Hf^{180} . Many new levels were identified. The level scheme of Hf^{180} as generated from the high-energy data alone is given in Fig. 2. None of the levels above 1 MeV were identifiable from the previously reported studies of the high-energy capture gamma rays from natural hafnium samples.

Four intense gamma transitions of special interest were identified in the level schemes of Hf^{179} and Hf^{181} . The two observed in Hf^{181} were from the neutron-capture state to the ground state ($\frac{1}{2}^-$) and to

Fig. 1. High-resolution gamma-ray spectra obtained with the Ge-diode assembly installed at a through hole at the CP-5 reactor. These curves illustrate the method of isotopic assignment used for the $\text{Hf}^{177}(n, \gamma)\text{Hf}^{178}$, $\text{Hf}^{178}(n, \gamma)\text{Hf}^{179}$, and $\text{Hf}^{179}(n, \gamma)\text{Hf}^{180}$ spectra. The labels "177" and "179" indicate the isotopes in which the capturing samples were enriched.

Fig. 2. Level scheme of Hf^{180} as derived from the high-energy gamma-ray data from the Ge-diode work.

the first excited state ($\frac{3}{2}^-$). These levels correspond to the first two levels in the [510] Nilsson band. The spacing of these levels is found to be 47 keV. A similar pair of intense transitions to the same Nilsson levels was observed in Hf^{179} , for which the $\frac{1}{2}^-$, [510] level is the 378-keV isomeric state. The spacing of these levels in Hf^{179} is 44 keV—almost the same as the spacing for Hf^{181} . In view of the interesting similarity between the levels in Hf^{179} and Hf^{181} , and also in the isotone W^{183} , the levels of Hf^{177} will be studied in the future by means of the reaction $\text{Hf}^{176}(n, \gamma)\text{Hf}^{177}$.

I-14-26. PULSED-BEAM EXPERIMENTS WITH THE
VAN DE GRAAFF MACHINE (51312-01)

Frank J. Lynch

IMPROVED TIMING WITH NaI(Tl)

Introduction

The time resolution obtainable with slowly decaying scintillators such as NaI(Tl) is limited primarily by the statistics of photoelectron production. The time resolution imposed by this effect alone was calculated by Post and Schiff¹ in 1950. They found that the probability that the Qth photoelectron is emitted in the time interval between t and $t + dt$ is

$$W_Q(t)dt = \frac{[f(t)]^{Q-1} e^{-f(t)} [df(t)/dt] dt}{(Q-1)!}, \quad (1)$$

where $f(t)$ is the average or expected number of photoelectrons emitted between the initial excitation (at $t = 0$) and time t . For the case of a scintillator producing on the average R photoelectrons per excitation and decaying exponentially with a mean life τ , one can write $f(t) = R(1 - e^{-t/\tau})$ and Eq. (1) becomes

$$W_Q(t) = \frac{R^Q (1 - e^{-t/\tau})^{Q-1} \exp[-R(1 - e^{-t/\tau})] e^{-t/\tau}}{\tau(Q-1)!}. \quad (2)$$

In a delayed-coincidence experiment, if the fast discriminator that produces the standardized timing pulse triggers when the anode pulse reaches the voltage corresponding to the Qth photoelectron, the time distribution measured should be given by Eq. (2). Figure 3 shows the time-resolution curves calculated from Eq. (2) for various values of R and for the three

¹R. F. Post and L. I. Schiff, Phys. Rev. 80, 1113 (1950).

Fig. 3. Calculated time-resolution curves for three different values of Q : (a) for $Q = 1$, (b) for $Q = 2$, and (c) for $Q = 5$.

indicated values of Q . It is clear that the best time resolution is obtained for $Q = 1$. In this case, the time distribution is nearly a pure exponential with effective mean life τ/R .

Although for low-energy gamma rays the best time resolution should be obtained by triggering at a level close to $Q = 1$, the dark current in most photomultipliers triggers the fast discriminator at such high rates that pile-up effects impair the time resolution. Therefore, it is necessary to discriminate at a level sufficiently high so that the triggering rates will be well below 10 000 counts/sec.

During the past year photomultipliers with bi-alkali (CsKSb) photocathodes have become available. According to published characteristics, these have an average peak quantum efficiency of 28% at 3850 Å which decreases to 14% at 3000 Å and 5200 Å. This provides excellent sensitivity to the scintillator light from the main emission band at 4200 Å as well as the band around 3450 Å which, according to Van Sciver,² supplies about a quarter of the total light output.

²W. J. Van Sciver, Phys. Letters 9, 97 (1964); Bull. Am. Phys. Soc. 10, 391 (1965) and duplicated text distributed at the meeting.

Fig. 4. Block diagram of the delayed-coincidence apparatus.

Furthermore, the photocathode has much less thermionic emission than the common S11 photocathode and therefore the discriminator can be set to trigger at or near the level corresponding to one photoelectron. The present measurements were undertaken to determine how much the time resolution could be improved by using the improved photomultipliers and solid-state electronics.

Experimental Arrangement

In order to utilize the near-ultraviolet component of the light emitted from NaI(Tl), the crystals were packaged with Al_2O_3 reflectors and quartz windows. They were mounted on an RCA-8575 photomultiplier which has a bi-alkali photocathode. The other detector was a 1×1-in. Naton-136 plastic scintillator mounted on an XP-1020 photomultiplier.

Figure 4 is a block diagram of the delayed-coincidence apparatus. In the usual manner, two signals are obtained from the photomultiplier: a fast timing signal and a slow integrated signal which is analogous to the energy. To obtain the timing signal, the anode current of the photomultipliers passes through an RG-63 coaxial cable (terminated

Fig. 5. Experimental time-resolution curves for a 1X1-in. NaI(Tl) crystal excited by 511-, 260-, and 110-keV radiations.

at each end with a 125- Ω resistor) and into an Esaki-diode discriminator. This fast discriminator supplies a standardized output pulse of about 1 μ sec duration to the time-to-pulse-height converter where it is suitably clipped by a length of coaxial cable, short circuited at one end. The time-to-pulse-height converter designed³ and built at Argonne is of the overlap type which produces an output only when the timing pulse in channel B is later than the timing pulse in channel A. In one experimental arrangement, the pulses from the time-to-pulse-height converter pass through a

linear gate into a multichannel pulse-height analyzer. The linear gate is controlled by a single-channel differential pulse-height analyzer whose window was adjusted to cover the desired range of energy. In the other experimental arrangement, a 1024-channel two-parameter pulse-height analyzer was used. Then time was recorded in 64 channels and energy in 16 channels, in order to accumulate time spectra for a range of energies. The pulses from the time-to-pulse-height converter were not corrected for the effect of variation of pulse amplitude in the energy channel.

Results

Figure 5 shows time distributions taken with the above apparatus and a Na²² positron source. The window was set on the upper

³R. G. Roddick and F. J. Lynch, IEEE Trans. Nucl. Sci. NS-11, No. 3, 399 (1964).

Fig. 6. Experimental time-resolution curves obtained with a 0.020×1-in. NaI(Tl) crystal excited by radiations of different energies. (a) Excitation by 130-keV Compton electrons from 511-keV gamma rays. (b) Excitation by 31.6-keV x rays from a Cs¹³⁷ source.

25% of the distribution of pulses due to Compton electrons produced in the plastic scintillator by the annihilation gamma rays of 511 keV energy. The pulse-height distribution corresponding to energy absorbed in a 1×1-in. NaI(Tl) scintillator was spread over 16 channels of the 2-parameter analyzer. Hence the effective window width was about 511/16 = 32 keV/channel at all energies. Time distributions are plotted for channels corresponding only to 511, 260, and 110 keV.

Figure 6(a) shows data taken in the same way with a thin detector [NaI(Tl), 0.020 in. thick × 1 in. O.D.] for a γ -ray energy of 130 ± 4 keV. Figure 6(b) shows the delayed-coincidence curve between the x rays (31.6 keV) and conversion electrons from a Cs¹³⁷ source. The window of the single-channel analyzer for the plastic scintillator was set over the peak due to the conversion electrons and the window for the

Fig. 7. Time distribution of the 31.6-keV Cs x rays, measured from the instant of emission of the 355- and 274-keV gamma rays. The prompt curve was taken with a Cs^{137} source.

NaI(Tl) scintillator had a width of 32 ± 5 keV and was centered on the x-ray photopeak. As a demonstration of the advantage of the good time resolution at low energy, the lifetime of the first excited state in Cs^{133} was measured. The Ba^{133} source decays by electron capture mainly to the 436-keV level which decays to the 81-keV level either directly or via the 160-keV level. The window of the plastic scintillator was set on the upper portion of the distribution of Compton electrons produced by the 355- and 274-keV gamma rays. In order to better demonstrate the time resolution at low energy, the window of the NaI(Tl) detector was set on the x ray (31.6 keV) rather than the 81-keV γ ray. The time distribution of the x rays (Fig. 7) includes x rays associated with electron capture (which can be considered prompt) and x rays from internal conversions of transitions from the 160-keV and 81-keV levels. The prompt time distribution was obtained by substituting a Cs^{137} source for the Ba^{133} without other change. The tail due to the lifetime of the first excited state at 81 keV is well separated from the prompt time curve and with rather poor statistics shows $T_{1/2} \approx 6.5$ nsec. Previous measurements gave $T_{1/2} = 6.0-6.25$ nsec.

TABLE I. Comparison of measured time resolutions. The theoretical half-lives were calculated for $\tau = 250$ nsec, $Q = 1$, with $P = 2.5$ or 9.0 p.e./keV.

E (keV)	Measured values						Calculated $T_{1/2}$	
	Naton 136		NaI (77°K)		NaI(Tl)		For	For
	FWHM (nsec)	$T_{1/2}$ (nsec)	FWHM (nsec)	$T_{1/2}$ (nsec)	FWHM (nsec)	$T_{1/2}$ (nsec)	P = 2.5 (nsec)	P = 9.0 (nsec)
511	0.36	0.042 ^a	0.8	0.105 ^b	0.52	0.10	0.14	0.04
130	0.4	0.07 ^a	1.2	0.25 ^c	0.85	0.17	0.53	0.15
31.6					1.6	0.63	2.2	0.61

^aReference 4.

^bReference 5.

^cReference 6.

Table I shows the full width at half maximum (FWHM) and the effective half-life $T_{1/2}$ obtained with NaI(Tl) for energies of 511, 130, and 31.6 keV. For comparison, the table also includes the resolutions obtained at other laboratories with NaI at 77°K and with Naton 136. The values for Naton 136 were reported by Schwarzschild⁴ who used $\frac{1}{2} \times \frac{1}{2}$ -in. scintillators mounted on 56 AVP photomultiplier tubes. The value for NaI at 77°K, reported by Braunsfurth and Körner,⁵ was for excitation by 511-keV gamma rays. The value for NaI at 130 keV was estimated from a measurement made at 200 keV by W. M. Currie *et al.*⁶

Implications

From the measured value of $T_{1/2}$, one can obtain an upper limit for τ/R . If one assumes that the scintillator decays exponentially with a mean life τ , the lowest possible value of $T_{1/2}$ is $(\tau/R)\ln 2$ and is obtained when $Q = 1$. Hence, $\tau/R = \tau/P \cdot E = T_{1/2}/\ln 2$, where P is the

⁴A. Schwarzschild, Nucl. Instr. Methods 21, 1 (1963).

⁵J. Braunsfurth and H. J. Körner, Nucl. Instr. Methods 34, 202 (1965).

⁶W. M. Currie, R. E. Azuma, and G. M. Lewis, Nucl. Instr. Methods 13, 215 (1961).

over-all conversion efficiency (electrons/keV) and E is the primary energy (keV) absorbed in the scintillator. The measured values of $T_{1/2}$ in Table I, particularly for energies of 31.6 and 130 keV, imply that τ/P is smaller than commonly believed. This could be due either to a larger value of P or to a smaller value of τ (i. e., to a fast component in the scintillation).

Assuming the generally quoted mean life $\tau = 250$ nsec, one finds

$$P = \frac{250}{E \cdot T_{1/2} / \ln 2}.$$

For $E = 31.6$ keV, $T_{1/2} = 0.63$ nsec, this gives

$$P = \frac{(250)(0.693)}{(31.6)(0.63)} = 8.7 \text{ photoelectrons/keV.}$$

For $E = 130$ keV, $T_{1/2} = 0.17$ nsec, the value is

$$P = \frac{(250)(0.693)}{(130)(0.17)} = 7.85 \text{ p. e. /keV.}$$

This value of P is not consistent with those given in the literature. In his book, Birks⁷ implies a value $P \approx 2.28$ p. e. /keV. Braunsfurth and Körner⁵ list $P = 1.63$ p. e. /keV. Currie et al.,⁶ who based their value on time-resolution measurements, reported $P = 2.5$ p. e. /keV and in a later measurement⁸ found 3.7 p. e. /keV.

The possibility that there might be an unrecognized fast component in the decay of the scintillation is worth considering. Eby and Jentschke⁹ observed a fast component in NaI(Tl) excited by alpha

⁷ J. B. Birks, Theory and Practise of Scintillation Counting (Macmillan Co., New York, 1964), pp. 473 and 243.

⁸ W. M. Currie (private communication, 11 November 1965).

⁹ F. S. Eby and W. K. Jentschke, Phys. Rev. **96**, 911 (1954).

particles. Van Sciver,^{2b} who studied the ultraviolet excitation of NaI(Tl) at 77°K, measured a component with $\tau < 7$ nsec and a wavelength of 3250 Å. When this measurement was repeated at Argonne with better time resolution, the value obtained was $\tau = 6.2 \pm 1$ nsec. However, it was not possible to measure this fast component when the temperature was raised to 300°K because of low yields of the emitted light.

In order to measure the shape of the scintillation pulse from gamma-ray excitation of NaI at 300°K, the probability technique of Bollinger and Thomas¹⁰ was used. In this method, the distribution in intensity of scintillation light is recorded directly by measuring the distribution of time interval between the excitation of the scintillator and the emission of individual photoelectrons at the cathode of the photomultiplier that views the scintillation. One photomultiplier is closely coupled to the scintillator that delivers a start signal to the time-to-pulse-height converter at the beginning of the light pulse. The stop pulse comes from the other photomultiplier, which is so weakly coupled to the scintillator that on the average only one photoelectron is produced for about 50 scintillations. To avoid Čerenkov light, the system employed a Co⁵⁷ source whose 123-keV gamma ray is below the Čerenkov threshold in NaI. Pulses from the time-to-pulse-height converter were analyzed and stored only if they were associated with full energy conversion of the gamma-ray quantum in the scintillator.

Figure 8 shows the time distribution representing the shape of the scintillation pulse over the initial 130 nsec. The initial rise shows

Fig. 8. Time variation of the intensity of the light emitted from a NaI(Tl) crystal.

¹⁰ L. M. Bollinger and G. E. Thomas, Rev. Sci. Instr. 32, 1044 (1961).

no fast component but only the rise time of the system, which is not easily evaluated. The measurement was repeated with light from the long-wavelength portion of the emission spectrum (above 4000 Å) and again with the short-wavelength portion (below 3500 Å) with identical results. Furthermore, delayed-coincidence measurements with filters demonstrated no appreciable difference in the time resolutions obtained with the short- and long-wavelength components. In order to see if the decay was affected by the thallium concentration, crystals with approximately three times the normal concentration were obtained from the Harshaw Chemical Corporation. The decay of the pulses in these crystals looked about the same, and delayed-coincidence measurements gave somewhat worse time and energy resolutions.

This demonstration that no appreciable fast component is present necessitated a re-examination of the possibility that P might be much higher than commonly believed. Another way of estimating P is by observing the pulse-height resolution obtained with a pulsed light source. It is well known that the photon emission of NaI(Tl) does not follow a normal statistical distribution; the pulse-height resolution is much worse than should be expected from the average number of photoelectrons produced.¹¹ For this measurement, the photocathode was illuminated by a pulsed light source with $\tau \approx \frac{1}{4}$ μsec, and the intensity was adjusted to give a pulse height equal to the average in the photopeak produced by a 662-keV gamma ray in NaI(Tl). Then if η , the full width at half maximum of the distribution, is assumed to be caused entirely by the photoelectron statistics, the average number of photoelectrons per scintillation can be shown¹² to be

¹¹Reference 7, pp. 152-158.

¹²Ernst Breitenberger, in Progress in Nuclear Physics, edited by O. R. Frisch (Pergamon Press, London, 1955), Vol. 4, p. 67.

$$R = \frac{5.545}{\eta} \left[1 + \frac{1.2 G}{G_1(G-1)} \right],$$

where G_1 is the average multiplication of the first dynode and G is the average value for the other dynodes.

For the 8575 tube, RCA¹³ measures the average value of η to be 3.5%. Then for the typical multiplications $G_1 = 5$ and $G = 3$, it follows that

$$R = \frac{5.545}{(0.035)^2} \left[1 + \frac{(1.2)(3)}{5(3-1)} \right] = 6155 \text{ p.e./scint.};$$

and hence for the 662-keV gamma ray,

$$P = \frac{6155}{662} = 9.3 \text{ p.e./keV.}$$

In 1962 S. I. Baker,¹⁴ who used this same method, measured $P = 6.4$ p.e./keV for an average DuMont 6363 photomultiplier and $P = 4.8$ p.e./keV for an average RCA 6810A. Also in 1962, Bollinger, Thomas, and Ginther¹⁵ reported $P = 10$ p.e./keV for an exceptionally good DuMont 6363.

Another method of obtaining P is from the efficiency of the scintillator and the quantum efficiency of the photomultiplier. For example, Van Sciver and Bogart¹⁶ measured the absolute efficiency of NaI(Tl) to be 13%; and the average efficiency of the RCA bi-alkali photocathode is 21%. Hence $P = 9.1$ p.e./keV.

¹³ Harold Krah, RCA, Lancaster, Pa. (private communication).

¹⁴ S. I. Baker (private communication).

¹⁵ L. M. Bollinger, G. E. Thomas, and R. J. Ginther, Nucl. Instr. Methods 17, 97 (1962).

¹⁶ Reference 7, p. 473.

Since there is no evidence for a fast component with gamma-ray excitation, the low value of τ/P implied by the time resolution requires a large value of P . This large value of P is consistent with values of P obtained from two independent measurements of P .

Summary

Remarkably good time resolution can be obtained with NaI(Tl), especially at photon energies below 100 keV. This is primarily a consequence of the improved efficiency and lower dark current of recent photomultipliers and secondarily of improvements in electronics. The observed resolution implies that $P \geq 8.7$ p. e. /keV.

Acknowledgments

I am indebted to William Kaiser of the Argonne Electronics Division for packaging the NaI(Tl) crystals and to William Managan of Harshaw Chemical Corporation for supplying scintillators of higher Tl concentration. I am also grateful to Irvin S. Sherman of the Argonne Electronics Division for calling my attention to the Argonne pulsed-light measurements of P .

I-19-13. NUCLEAR RESONANCE ABSORPTION OF GAMMA RAYS

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(51320-01)

MÖSSBAUER STUDY OF Kr^{83} IN THE COMPOUND KrF_2 Introduction

Since the discovery of noble-gas compounds some three years ago,¹ many efforts have been made to clarify the various chemical structures. A purpose of the present investigation was to use Mössbauer spectroscopy to help confirm that KrF_2 is indeed closely analogous to XeF_2 . Another purpose was to find the quadrupole moment of the first excited state of Kr^{83} . Before the discovery of the rare-gas compounds, no environment was known with an electrical asymmetry adequate for this purpose. The successful Mössbauer measurements² on XeF_2 and XeF_4 clearly suggested that KrF_2 would be a suitable compound.

Description of Experiment

Basically the experiment was a straightforward Mössbauer transmission measurement. The unusual features of the experiment derive mainly from the source and absorber which we discuss in turn. Figure 9 shows a simplified decay scheme for Kr^{83} . A significant feature to notice is the low energy (9.3 keV) of the pertinent γ ray; many

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¹ The work in this field during the first year is well summarized in the book, Noble Gas Compounds, edited by H. Hyman (University of Chicago Press, 1963). A recent comprehensive review article on xenon chemistry is J. G. Malm, H. Selig, J. Jortner, and S. A. Rice, Chem. Rev. 69, 199 (1965).

² G. J. Perlow and M. R. Perlow, Rev. Mod. Phys. 36, 353 (1964); G. J. Perlow, Phys. Rev. 135, B1102 (1964).

Fig. 9. Simplified decay scheme of Kr^{83} .

experimental difficulties arise from the necessity of keeping adequate transmission for this soft radiation. We have employed Rb^{83} as a radioactive parent; this 83-day isotope then generates the Kr^{83*} continuously.

Rb^{83} was formed by the $\text{Br}^{81}(\alpha, 2n)\text{Rb}^{83}$ reaction induced by bombarding CaBr_2 with 30-MeV alpha particles in the Argonne cyclotron. After dissolving the sample in water, most of the calcium was eliminated by precipitation with CO_2 , the volume was reduced by evaporation, and the remainder was put onto two absorbent papers in the source cup. After drying, this cup was sealed with a 5-mg/cm^2 Mylar window. This will be referred to below as the Rb source. A serious defect of this source (discussed further below) is that its line width is at least seven times that of the "natural" source. The reasons for this have not yet been clarified. Separate experiments to investigate other methods of making Kr sources by use of Rb^{83} did not produce sharper lines.

Krypton emits some ten 12.6-keV x rays for each of the 9.3-keV gamma rays in which we are interested.³ A major problem is

³I. Dostrovsky, S. Katcoff, and R. W. Stoermer, Phys. Rev. **136**, B44 (1965).

to prevent windows, coolants, and other absorbing materials in the beam path from further decreasing this already poor ratio of γ rays to x rays. The absorber cell had to satisfy several difficult requirements. Our partially satisfactory final design employed a nickel body, with a nickel tube for filling, with 10-mil knife edges upon which transparent 30-mil Teflon disks were pressed by outer aluminum plates. Before attachment, the centers of the disks were machined down to 8 mils to form windows. Several times the windows imploded; frequently there were small vacuum leaks at low temperatures. Storing the cells in dry ice resulted in a substantial amount of CO_2 in our older cells; this apparently had no harmful effects on the KrF_2 . The forming procedure consisted in dropping liquid nitrogen onto a horizontal Teflon window (slightly concave since the internal pressure is below 1 atm) of a cold cell while warming the nickel wall to drive off KrF_2 frozen there.

The preparation of the KrF_2 followed an electrical-discharge procedure described in Ref. 1. The product is purified by pumping while at dry ice temperatures. The method of transferring it to the absorber cell leaves the final amount of KrF_2 in the absorber somewhat uncertain; we attempted to add about 10 mg/cm^2 of KrF_2 although γ -ray transmission measurements later suggested a result more like half that for our most-used cell.

The γ rays were detected with commercially available Ar-CH_4 and Kr-CH_4 counters. The counters were of appropriate thickness to detect most of the γ rays while transmitting most of the x rays. It is essential to get the smallest possible resolution width (about 11% at this energy) or the tail of the x rays will wipe out the small γ peak. Despite such precautions, the number of x rays in our channel was about three times the number of γ rays during runs with the absorber in place.

The data were analyzed by use of a least-mean-square fitting program originally created by William Davidon. As adapted to Mössbauer spectroscopy, it allows for the fitting of up to eight Lorentzian

lines to the experimental data.⁴ Each line is described by three parameters—one each for amplitude, width, and position; the base line or off-resonance rate is another variable parameter. The computer calculates the spectrum for a set of trial parameters, evaluates the variance F between this spectrum and the experimental data, computes the derivatives of F with respect to each parameter, and then adjusts the parameters to minimize F . This process is continued until the rate of decrease in F is negligible, thus finding χ^2 . For our 400-channel spectra with some 15 free parameters, the distribution in χ^2 will have a maximum at 385 and a width of about 40. Thus, fits characterized by $365 < \chi^2 < 405$ are to be regarded as satisfactory.

The final choices of the parameters are printed out along with an error matrix which allows the evaluation of the standard "statistical" error in a derived quantity for any given run. An important feature of the program is its ability to impose linear relationships among the parameters. This is used here to require all line widths to be equal (this is approximately correct physically) and sometimes to force the line positions to be consistent with a pure quadrupole interaction Hamiltonian, as discussed below.

The line positions are given by

$$\nu_{m^*,m} = \frac{e^2 q Q}{4} \frac{c}{E_Y} [R C(m^*, I^*) - C(m, I)] + s, \quad (1)$$

where $C(m, I) = [3 m^2 - I(I+1)] / [I(2I-1)]$, $R = Q(\frac{7}{2})/Q(\frac{5}{2})$, $I^* = \frac{7}{2}$, $I = \frac{9}{2}$; m^* and m are the components of nuclear spin on the z axis, and s is the isomer shift. It is convenient to let $A = (e^2 q Q/4) \times (c/E_Y)$, where q is the value of $\partial^2 V / \partial z^2$ at the nucleus. For any given A , R , and s , eleven line positions are found by use of Eq. (1). (The intensity of each

⁴W. C. Davidon, Variable-Metric Method for Minimization, Argonne National Laboratory Report ANL-5990 (Rev.). The version of the program used here is called Phy 103.

line is the square of the appropriate Clebsch-Gordan coefficient.)

Figure 10, which shows possible spectra for various values of R , was made to assist in the search for reasonable values of these three parameters.

To get the best values for A , R , and s from an experimental spectrum, the information from Eq. (1) or Fig. 10 was fed to the computer via the constraint equations. Under these constraints, each line cannot be separately moved to minimize χ^2 but instead the lines are all locked together and in effect A , R , and s become the adjustable parameters for fitting the line positions. It must be noted that between the initial guesses for the parameters and the constraint equations, the computer has much of the information needed to satisfy the experimenter's prejudices about the data. Especially for data of poor quality, as we have here, it is best to regard the computer as merely refining and quantifying one's guesses and to continue to take a wary attitude toward any single "fit."

Fig. 10. Possible pure quadrupole spectra showing the dependence on the ratio of the unknown to known quadrupole moment.

Results

From the known lifetime⁵ of 147 nsec for the 9.3-keV level, the minimum experimental width 2Γ (for a "natural" source and

⁵S. L. Ruby, Y. Hazoni, and M. Pasternak, Phys. Rev. 129, 826 (1963).

Fig. 11. Analogue form of the raw data from each of two 4-day runs with a KrF_2 absorber and a Rb source.

absorber, both thin) is calculated to be 0.20 mm/sec. With krypton ice as both source and absorber, the experimental full width at half maximum (FWHM) is 0.33 ± 0.03 mm/sec; the extra width is probably due to blackness effects in source and absorber. For a krypton ice source with clathrate absorber, the FWHM rises to 0.6 mm/sec; for clathrate source with clathrate absorber, it becomes 0.7 mm/sec. Finally, with the Rb source with clathrate absorber, the FWHM is

1.1 ± 0.1 mm/sec. In all these measurements, the line position was at zero relative velocity (0.0 ± 0.03 mm/sec). The extra width for the Rb source is quite detrimental. Although the area of the dip is maintained, the broadened source decreases the amplitude of the effect and in our case pushes it almost down into the statistical fluctuations. For this source, this reduction is about a factor of five or six.

Figure 11 shows tracings of the analogue output from two of the best runs. Each of these needed about four days of running to accumulate $\sim 250\,000$ counts/channel. This gives fluctuations of $\pm 0.2\%$ merely due to statistics. The line widths were expected to be about 1.2 mm/sec; the velocity scale is here 0.2 mm/sec/channel so that a peak should be spread over some six channels. A 1% absorption dip should be easily seen in such data; 0.10% peaks would probably be missed. It is clear that we have several dips of about 0.5%.

The small amplitude of these absorption dips is readily understood, even though the resonant fraction f for the source is greater than 50%. However, this must be divided by five for the extra source

width, and another factor of four to take account of the dilution of the rate by the x-ray tail. Thus, even a black absorber would give rise to a maximum effect of only 2—3%. Our absorber was designed to be nearly black for the more intense absorption lines if the KrF_2 uniformly covered the window of the cell. Despite careful efforts during "forming," this condition was not achieved since the material did not deposit as a uniform 1-mil-thick film, but rather grew as crystals. The remaining factor between the experimental amplitudes and 2% is easily explained by the gaps between the crystals.

Despite the poor quality of the data, careful comparisons of Figs. 10 and 11 soon lead to the estimate $R \approx 1.6$. Note, for example, the broad dip at about -22 mm/sec with the single dip at about -28 mm/sec as well as the strong absorption near zero velocity. However, the data were first analyzed directly just for simple line positions. The second and third columns of Table II show the results of the curve-fitting program when these two independent runs were analyzed for the positions of the seven most intense lines. The reproducibility of the computed line positions was most encouraging.

Next the data from both runs were combined, and analyzed with A, R, and s constraints, in addition to those for equal line widths. Column 4 shows the results obtained from this analysis. It should be noted that χ^2 is not increased by the imposition of these constraints and that all of the seven independent positions found in columns 2 and 3 are reproduced. The values of A, R, and s shown in the table were calculated from the line positions of column 4.

It is necessary to be sure that this is not an "accidental" fit and that some other quite different triplet of A, R, and s might not do better. To verify our fit, the relative line intensities were next examined. Absorber thickness is discussed in terms of the reduced thickness parameter $t = n\sigma f$, where n is the number of resonant nuclei

TABLE II. Curve-fitting results for line positions and intensities.

Line no.	Line positions (mm/sec)			Intensities (arbitrary units)		
	Run Kr21 $\chi^2 = 395$ (± 0.15)	Run Kr22 $\chi^2 = 374$ (± 0.15)	Runs ^a Kr21+Kr22 $\chi^2 = 390$ (± 0.09)	Theory (t = 0)	Theory (t = 12)	Runs Kr21+Kr22
1	33.12	33.33	33.26	36	27.2	27.2 $\pm$ 3.0
11	-22.11	-22.74	-22.74	30	25.8	25.6 $\pm$ 3.0
4	-0.12	-0.19	-0.16	28	25.2	29.0 $\pm$ 3.0
7	-20.35	-20.96	-20.64	21	22.4	23.3 $\pm$ 2.5
8	-10.00	-9.90	-9.79	18	20.9	21.1 $\pm$ 2.5
10	-27.75	-28.14	-27.95	15	18.9	16.4 $\pm$ 2.5
5	16.31	16.10	16.11	14	18.0	15.4 $\pm$ 2.0
2			55.00	8		
9			-4.37	6	9.8	10.0 $\pm$ 2.0
6			26.93	3		
3			71.15	1		

^aThe a, R, and s constraints were imposed in finding the line positions. From the line positions, we compute that $A = 5.422 \pm 0.045$ mm/sec so that $e^2qQ = 960 \pm 9$ MHz, $R = 1.694 \pm 0.007$, and $s = 1.50 \pm 0.05$ mm/sec.

per cm^2 in the beam, σ is the maximum resonant absorption cross section, and f' expresses the Debye-Waller factor for the absorber. It should be recalled that since the hyperfine splitting divides the absorption among eleven lines, the thickness for a single line is the above-defined parameter divided by a factor equal to the ratio of the intensity of the single line to the sum of all eleven intensities. The first of the intensity columns in the table shows the relative intensities to be expected for a thin ($t = 0$) absorber; the next column shows the expected relative intensities for an absorber whose thickness ($t = 12$) is about that of our

absorber. The last column gives the experimental line intensities as determined by the curve-fitting program after normalization to the same sum as for the theoretical numbers. The striking agreement between the theoretical and experimental intensity ratios is our strongest evidence that the lines are correctly assigned.

It will be noted that lines 2, 3, 6, and 9 are missing in the first two columns. Lines 2 and 5 fall outside the velocity range studied; lines 6 and 9 were simply too weak to be interpreted by simple visual examination.

Having found A, R, and s by use of the stronger lines, the calculated positions and intensities of these four weak lines can now be considered as "predictions." Our next measurements were undertaken in an attempt to find the

position and intensity of line 9 to check this prediction. A second reason was to examine line 4 carefully to verify that ordinary krypton from dissociated KrF_2 did not make an important contribution to the line at zero velocity. Both problems could be handled by merely decreasing the maximum drive velocity so that in the same four days per run, we could get the same number of counts in the smaller velocity range.

Figure 12 shows the raw data from the sum of two such runs along with two fitted spectra. The first fitting allowed only one line;

Fig. 12. Computer output for the sum of two 4-day runs with a KrF_2 absorber and a Rb source. The data are analyzed twice—first allowing only one absorption peak, then allowing two.

TABLE III. Curve-fitting results for line positions and intensities.

Line no.	Line positions (mm/sec)			
	Runs Kr21 + Kr22	Run Kr24	Run Kr26	Run Kr33
4	-0.16 ± 0.09	-0.17 ± 0.04	-0.17 ± 0.05	-0.15 ± 0.06
9	-4.37 ± 0.09	-4.28 ± 0.13	-4.41 ± 0.18	-4.13 ± 0.24

Intensity ratio (line 4 to line 9)				
Theory	Runs Kr21 + Kr22	Run Kr24	Run Kr26	Run Kr33
$\left\{ \begin{array}{l} 4.7 \text{ if} \\ t = 0 \end{array} \right\}$	2.9 ± 0.9	3.2 ± 1.0	4.3 ± 1.8	3.6 ± 1.5
$\left\{ \begin{array}{l} 2.6 \text{ if} \\ t = 12 \end{array} \right\}$				

the second fit allowed two. It will be noticed that this extra line leads to a significant improvement in χ^2 . However, a better test of its reality is to consider its amplitude and position. Table III, which gives this information for the three independent runs so performed, shows that indeed there is a weak line very near the location predicted from the first, wider-ranging measurements; the last columns show that its intensity is consistent with that of line 4.

As for the larger peak, it is established that its line position is not at zero but does indeed lie at -0.15 ± 0.02 mm/sec as predicted by the first measurements. Other fits have indicated that if there is any extra absorption at zero velocity, it is less than 20% of the amplitude of peak 4. Combining these data and making estimates for possible sources

of error (including nonlinearities of the drive), we get $e^2 qQ = +130.1 \pm 4.0$ mm/sec = 960 ± 30 MHz, $R = 1.70 \pm 0.02$, and $s = 1.50 \pm 0.10$ mm/sec.

Conclusions

The value $R = 1.70 \pm 0.02$ is a new result. Since the ground-state moment is $+0.2701$ b,⁶ it follows that $Q(\frac{7}{2}) = +0.459 \pm 0.006$ b. There is only one other measurement of the quadrupole moment of a nucleus with the same spin and nearly the same mass; this is for $\text{Se}^{79}(\frac{7}{2}^+)$ which differs from $\text{Kr}^{83}(\frac{7}{2}^+)$ by one a particle. The quadrupole moment for the Se^{79} is given as $+0.92$. It is surprising that these moments should be so different from each other.

The following interpretation of the field gradients and charge densities at the krypton nucleus will seem "thin" in comparison with the comparable work on some other Mössbauer nuclides. Mainly this is the unfortunate consequence of KrF_2 being the only compound⁶ of this element so that information coming from a related series of compounds, or cross checks using results computed from several different electronic states, will not be available. In particular, any conclusions to be drawn on the change in the nuclear charge radius for Kr^{83} must be based on this single isomeric shift.

The quadrupole interaction energy $e^2 qQ = (960 \pm 30)$ MHz found here is produced by an electric field gradient at the position of the nucleus. This is interpreted as the result of some of the 4p electrons of the krypton outer shell being shared with the fluorine atoms. An attractive rationalization of the bonding in this compound is the following. (a) Let one of the krypton 4p electrons become attached to a strongly electronegative fluorine. (b) The bromine-like Kr^+ ion and the other

⁶H. Selig and R. D. Peacock [J. Am. Chem. Soc. 86, 3895 (1964)] recently produced a closely related compound $\text{KrF}_2 \cdot \text{SbF}_5$, but it is too poorly understood to be a useful substance for experimental comparisons.

fluorine can then form a covalent bond similar to that in BrF . (c) To keep the fluorines indistinguishable, this structure could resonate between the two fluorines. If the electronegativity of Kr^+ and F^- are similar, this would result in the removal of one $4p_z$ electron from the krypton atom.

The measured interaction energy can be used to find the number U_p of unbalanced p electrons as has previously been done for Xe.⁷ The electronic wave distribution is taken as $\psi_{410} = (3/4\pi)^{1/2} R(r) \cos\theta$ for this normalized p_z electron ($U_p = 1$), and by direct calculation the interaction energy is found to be

$$e^2 qQ = e^2 Q \left\langle \psi_{410} \left| \frac{3 \cos^2 \theta - 1}{r^3} \right| \psi_{410} \right\rangle = +\frac{4}{5} e^2 Q \langle r^{-3} \rangle. \quad (2)$$

Instead of attempting to evaluate $\langle r^{-3} \rangle$, this result will be compared with the atomic-beam result of Faust and Chiu⁸ who report an interaction constant $b = -452.2$ MHz for the similar $4p^5 5s$ configuration of the 3P_2 state of krypton. However, in atomic-beam work it is convenient to work with a $(1/\sqrt{2})(p_x + ip_y)$ wave function rather than with p_z , and as a result their value of b is calculated⁹ to be $-(2/5)e^2 Q \langle r^{-3} \rangle$. Assuming that $\langle r^{-3} \rangle$ is the same for the state observed in the work with atomic beams as for that of KrF_2 , we find $U_p(\text{KrF}_2) = 960/(2 \times 452.2) = 1.06$. This result is supported by NMR studies¹⁰ of the chemical shift in fluorine in KrF_2 . These measurements are interpreted to show 0.47 added electrons per fluorine and thus to imply a loss of 0.94 electrons/krypton.

⁷G. J. Perlow, J. Chem. Phys. 41, 1157 (1964).

⁸W. L. Faust and L. Y. Chow Chiu, Phys. Rev. 129, 1214 (1963).

⁹C. H. Townes, in Handbuch der Physik (Springer-Verlag, Berlin, 1959), Vol. XXXVIII, Table 9, p. 412.

¹⁰F. Schreiner, J. G. Malm, and J. C. Hindman, J. Am. Chem. Soc. 87, 25 (1965).

This result for U_p can be compared with those for the analogous linear molecules XeF_2 and ICl_2^- whose hyperfine interactions have been studied with both Mössbauer^{7,11} and atomic-beam^{12,13} methods. For XeF_2 , $U_p = 1.53$ and for ICl_2^- , $U_p = 1.33$. The similarity between the new result for U_p in KrF_2 and these older ones reinforces our belief that KrF_2 is indeed an analogous compound.

The isomer shift can be written¹⁴

$$s = \frac{c}{E_\gamma} F(Z) \frac{\delta r}{r} [\psi_{\text{abs}}(0) - \psi_{\text{source}}(0)], \quad (3)$$

where $F(36) = 0.377 \times 10^{-4} \text{ a}^3$, $E_\gamma = 9.3 \text{ keV}$, $\delta r = r(\frac{7}{2}^+) - r(\frac{9}{2}^+)$, r is the mean charge radius of the nucleus, and $\psi^2(0)$ is the total electronic charge density at the nucleus. If the difference in charge density is known, then the change in nuclear radius can be found. It is anticipated that the removal of a single 4p electron will decrease the shielding of the 4s electrons and they will be pulled closer to the nucleus so that $\psi^2(0)$ will be increased.

Dr. Paul Bagus of this laboratory, using Hartree-Fock self-consistent methods, has computed wave functions for Kr and Kr^+ . A test of these wave functions is that the value of $\langle r^{-3} \rangle$ computed from them agrees (within 10%) with the number calculated from the atomic-beam measurement. His result for the charge-density difference resulting from the removal of 1.06 4p_z electrons is $3.22/\text{a}^3$. Inserting our

¹¹ G. J. Perlow and S. L. Ruby, *Phys. Letters* 13, 198 (1964).

¹² M. N. McDermott and W. Lichten, *Phys. Rev.* 119, 134 (1960).

¹³ V. Jaccarino, J. G. King, R. A. Satten, and H. H. Stroke, *Phys. Rev.* 94, 1798 (1954).

¹⁴ A. J. F. Boyle and H. E. Hall, in *Reports on Progress in Physics* (Physical Society, London, 1962), Vol. 25, p. 491.

experimental value $s = 1.50 \pm 0.10$ mm/sec yields $\delta r/r = +3.9 \times 10^{-4}$. Our emotions concerning the accuracy of this result can be summarized by concluding that $\delta r/r = (+4 \pm 2) \times 10^{-4}$. It is difficult to be quantitative here, but this error estimate is double the amount indicated by previous experience with the computational program.

Uher and Sorensen¹⁵ have recently made the first comprehensive calculation of the difference δr between the nuclear radius in the ground state and that in the first excited state. Their procedure, which they described as "a pairing-plus-quadrupole model," leads to the prediction $\delta r/r = +10.4 \times 10^{-4}$, which is some two times our result and has the correct sign.

¹⁵R. A. Uher and R. A. Sorensen, Bull. Am. Phys. Soc. 10, 1084 (1965) and private communication.

I-22-20. SCATTERING OF CHARGED PARTICLES (51312-01)

R. H. Siemssen, T. H. Braid, D. Dehnhard, and B. Zeidman

THE SCATTERING OF 33-MEV He^3 ON THE EVEN-A
NICKEL ISOTOPES¹

In view of the increasing importance of He^3 -induced reactions as a spectroscopic tool, systematic studies of He^3 scattering are important. For this investigation we have chosen as targets the four even-A isotopes of nickel, so as to study in detail the variation of the scattering over a range of 6 in neutron number ($N = 30, 32, 34$, and 36) while Z is constant ($Z = 28$). Over such a small range the strength and shape of the nuclear potential as given by the optical model should vary only slowly, but should nevertheless be capable of describing He^3 scattering in fair detail. We have found that even if the potential parameters are constant for all the isotopes, the increase in the radius of the nucleus as pairs of neutrons are added results in very distinct differences in the predicted angular distributions for the different isotopes. The character and magnitude of these predicted differences explain nearly all of the differences observed in the scattering. The optical model is therefore very successful in describing He^3 scattering on nickel at our energy. With small changes in the potential parameters the description can, of course, be improved.

We also expected that the study of the scattering from different isotopes might yield information on the nuclear symmetry term in the optical potential. This term was first predicted by Lane but so far has only been established for nucleon scattering. Our He^3 scattering data show some evidence for the predicted ($N - Z$) dependence. The effects of this term on the angular distributions are small, however, and therefore the ($N - Z$) term cannot be conclusively derived from our data.

¹R. H. Siemssen, T. H. Braid, D. Dehnhard, and B. Zeidman, Phys. Letters 18, 155 (1965).

Fig. 13. Superposition of the experimentally obtained angular distributions of He^3 elastically scattered from Ni^{58} and Ni^{64} . This illustrates the considerable differences between the isotopes.

In the experiment, 33-MeV He^3 particles from the Argonne 60-in. cyclotron were scattered from isotopically enriched targets of Ni^{58} , Ni^{60} , Ni^{62} , and Ni^{64} in the 18-in. scattering chamber. A solid-state counter telescope was used for particle detection and identification.

Differential cross sections have been measured in the angular range from 25° to 90° in 2.5° steps at forward angles and 3° steps at larger angles. Figure 13, in which these angular distributions for Ni^{58} and Ni^{64} have been superimposed, shows marked differences in both the prominence

and the relative positions of the maxima and minima. In Fig. 14, the results for all four isotopes are compared with the optical-model calculations described below.

Extensive optical-model calculations have been performed with the search code JIB3 written by F. Perey. The calculations were made with potentials of the Woods-Saxon type with the radius of the imaginary well approximately 1.5 times as large as that of the real potential well. Closely the same parameters were obtained for Ni^{60} , Ni^{62} , and Ni^{64} ; but the imaginary potential for Ni^{58} differs significantly from that of the other three isotopes. The differences in the potential of Ni^{58} with respect to the other isotopes suggest the presence of strong coupling effects which are known to be important at lower bombarding energies. The parameters are listed in Tables IV and V.

Fig. 14. Differential cross sections, expressed as σ/σ_R , for the elastic scattering of 33-MeV He^3 particles on the even-A Ni isotopes. The solid curves are the results of optical-model calculations with a common potential for all four isotopes, in which $V = 138$ MeV. The dotted curves were calculated with an optimum potential for each isotope. Note that the common potential gives almost as good an agreement with the data as do the potentials chosen to give the best fits for each isotope.

From these optimum parameters we have chosen "average" values for the four nuclei. In particular, an average $V = 138$ MeV was chosen. This value of V , with the other "averaged" parameters, provided a common potential from which predicted angular distributions for all four isotopes were calculated. It is to be emphasized that the only difference between the isotopes in this calculation was therefore the variation of the radius in proportion to $A^{1/3}$.

From Fig. 14 it can be seen that the common set of parameters is remarkably successful in reproducing the general shape

TABLE IV. He^3 optical-model parameters for the even-A Ni isotopes from a search on all parameters except r_0 . Potentials are of the independent Woods-Saxon type with $r_c = 1.4$.

	V (MeV)	r_0 (fm)	a (fm)	W (MeV)	r_0' (fm)	a (fm)	χ^2/N
Ni ⁵⁸	137.0	1.082	0.814	14.0	1.715	0.757	0.61
Ni ⁶⁰	136.9	1.082	0.796	16.4	1.654	0.797	0.84
Ni ⁶²	138.9	1.082	0.816	17.2	1.635	0.815	0.50
Ni ⁶⁴	140.6	1.082	0.797	17.0	1.632	0.817	0.88

TABLE V. Potentials obtained from search on V alone with average shape parameters and W; $r_c = 1.4$.

	V (MeV)	r_0 (fm)	a (fm)	W (MeV)	r_0' (fm)	a (fm)	χ^2/N
Ni ⁵⁸	137.4	1.082	0.805	16.1	1.66	0.795	1.33
Ni ⁶⁰	136.8	1.082	0.805	16.1	1.66	0.795	0.99
Ni ⁶²	138.4	1.082	0.805	16.1	1.66	0.795	0.98
Ni ⁶⁴	140.8	1.082	0.805	16.1	1.66	0.795	0.99

of the experimental angular distributions and the major differences between isotopes. At angles less than 30° the agreement (for all our calculations) is not very good, but otherwise the correspondence with the data is close except at large angles in Ni⁵⁸. This behavior illustrates the point, made earlier, that Ni⁵⁸ seems to differ significantly from the other three isotopes. The theoretical curves calculated with the best parameters for the individual isotopes actually fit the data better; but the difference is small except in the case of Ni⁵⁸ at large angles (Fig. 14).

Fig. 15. Differential cross sections for the inelastic scattering of 33-MeV He^3 particles from 2^+ and 3^- levels in the even-A Ni isotopes.

Except for Ni^{58} , both the magnitude and the sign of the observed variation in the real potential from one isotope to the other are consistent with the predicted $(N - Z)$ term in the nuclear optical potential. Therefore, although the angular distributions are little affected by the observed variation in V , it is felt that the effect is real. To establish the $(N - Z)$ dependence conclusively, however, a measurement at higher bombarding energy would be desirable.

The ability to reproduce the major differences in the angular distributions from one isotope to the other with one set of parameters and also the good fits over an angular range in which the differential cross sections vary by four orders of magnitude are a striking success of the optical model of He^3 scattering. A notably poorer fit, however, was obtained with parameters corresponding to a family with a real well depth of ~ 100 MeV. This result indicates that with the data taken at 33 MeV it is possible to discriminate between the different potentials. The real well depth of ~ 138 MeV is roughly equal to the sum of the individual potentials of the three nucleons constituting He^3 , much as the best deuteron potentials appear to be roughly the sum of the potentials of the proton and the neutron of the deuteron.

We have also observed the inelastic scattering from a number of levels. Figure 15 shows the angular distributions from the 2^+ and 3^- levels in each isotope. These distributions follow the Blair phase rule.

I-32-1. BLOCKING EFFECTS IN THE EMERGENCE OF CHARGED
PARTICLES FROM MONOCRYSTALS (51312-01)

D. S. Gemmell and R. E. Holland

When a beam of energetic positively-charged particles is passed through a monocrystal which has been oriented with a major symmetry axis in the beam direction, one observes many effects produced by "channeling" of the incident beam.¹⁻⁶ These effects are presumed to result from the influence of parallel layers of atoms which, through a series of small-angle Rutherford scatterings, confine a part of the beam to the open "channels" between low-index planes.

We have observed⁷ a related but distinct phenomenon which occurs when one observes charged particles that have been emitted from lattice sites. Such emission results from nuclear reactions or from large-angle Rutherford scattering. One would expect that "blocking" by the nearest neighbors of the emitting atom would lead to an absence of particles in directions corresponding to major crystallographic axes. A highly simplified treatment, which assumes a rigid lattice, indicates that the region of extinction has an angular width $\beta = [16 Z_1 Z_2 e^2 / \ell E]^{1/2}$, where $Z_1 e$ and $Z_2 e$ are the charge of the particle and lattice nucleus,

¹R. S. Nelson and M. W. Thompson, Phil. Mag. 8, 1677 (1963).

²G. Dearnaley, IEEE Trans. Nucl. Sci. 11, 249 (1964).

³E. Bogh, J. A. Davies, and K. O. Nielsen, Phys. Letters 12, 129 (1964).

⁴C. Erginsoy, H. E. Wegner, and W. M. Gibson, Phys. Rev. Letters 15, 357 (1965).

⁵M. W. Thompson, Phys. Rev. Letters 13, 756 (1965).

⁶J. P. Schiffer and R. E. Holland, Bull. Am. Phys. Soc. 10, 54 (1965).

⁷D. S. Gemmell and R. E. Holland, Phys. Rev. Letters 14, 945 (1965).

Fig. 16. Reproduction of a photographic plate exposed to protons scattered by a monocrystal of germanium. The $\langle 001 \rangle$ axis of the crystal was directed at the emulsion and made an angle of 19.5° with respect to the incident beam of 4-MeV protons. The emulsion is darkened by the particles so that a white area indicates that a reduced number of particles struck the emulsion there.

Fig. 17. A series of spatial distributions for protons scattered from a monocrystal of silicon and detected with a position-sensitive detector. The "position spectra" for the different energy ranges of the scattered particles are arranged in order from the lowest energy at the bottom to the highest energy at the top. The pulse height (channel number) plotted as abscissa is proportional to position. The ordinate is the number of counts as function of position. The energy spectra of the detected protons were divided into equal intervals and the number of protons detected in each energy interval was plotted as a function of position. (a) Spectra taken with 4-MeV protons incident at an angle of 15° relative to the $\langle 112 \rangle$ axis in the (111) plane. The detector was placed at 30° to the beam direction. The peak in the energy distribution occurs at 3.3 MeV. Each spectrum represents an energy interval of approximately 240 keV. (b) Spectra taken with 7-MeV protons incident along the $\langle 112 \rangle$ axis. The detector was placed at 15° to the beam direction. The peak in the energy distribution occurs at 6.5 MeV. Each spectrum represents an energy interval of approximately 120 keV.

respectively, ℓ is the distance between nearest neighbors, and E is the energy of the particle. For 4-MeV protons in a silicon lattice, Eq. (1) yields $\beta \approx 1^\circ$.

We have investigated the phenomena described above by observing the protons scattered at large angles by monocrystals of silicon and germanium. Figure 16 shows the result obtained when a photographic plate is exposed to protons scattered by a germanium monocrystal. The easily recognized lines representing blocking of scattered particles indicate that the blocking occurs in the direction of crystal planes rather than along axes.

These lines were studied with better angular resolution and as a function of the energy of the scattered particle by using a position-sensitive detector mounted 160 cm from the target. The sensitive region of the detector was defined by a collimator 20 mm long. Thus the total angle subtended by the detector was 0.7° . Figure 17 shows data on the spatial distribution of protons scattered by a monocrystal of silicon. For both 4.0-MeV and 7.0-MeV incident protons, the dip occurs where the (111) plane of the silicon target intersects the detector. The widths of the dips observed in these two cases are typical: 0.13° at 4.0 MeV and 0.10° at 7.0 MeV, much smaller than $\beta \approx 1^\circ$. Under certain conditions a peak [Fig. 17(a)] is observed in the number of higher energy scattered particles.

These experiments, considered in conjunction with those on channeling, show that care should be taken in measuring nuclear cross sections with a crystalline target. For instance, if the incident beam in such a measurement happened to lie in a channeling direction and the detector happened to be in a blocking direction, the measured cross section could easily be an order of magnitude too low.

It is possible that blocking measurements may be a useful tool in crystallographic studies. In this connection, it is interesting to

note that the technique applies to crystals observed in reflection. This could be of use when thin samples are unavailable.

One of the more attractive possibilities for an application in nuclear physics is the possible use of the effect to measure short nuclear lifetimes. Consider a short-lived nuclear state produced as the result of a nuclear reaction in a monocrystal. The excited product nucleus usually will recoil out of a lattice site at a velocity of the order of 10^9 cm/sec. If the state has a lifetime around 10^{-17} sec, then the nucleus will travel about $1 \text{ \AA}$ on the average before decaying. Then observation of charged decay products emitted parallel to a crystal plane would be expected to show a maximum caused by channeling effects. On the other hand, if the decay time were much shorter, one would expect to see blocking effects such as were observed with the (d,p) and elastic-scattering reactions.

II. MASS SPECTROMETRY

II-25-1. ELECTRON EMISSION FROM METAL MONOCRYSTALS UNDER HIGH-ENERGY ION IMPACT (51320-01)

Manfred Kaminsky

DEPENDENCE ON CRYSTALLINE ORIENTATION OF TARGET SURFACE

There has been a complete lack of data on secondary emission from atomically-clean metal surfaces and in particular from clean surfaces of metal monocrystals for the Rutherford collision region (the energy range in which the incident particle interacts with the lattice atoms through Coulomb repulsion between their nuclear charges). Moreover, for the systems studied in the present experiments, the energies of the incident ions were high enough to satisfy the condition $\eta = (2v/u)^2 \gg 1$, where v is the translational velocity of the incident ion and u is the velocity of the outermost orbital electron. This means that the Bohr-Bethe theory becomes more applicable than at lower energies and hence the inelastic collision processes can be treated with sufficient accuracy by means of Born's approximation. Furthermore, for this energy region several simplifying features emerge in certain processes involved in the production of secondary electrons and in their escape mechanism. For instance, the escaping electrons originate in a target region in which the incident ions still have nearly their original energy, since the mean free path λ_i of high-energy ions is considerably larger than the mean free path λ_e of the secondary electrons (e.g., for 500-keV D^+ ions incident on Cu, $\lambda_i = 8 \times 10^{-5}$ cm while $\lambda_e \approx 10^{-7} - 10^{-6}$ cm).

Fig. 18. Schematic diagram of the experimental arrangement.

Furthermore, the direction of the incident beam remains almost unchanged within the target region in which the observed secondary electrons are formed.

The present experiments provide the first adequate test of two theoretical models^{1,2} proposed for the Rutherford collision region; in particular it becomes possible to check if the yields are independent of the target material and of the crystalline orientation of the target surface, as predicted theoretically.¹

Apparatus and Procedures

A beam of H^+ , H_2^+ , D^+ , or He^+ ions from a 2-MeV Van de Graaff accelerator was steered electrostatically to a double-focusing 90° bending magnet (40-in. mean radius of curvature) and, after being analyzed, was focused by two pairs of magnetic alternating-gradient lenses and passed through four tantalum collimators before striking a target spot about 1.2 mm in diameter, as shown schematically in Fig. 18.

¹E. J. Sternglass, Phys. Rev. 108, 1 (1957).

²S. N. Ghosh and S. P. Khare, Phys. Rev. 125, 1254 (1962); *ibid.* 129, 1638 (1963).

A bellows-operated insulated beam shutter was placed in the beam line to facilitate measurement of beam current during the original beam alignment. The energy of the bombarding ions was varied between 0.18 and 1.0 MeV, and the ion-energy spread $\Delta E/E$ was usually of the order of 0.1% over the whole energy range. The current density of the analyzed beam was varied between 500 and 2000 $\mu\text{A}/\text{cm}^2$ for different runs and the total charge put on a target varied from 3.6 mC to 3.6 C.

The monocrystals of electrolytic copper (99.999% Cu) used in the experiments measured approximately $5 \times 5 \times 8$ mm. The actual crystal surface of each monocrystal was parallel within 3° to the (100), (110), or (111) crystallographic plane, as determined by Laue patterns. In a cycle, repeated three times, the surfaces were mechanically polished to a microfinish (ASA B46.1-No. $\frac{1}{2}$) and subsequently etched. Sometimes it appeared necessary to smooth the surfaces by electropolishing in an additional step. The surfaces obtained had a mirror finish and optical and electron micrographs were taken before and after the bombardment. The Laue patterns were taken after the surface treatment to ensure that work-hardened surface layers had been removed by the etching and electropolishing procedure. The target chamber was fitted with a triple-bellows system^{3,4} by which the crystal could be rotated around an axis parallel to the surface plane being bombarded and could also be moved horizontally and vertically in a plane perpendicular to the direction of the incident beam. With this arrangement, the secondary-electron emission could be studied for various angles of incidence and a fresh target spot could be bombarded in each run.

³M. Kaminsky, Phys. Rev. 126, 1267 (1962); Argonne National Laboratory Report ANL-6488, January 1962.

⁴M. Kaminsky, in Advances in Mass Spectrometry (Pergamon Press, London, 1965), Vol. 3 (in press), paper No. 4.

The differential pumping system used in the experimental arrangement is shown schematically in Fig. 18. Without baking, pressures of 1.5×10^{-8} mm Hg in the target chamber could readily be obtained during a run. At this background pressure and with an incident beam intensity of the order of 1 mA/cm^2 , the continuous sputtering of the surface layers guarantees a clean metal surface. (The sputtering ratio S varies between approximately 10^{-2} and 10^{-3} atoms/ion for the energy region considered.)

Two different collector systems have been used in the investigations. In the first, the collector was a split Ag cylinder enclosing the target; its inner diameter was 32 mm. A grid (87% transmission copper mesh, 0.0002-in. diameter wire) with an outer diameter of 26 mm was placed between target and collector in order to apply appropriate bias voltages to facilitate measurements of tertiary particle currents at target and collector, respectively. For example, such collector currents might be due to such tertiary processes as electron emission from the collector as a result of the impacts by ions sputtered and/or reflected from the target or of soft x rays emitted by it. The measured target and collector currents could then be appropriately corrected so that the true yield of secondary electrons could be obtained. The collector was placed inside a metal shield to prevent stray electrons from reaching its outer surface.

In a second arrangement, the collector consisted of 24 strips (nichrome ribbons measuring $0.03 \times 0.03 \times 4.25$ in.) which were mounted on the inside wall of the quartz tube (28 mm I. D.) along its long axis and spaced approximately 0.04 in. from each other in order to facilitate angular-distribution measurements of the secondary emission of electrons and of ions. In these experiments, the target and grid were at the same potential in order to create a field-free drift region between them. The grid has an inside diameter of 26 mm and is spaced 1 mm from the collector.

The kinetic energy distribution $N(E_e)$ of secondary electrons was determined by applying retarding potentials U_{ct} between target and electron collector, with the grid and collector connected, and measuring the collector and target currents I_c and I_t , respectively. The quantity $\gamma = I_c / (I_t + I_c)$ was then plotted as a function of U_{ct} , the retarding potential being corrected for the contact potential difference between target and collector (by use of published values of the work function as well as of contact potentials). It is also necessary to determine how much the function $\gamma(U_{ct})$ is influenced by effects such as the loss of electrons through the entrance aperture of the collector, a distortion of the field between target and collector because of the entrance aperture, the behavior of secondary and tertiary target and collector currents, and the fact that the actual target is not a point and the actual collector is not a sphere. The latter effect tends to give spuriously low electron energies since the retardation field near the target acts only on the normal component of the electron velocity. Therefore, electrons escaping in directions nearly parallel to the surface will be returned to the metal at much smaller retarding fields than would be indicated by their actual energy E_e . Treating the field distribution between target and collector as approximately that between two concentric cylinders, we estimated that all electrons reach the collector for $U_{ct} = 0.91 E_e / e$. Furthermore, since the fields near the small entrance aperture of the collector were small, no significant distortion of the field distribution between target and collector could be expected. Finally, for the case $U_{ct} < 0$ (collector negative with respect to target), the function $N(E_e) = d\gamma/dU_{ct}$ is negligibly influenced by such secondary and tertiary currents as ions reflected or sputtered from the target and secondary electrons released from the collector by the impact of these ions or by soft x rays. To a good approximation, these particle currents remain independent of U_{ct} ($U_{ct} < 0$). In most of the present work, currents to the target,

Fig. 19. Total secondary electron yields γ for the (110), (100), and (111) planes of Cu monocrystals in dependence on the energy E of D^+ incident normal to the surface.

collector, and grid were recorded as functions of U_{ct} for constant primary-ion current, while U_{ct} was varied in 0.1- or 0.2-V steps over the range $-25 \text{ V} < U_{ct} < +25 \text{ V}$ and in bigger steps (0.5 V) over the regions $-100 \text{ V} < U_{ct} < -25 \text{ V}$ and $+25 \text{ V} < U_{ct} < +100 \text{ V}$. (The experiments with $U_{ct} > 0$ were conducted to determine the energy distribution of the secondary ions.) The target and collector currents were recorded with a two-pen Leeds & Northrup Speedomax recorder. The curve $N(E_e) = d\gamma/dU_{ct}$ is obtained from the stepped curve $\Delta\gamma/\Delta U_{ct}$ by smoothing (weighting neighboring points equally).

Results

Yield Values for Different Crystallographic Planes

The data for the secondary-electron yield γ obtained for D^+ bombardment of the clean (111), (110), and (100) planes of copper monocrystals at normal incidence are plotted as functions of the deuteron energy in Fig. 19. The measurements could be reproduced to within 4% and it appears that the data contain no systematic error greater than this. The curves $\gamma(E)$ reveal a distinct dependence of the yield on the crystal-line orientation of the emitting surface,⁵⁻⁷ a behavior which is in

⁵ M. Kaminsky, Bull. Am. Phys. Soc. 8, 428 (1963).

⁶ M. Kaminsky and G. Goodwin, Report of the 25th Annual Conference on Physical Electronics, MIT, March 1965, pp. 213-222.

⁷ K. Swenson and M. Kaminsky, Bull. Am. Phys. Soc. 10, 432 (1965).

contrast to the predictions made by Sternglass.¹ Also Ghosh and Khare's model of the secondary-electron emission—according to which $\gamma \propto N \sigma_i^{nl} P$ —cannot account for the observed results. Here N is the number of metal atoms per cm^3 , σ_i^{nl} is the cross section for ionizing the nl shell of the metal atom by ion impact, and P is the probability that a secondary electron reaches the surface and escapes. (According to the authors, this P is approximately equal to the reciprocal of the secondary-electron "adsorption coefficient" α .)

However, the results can be interpreted qualitatively by assuming that γ is proportional to the effective collision area $\sigma_i^{nl} N_1$ available within a layer (where N_1 is the number of target atoms per unit area) to the number N_2 of layers contributing to the formation of secondary electrons, and to P . That is, $\gamma \propto (N_1 \sigma_i^{nl}) N_2 P$. Our observation that $\gamma(111) > \gamma(100) > \gamma(110)$ [e.g., $\gamma(111) = 1.25 \gamma(100)$ at 0.2 MeV] then becomes plausible since $(\sigma_i^{nl} N_1)_{(111)} > (\sigma_i^{nl} N_1)_{(100)} > (\sigma_i^{nl} N_1)_{(110)}$ [e.g., $(\sigma_i^{nl} N_1)_{(111)} / (\sigma_i^{nl} N_1)_{(100)} = 1.75$]. Besides these more geometrical considerations, one has to take into account that the incident deuterons are more effectively channeled along the $[100]$ directions than along the $[111]$ directions during bombardment of the (100) planes of Cu and between the (111) planes during bombardment of the (111) planes.^{5,8} However, such good channeling of the incident ion decreases the formation of secondary electrons (less ionization processes) in those layers near the surface which contribute predominantly to the emission of secondary electrons. Channeling thereby contributes to the observation that $\gamma(111) > \gamma(100) > \gamma(110)$.

The observed decrease of the yield γ with increasing ion energy E results primarily from a corresponding decrease of the cross section σ_i^{nl} for the energy region considered (Rutherford collision region).

⁸ M. Kaminsky, Atomic and Ionic Impact Phenomena on Metal Surfaces (Springer-Verlag, New York, 1965), pp. 179 ff.

Fig. 20. Total secondary electron yield for a Cu(111) plane under H_2^+ bombardment at normal incidence for two different values of the background pressure p . For $p = 1.3 \times 10^{-8}$ Torr the continuous sputtering of surface layers (sputtering rate $S \approx 10^{-3}$ to 10^{-2} atoms/ion for the energy region studied, incident beam intensity of the order of 1 mA/cm²) guarantees a clean surface.

But to a lesser extent it is attributable to a decrease in the value of P ; as E increases, the ion impact results in more secondary electrons being formed deeper within the target and the diffusion path length of these electrons to the surface is increased. As a result, not all the secondary electrons formed will have a chance to reach the surface and to escape.

A gas coverage of the bombarded plane increases the yield values significantly as illustrated in Fig. 20 for the case of H_2^+ ion bombardment of a Cu(111) plane at background gas pressures of 1.3×10^{-8} Torr and 3×10^{-6} Torr. For the lower pressure, the surface is clean since the rate of ejection of sputtered particles is roughly equal to the rate of arrival of gas particles at the surface; at the higher pressure, the surface is gas covered.

This behavior explains in part why the few available data⁸ on secondary-electron yields for the Rutherford collision region are 2—5 times those reported here for the same type of incident ion but for clean copper monocrystal surfaces; the earlier data were obtained for gas-covered polycrystalline metal surfaces. It appears that a gas coverage of metal surfaces tends to reduce the influence of the target material on the actual yield. In this connection it should be noted that Ghosh and Khare calculated their yield values by adjusting one parameter in their expression for γ to fit the experimental data obtained for

gas-covered surfaces, and in this way obtained γ values which are of course higher than those reported here for clean surfaces. For the same type of incident ion, Sternglass's theory (which considers the target material to have a negligible influence on γ) gives yield values that are 4—5 times those obtained in our experiments.

Energy Distribution of Secondary Electrons

The energy distribution was studied in order to gain more insight into the actual processes involved in the emission of secondary electrons. One may consider the emission of secondary electrons as occurring in two steps. The first is the production of energetic electrons within the lattice by processes such as the ionization of lattice atoms by ion impact, by the subsequent interaction of such electrons with other metal electrons (cascade process), and (to a lesser degree) by direct ion-electron collisions (δ rays). The second step is the transport of these energetic electrons from the interior to the surface. Along their path, they lose energy in interactions with other metal electrons and (to a much smaller degree) with phonons and lattice defects, until they either sink back below the Fermi level or have a large enough momentum component p_n normal to the surface to pass over the surface barrier W_a . The requirement for escape is $p_n^2/2m_e > W_a = E_f + e\phi$, where $e\phi$ and E_f are the work function and the Fermi energy of the target material, respectively. However, as pointed out by Probst,⁹ there exists a certain probability that even electrons with $p_n^2/2m_e < W_a$ may cause the ejection of secondary electrons by interactions with free metal electrons.

The external energy distribution $N(E_k)$ can be considered as a product of the distribution $N_i(E_k)$ of the internal electrons and the escape probability $P_e(E_k)$, i. e.,

⁹F. M. Probst, Phys. Rev. 129, 7 (1963).

$$N(E_k) = N_i(E_k) \times P_e(E_k), \quad (1)$$

where $P_e(E_k)$ can be expressed as

$$P_e(E_k) = \int_0^{2\pi} \int_0^{\theta_c} P_{\Omega}(\theta, E_k) \sin\theta \, d\theta \, d\phi. \quad (2)$$

Here $P_{\Omega}(\theta, E_k)$ is the angular distribution of electrons with energy E_k , and the angle

$$\theta_c = \cos^{-1} \sqrt{W_a/E_k}$$

is the maximum angle for which an electron of energy E_k can escape over the surface barrier. If one assumes in a first approximation that the angular distribution is spherically symmetric (s-wave scattering), the escape probability becomes¹⁰

$$P_e = \begin{cases} \frac{1}{2} (1 - \sqrt{W_a/E_k}) & \text{for } E_k > W_a, \\ 0 & \text{for } E_k < W_a. \end{cases} \quad (3)$$

From Eqs. (1) and (3) it becomes apparent that the observed external distribution should reflect the internal energy distribution and the influence of the potential barrier W_a on the escape of the secondaries. In the following, the energy distribution $N(E_k)$ will be written as a function of the kinetic energy $E_e = E_k - W_a$ of the emitted electron.

Figure 21 shows the experimentally determined differential energy distributions $N(E_e)$ vs E_e for secondary electrons emitted from a Cu(111) plane bombarded at normal incidence by 400-keV H^+ , by 500-keV D^+ , and by 400-keV He^+ . Figure 22 demonstrates the influence of the incident-ion energy on the energy distribution of electrons from a Cu(111) plane bombarded at normal incidence by 400-keV and 800-keV He^+ ions

¹⁰H. D. Hagstrum, Phys. Rev. 96, 336 (1954).

Fig. 21. Differential kinetic energy distribution curves for secondary electrons emitted from a clean Cu(111) plane under the impact of 400-keV H^+ , 500-keV D^+ , and 400-keV He^+ ions at normal incidence.

Fig. 22. Differential kinetic energy distribution curves for secondary electrons emitted from a clean Cu(111) plane under the impact of 400-keV and 800-keV He^+ ions and from a clean Mo surface under 1-keV He^+ ion bombardment (Hagstrum, Ref. 11). In the latter case, the distribution includes electrons from "potential emission" ("external Auger process").

and from a clean polycrystalline Mo surface bombarded by 1-keV He^+ ions.¹¹ (The "potential emission" of electrons cannot be neglected in the latter case.)

The curves in Figs. 21 and 22 reveal several interesting features. The striking similarity between the shapes of the energy distributions for incident H^+ , D^+ , and He^+ ions (Fig. 21) suggests that for the high-energy region the shape of the distribution is determined almost entirely by the transport and escape processes of the energetic electrons produced within the lattice—not by the production mechanism.

¹¹H. D. Hagstrum, Phys. Rev. 104, 672 (1956).

The observation that the shape of the energy distribution of secondaries ejected by 400-keV He^+ bombardment of the (111) plane is very similar to the one for 800-keV He^+ (except that the high-energy tail is somewhat more pronounced in the latter case) seems to confirm this view.

For all cases investigated here, the distribution curve has a marked maximum between 1.5 and 2.5 eV. In addition, two subsidiary maxima at about 4.5 eV and 7.5 eV are observed—the one at 7.5 eV being somewhat more pronounced than the one at 4.5 eV. The half-widths of the distribution curves shown in Fig. 21 vary between 4 eV and 5 eV. These half-widths are considerably smaller than the 10–12 eV observed^{1 1} for instance for low-energy (1-keV) He^+ ions incident on clean W or Mo. It is also of interest to note from the distribution curves shown in Fig. 21 that 95–98% of the emitted electrons have energies less than 20 eV. However, the fact that an appreciable fraction of the secondary electrons have energies greater than 10 eV seems to rule out any mechanism invoking thermionic emission^{1 2} for high-energy ion bombardment.

For the energy region considered, no quantitative treatment of the function $N(E_k)$ is able to account for the observed phenomena. In principle, such an expression might be obtained from Eq. (1) by deriving an expression for the internal electron-energy distribution $N_i(E_k)$. But this requires certain assumptions about the transition probabilities for the processes leading to energetic internal electrons and about the probability that an electron released at a distance x from the surface will have an energy between E_k and $E_k + dE_k$. Hence, no such derivation will be attempted here; it does not seem worthwhile until there is more experimental information on the function $N(E_e)$, in particular

^{1 2}R. M. Silitto, Proc. Phys. Soc. (London) 60, 453 (1958). References to similar models proposed by other authors are given in this article.

its dependence on the work function, Fermi energy, crystal structure, and density of electronic states of the target crystal. However, a qualitative explanation for the observed results will be offered.

The inelastic collision processes an energetic electron will undergo in its motion towards the surface will tend to smooth the quasi-discrete peaks in the distribution function and will lead to an increase of the density of electronic states in the vicinity of the Fermi level. Although the density of occupied levels in metals increases towards low energies, the strong influence of the surface barrier W_a on slow electrons results in a sharp cutoff of the distribution on the low-energy side and produces a maximum at a nearly constant distance from the vacuum level.

Only for energies E_k considerably above W_a will the influence of the potential barrier diminish; and at these energies the special features of the distribution curve (especially the two subsidiary maxima) can be related to the density of occupied electronic states in bands near the surface and the occurrence of internal Auger processes. (In these processes an electron is excited from a deeper filled band by primary collision. The created hole is filled with an electron from a higher band and the energy released by this process may be balanced by the ejection of an electron from the valence band.) In copper, a broad 4s band, which has a low density of states and is about 9.5 eV wide, is overlapped by a narrower 3d band (with a width of about 5.5 eV). The latter has a high density of states and shows especially large concentrations of states about 3 eV apart, towards the ends of the energy region. This spacing between the peaks corresponds well with the distance between our observed subsidiary maxima.

Summary

The measured kinetic energy distributions of secondary electrons emitted from clean copper monocrystals under high-energy

ion impact contradict the theoretical predictions^{1,2} that the yield γ would be nearly independent of the crystallographic orientation of the surface. For all ions used, γ was significantly greater for the (111) plane than for the (100) or (110). The decrease of γ with increasing velocity v indicates a close relationship between $\gamma(v)$ and the cross section $\sigma_1(v)$ for ionizing a lattice atom by ion impact.

The experimental distributions at these high energies (0.2—1.0 MeV) also showed surprising differences from those observed with light incident ions ($Z \leq 4$) at low energies (the 1-keV region). In particular, a very pronounced maximum is observed at electron energies between 1.5 and 2.0 eV, and this is followed by two subsidiary maxima near 4.5 eV and 7 eV. The half-width of the distribution is considerably smaller than those observed for light ions incident at low energies. The position of the main maximum was almost independent of the species of incident ion and of energy in the range studied, a behavior related to the angular and energy distributions of the energetic electrons in the metal and to the potential barrier at the surface. The two smaller peaks can be related to the density of occupied electronic states in the bands near the Fermi level and to the occurrence of internal Auger processes.

These studies are being extended to different monocrystalline target materials and to incident ions of higher energies (0.2—2.0 MeV).

II-30-1. MASS SPECTROMETER WITH PHOTOIONIZATION SOURCE

J. Berkowitz and W. A. Chupka

(51320-01)

A new mass spectrometer has been designed, constructed, and placed into operation. In the design, major emphasis has been placed upon versatility of application to a large number of experiments in chemical physics, including photoionization, atomic and molecular scattering of a reactive and non-reactive type, ion-molecule reactions, flames, discharges, etc. The various experimental chambers can be prepared in advance, then rolled into position and bolted to the mass analyzer. Massive pumping minimizes the pumping-down period.

The first experiments with the new system have been studies of photoionization of gases. The apparatus was found to have roughly 100 times greater sensitivity than that of similar equipment at other laboratories. This large increase in sensitivity makes possible many experiments which have not been feasible heretofore.

Photoionization is much superior to electron-impact ionization for precise determinations of such quantities as molecular-bond energies, ionization potentials, electron affinities, etc., because electron beams invariably have a thermal-energy spread and also because the threshold behavior of photoionization phenomena is inherently more abrupt than the corresponding electron-impact phenomena. Photoionization is also vastly superior in resolution of fine structure and yields much more information on details of ionization, auto-ionization, and fragmentation of ions. On the other hand, the photoionization technique has the following disadvantages: (1) the difficulty of getting intense continuum sources of photons in the vacuum ultraviolet; (2) the necessity of working in the windowless region of the vacuum ultraviolet for photon energies in excess of ca. 11 eV; (3) the relatively weak ion beams that can be obtained. The maximum intensity reported by earlier workers has been ca. 10^4 ions/sec.

Previous workers had used a Seya-Namioka design of ultraviolet monochromator, which incorporates some simplicity in engineering. However, its inherent astigmatism results in a loss of photon intensity of at least a factor of three. We have been able to adapt a near-normal-incidence monochromator to the mass spectrometer, thus recovering the loss due to astigmatism and improving the resolution as well. The photoionization chamber is an open structure and most of the ions formed therein are focused on the entrance slit of the mass spectrometer by a pair of electrostatic quadrupoles. With this design, we have obtained ion intensities of ca. 10^6 — 10^7 ions/sec.

The monochromator, a commercial device, is equipped to operate without a window even with a pressure in the light source close to one atmosphere. Thus, photons with energies in excess of 20 eV can be obtained in useful intensity with an energy spread of about 0.01 eV.

The first photoionization experiments carried out were studies of relative cross section as a function of wavelength for production of parent and fragment ions from ethane, propane, and butane. Earlier photoionization studies were hindered by low ion intensities and were limited by the transmission of optical windows to wavelengths above $1060 \overset{\circ}{\text{A}}$. The present results provide the first accurate photoionization data on the fragmentation processes of ethane and propane ions. Also, for the first time, ion-pair production of the type

$\text{C}_n\text{H}_{2n+2} + h\nu \rightarrow \text{C}_n\text{H}_{2n+1}^+ + \text{H}^-$ was observed for all three hydrocarbons studied. This process had only recently been observed by electron impact in controversial experiments of Hamill and collaborators. The observed effect is of such low intensity that it could not be detected in earlier photoionization experiments. The present results show that this type of pair production is relatively much less abundant in photoionization than in electron impact. Nevertheless, the reliability of the photoionization measurements is much greater than those made by electron impact. If the latter are correct, then there are greater fundamental differences

between electron and photon impact near the ionization threshold than have been suspected. There is considerable current interest in the "superexcited" (i. e. , excited above the ionization potential) states of molecules which can undergo such ion-pair production or alternatively auto-ionization or dissociation into neutral fragments. Observation of both ion-pair production and ionization by electron ejection as a function of photon energy makes it possible to study the competition between these processes.

In the present mode of operation, gas samples are injected into the ionization chamber and pass directly into the trap and throat of a 6-in. diffusion pump. In this way, molecular-beam "pressures" of ca. 10^{-2} mm Hg can be obtained in the ionization chamber.

For studies of vapors of refractory materials, an oven is mounted below the ionization chamber. In the initial experiments with MgI_2 , mass analyzed photoionization currents in excess of 10^4 ions/sec were readily obtained.

Although some primitive and very limited photoionization experiments were performed on high-temperature vapors ca. 35 years ago, this is the first successful venture in this area with modern technology. One goal of this type of study is to obtain accurate ionization potentials of a large number of molecules and some atoms. Another important goal is to obtain molecular bond energies by determining the onset potentials for fragmentation processes. For example, in the case of MgI_2 we have succeeded in establishing not only the simple ionization potential corresponding to the reaction

but also for the fragmentation process

If we can produce a beam of MgI molecules and determine the ionization potential of MgI, we will in effect have determined the dissociation energy of the I—MgI bond. In those cases where the Boltzmann spread of internal energies in the molecular beam is not too great, this approach should enable us to determine heats of formation more accurately than by other existing techniques. In addition, in the area of high-temperature thermodynamics there are a number of problems in which large discrepancies exist between the results obtained by different methods or approaches. It is hoped that the photoionization approach, which is less equivocal if data can be obtained, may resolve these discrepancies.

The high sensitivity that has been achieved should also enable us to examine the photoionization behavior (i. e. , appearance potential, cross section, and ionization efficiency curve) of free radicals and other transient molecular species that are present in relatively low abundance.

V. THEORETICAL PHYSICS, GENERAL

V-2-20. PROPERTIES OF LIGHT NUCLEI (51311-01)

Dieter Kurath

GAMMA TRANSITIONS IN B^{10}

There is a large amount of experimental information about and interest in gamma transitions in B^{10} . A recent calculation¹ obtained strengths of M1 transitions and beta decays for the mass-10 nuclei. As a supplement, the strengths for E2 transitions have been calculated with the wave functions derived in Ref. 1. However, it is well known that observed E2 strengths in the 1p shell are usually enhanced by factors of two to five above the values obtained from 1p configurations. Therefore, the results indicated in Table VI serve only to indicate those cases in which a strong E2 transition should be expected, since the transitions calculated to be strong within the 1p configuration are usually the ones observed to be enhanced.

Results are given in Table VI for the various interactions derived in Ref. 1, but there is not much variation with interaction. The E2 strengths are given in terms of the harmonic-oscillator parameter β which occurs as $\exp[-\frac{1}{2}\beta r^2]$ in 1p wave functions. If one chooses $[2\beta]^{-1} = 2 \times 10^{-26} \text{ cm}^2$, corresponding to the expectation value $\langle r^2 \rangle_{1p, 1p} = 10^{-25} \text{ cm}^2$, then

$$\Gamma_{E2}(I_1 \rightarrow I_2) = 0.128 (E/10)^5 \Lambda_{E2}(I_1 \rightarrow I_2), \quad (1)$$

¹S. Cohen and D. Kurath, "Effective Interactions for the 1p Shell," Nucl. Phys. 73, 1 (1965).

TABLE VI. E2 transition strengths in B^{10} . The quantity tabulated is $(2I_1 + 1) \Lambda_{E2}(I_1 \rightarrow I_2) = (2I_2 + 1) \Lambda_{E2}(I_2 \rightarrow I_1)$ and is given in units of $[2\beta]^{-2}$. The harmonic-oscillator parameter β appears in the wave functions as $\exp[-\frac{1}{2}\beta r^2]$. Columns 1 and 2 identify $(I_1 T_1)$ and $(I_2 T_2)$; the asterisks indicate whether the state is the lowest (unmarked), first excited (*), or second excited (***) state of the specified (IT) . Columns 3—6 refer to the various interactions used to obtain the wave functions.

$(I_1 T_1)$	$(I_2 T_2)$	Inglis ($a/K = 4.5$)	(8—16) POT	(8—16)2B	(6—16)2B
40	30**	9.87	2.19	2.02	2.05
	30*	0.03	4.35	5.15	6.81
	30	41.65	47.70	47.50	46.67
	20*	2.79	0.74	2.35	4.27
	20	16.58	14.37	13.03	11.54
	21*	0.81	0.00	0.02	0.37
	21	2.49	3.47	3.14	3.20
30**	30**	8.00	1.18	0.37	0.05
	30*	9.22	9.62	8.61	7.92
	30	0.46	1.05	0.56	0.74
	20*	23.77	25.98	32.89	33.61
	20	0.49	7.76	3.43	0.26
	10**	0.23	3.71	3.46	1.59
	10*	6.77	6.32	8.04	8.42
	10	0.99	0.05	0.03	0.00
	21*	1.58	0.02	0.29	0.51
	21	0.23	1.53	1.66	2.66
30*	30*	0.02	16.92	23.16	23.12
	30	1.63	6.01	5.87	3.23

TABLE VI. (Cont'd.)

$(I_1 T_1)$	$(I_2 T_2)$	Inglis ($a/K = 4.5$)	(8-16) POT	(8-16)2B	(6-16)2B
	20 [*]	5.22	1.85	2.13	3.80
	20	22.61	10.52	7.91	8.36
	10 ^{**}	0.39	0.58	0.92	0.83
	10 [*]	11.99	8.94	8.80	5.62
	10	17.46	18.61	17.22	19.67
	21 [*]	0.45	0.36	0.13	0.00
	21	6.27	2.26	2.07	2.43
30	30	51.93	48.67	48.71	51.26
	20 [*]	2.28	2.13	1.09	0.96
	20	3.63	4.68	5.82	6.25
	10 ^{**}	0.03	0.63	0.95	0.76
	10 [*]	9.45	1.40	1.02	1.35
	10	2.35	7.33	7.44	8.17
	21 [*]	0.32	0.70	0.50	0.11
	21	1.15	0.31	0.49	0.33
20 [*]	20	12.24	2.26	0.35	0.17
	10 ^{**}	2.93	4.90	3.79	2.06
	10 [*]	16.65	1.47	3.66	4.79
	10	0.90	12.65	7.23	3.50
	21 [*]	0.01	0.06	0.07	0.11
	21	2.22	0.48	0.26	0.55
	01	0.15	0.30	0.38	0.76

TABLE VI. (Cont'd.)

$(I_1 T_1)$	$(I_2 T_2)$	Inglis ($a/K = 4.5$)	(8-16) POT	(8-16)2B	(6-16)2B
20	10**	2.86	1.76	1.65	2.96
	10*	9.05	10.29	6.72	7.26
	10	12.25	19.83	28.57	27.30
	21*	0.69	0.02	0.04	0.21
	21	0.10	0.59	0.73	0.67
	01	2.01	0.49	0.46	0.40
10**	10*	5.75	0.01	0.08	0.14
	10	0.03	4.73	4.12	4.30
	21*	0.06	0.03	0.01	0.14
	21	1.93	3.43	2.11	2.31
10*	10	2.74	2.25	1.52	3.87
	21*	0.96	0.06	0.38	1.44
	21	0.16	2.43	2.70	2.53
10	21*	0.87	0.82	0.51	0.71
	21	2.04	0.02	0.02	0.00
21*	21	21.18	27.84	28.67	21.54
	01	1.24	0.08	0.21	1.61
21	01	18.29	20.59	20.62	18.87
21*	21	10.21	24.35	22.75	8.73
	01	2.92	9.11	7.89	3.11
21	01	27.98	22.18	23.73	28.91

where Γ_{E2} is in eV and the energy E is in MeV. Results from electron scattering indicate that $[2\beta]^{-1} \approx 1.3 \times 10^{-26} \text{ cm}^2$ is a more likely value in this region; this would lead to lower values than are calculated from Eq. (1).

A Weisskopf

estimate for $\Lambda_{E2}(I_1 \rightarrow I_2)$ indicates that a large transition strength in Table VI is one for which $\Lambda_{E2} \gg 2$. There are very few transitions for which this is

true. Only eight cases in Table VI have such large matrix elements, namely $(40-30)$, $(30-30)$, $(30^{**}-20^*)$, (30^*-30^*) , (30^*-10) , $(20-10)$, $(21-21^*)$, and $(21-01)$. Some of these large matrix elements would be expected from a rotational-model interpretation. For example, the $(40-30)$ and $(30-30)$ would be members of a $K=3$ rotational band. However, the strong $(21-21^*)$ case would certainly not arise in a rotational interpretation. The number of K bands in an odd-odd nucleus such as B^{10} usually is large, and prevents any simple interpretation on a rotational model.

Another point of interest in B^{10} concerns the connection between M1 transition strengths and Gamow-Teller beta decays involving the levels (01) , (10) , and $(10)^*$ shown in Fig. 23. The M1 decays between (01) and (10) states are given to good approximation by keeping only the spin-dependent part of the M1 operator. The transition strength then is

$$\Lambda_{M1}(01 \rightarrow 10) \doteq \frac{3}{4} (\mu_n - \mu_p + \frac{1}{2})^2 \langle 10 | \sigma_1^1 \tau_0^1 | 01 \rangle^2. \quad (2)$$

This part predominates because in $\Delta T = 1$ transitions the contributions from the neutron and proton spins are coherent and give a large coefficient. The beta-decay transition strength is

Fig. 23. Beta decay of C^{10} and the related M1 transitions in B^{10} . The excitation energies shown are in MeV.

$$\Lambda_{GT}(01 \rightarrow 10) = \frac{3}{2} \langle 10 | \sigma_1^1 \tau_{-1}^1 | 01 \rangle^2. \quad (3)$$

The matrix elements are equal, so that in this approximation, good to about 20%,

$$\begin{aligned} \Lambda_{M1}(01 \rightarrow 10) &\doteq \frac{1}{2} (\mu_n - \mu_p + \frac{1}{2})^2 \Lambda_{GT}(01 \rightarrow 10) \\ &= 8.85 \Lambda_{GT}(01 \rightarrow 10). \end{aligned} \quad (4)$$

For the $(10)^*$ case, the experimental value for the M1 transition² strength Λ_{M1} is

$$3\Lambda_{M1}(10^* \rightarrow 01) = \Lambda_{M1}(01 \rightarrow 10^*) = 3.9 \pm 0.6.$$

This leads to $\Lambda_{GT}(01 \rightarrow 10^*) = 0.44 \pm 0.07$ and to

$$\log ft(01 \rightarrow 10^*) = 3.63 - \log \Lambda_{GT} = 4.0 \pm 0.1,$$

which is consistent with the limit on this branch in the observed decay.

For the (10) case, the measured $ft = 1.0 \times 10^3$ leads to $\Lambda_{GT}(01 \rightarrow 10) = 4.3$, and via Eq. (4) to $\Lambda_{M1}(01 \rightarrow 10) = 38$. This leads to $\Gamma_Y = 0.11$ eV, or $\tau_{M1} = 0.06 \times 10^{-13}$ sec. The experimental lifetime is reported² to be $\tau_{M1} = 1.5 \times 10^{-13}$ sec, so there is a large discrepancy.

Either the approximation represented by Eq. (4) is not valid, or one of the experimental numbers is incorrect. In support of Eq. (4), it should be remarked that the relationship holds for transitions in $A=6$ nuclei, and a similar expression is verified for $A=12$ nuclei.

²J. A. Lonergan and D. J. Donahue, Phys. Rev. 139, B1149 (1965).
The branching ratio was obtained from R. Segel (private communication).

V-9-2. SHELL-MODEL CALCULATIONS

(51311-01)

R. D. Lawson and J. M. Soper*

CONCEALED CONFIGURATION MIXING IN THE NUCLEAR
SHELL MODEL

In nuclear-structure calculations, one often assumes that only single-particle states belonging to one shell need be used in diagonalizing the Hamiltonian. If the consequences of this assumption are borne out by experiment, it is tempting to say that this confirms the hypothesis that the shell is fairly pure. To show that this conclusion is not warranted, we have considered a problem that is exactly soluble.

The model used is one in which the $1d_{3/2}$ and $1f_{7/2}$ single-particle levels are assumed isolated from all other single-particle states. Further, we consider the case in which only neutrons are present and take the residual neutron-neutron interaction to be

$$V = V_{10} \left(\frac{1 - \vec{\sigma}_1 \cdot \vec{\sigma}_2}{4} \right) \frac{e^{-r/a}}{r/a} + V_{11} \left(\frac{3 + \vec{\sigma}_1 \cdot \vec{\sigma}_2}{4} \right) \frac{e^{-r/a}}{r/a}, \quad (1)$$

where the potential strength when the two interacting neutrons are in a spin-singlet state is $V_{10} = -30$ MeV and the spin-triplet strength is $V_{11} = -10$ MeV. Matrix elements of the residual two-body force were evaluated by use of harmonic-oscillator wave functions $\phi \propto \exp -\frac{1}{2}(r/b)^2$ for the single-particle levels. The range parameter that comes into the calculation is $\lambda = a/(\sqrt{2} b) = 0.665$. The Hamiltonian of this model can be set up and diagonalized exactly.¹ This has been done for all J values and all numbers of neutrons in the range $2 \leq N \leq 12$.

* On attachment from A. E. R. E., Harwell.

¹ This was done with the aid of the Argonne shell-model programs developed in collaboration with S. Cohen, D. Kurath, M. H. Macfarlane, and M. Soga.

In this discussion we shall consider the case in which the $1d_{3/2}$ and $1f_{7/2}$ levels are degenerate. For $N = 4$, there is then only about a 9% probability of finding the closed-shell configuration $(d_{3/2})^4$ in the lowest $J=0$ state. For $N = 5$, the probability that the lowest $\frac{7}{2}^-$ state can be described as a single $f_{7/2}$ nucleon outside a closed $d_{3/2}$ shell is only about 17%. In spite of this, the calculated spectra exhibit the following regularities: (a) For all even values of N , the ground-state spin is zero. (b) For all odd values of N , $5 \leq N \leq 11$, the lowest state is $\frac{7}{2}^-$. (c) For $N > 4$, the spins of the lowest even-parity states for N even and odd-parity states for N odd are those that would arise if one had $f_{7/2}$ neutrons moving outside a closed $d_{3/2}$ shell. The eigenvalues etc. of our exact calculations for these nuclei will be labeled the "pseudo-experimental results." The nuclei from $N = 4$ to $N = 12$ will be called the pseudonium nuclei and henceforth will be denoted by Ps^{40} for $N = 4$, Ps^{41} for $N = 5$, etc.

In view of item (c), it is interesting to see if one can fit the pseudo-experimental energies for $N > 4$ on the assumption that one has only $f_{7/2}$ particles moving outside a closed $d_{3/2}$ shell. If one measures all energies relative to the $N=4$, $J=0$ state (i.e., relative to the "closed shell") then there are 31 states that can arise from putting 1–8 neutrons into the $f_{7/2}$ level. The residual two-body interaction between the $f_{7/2}$ neutrons can be characterized by four parameters, E_0 , E_2 , E_4 , and E_6 —the interaction energies in the $J=0, 2, 4$, and 6 states, respectively. These four quantities together with the energy binding the single $f_{7/2}$ particle to the closed shell give five parameters with which to fit the pseudo-experimental data. The fit to the binding energies is shown in Table VII and an example of the fit to the pseudo-experimental spectra is shown in Fig. 24. The rms error in the energy of any one of the 31 fitted states is 161 keV—a result as good as any obtained in real nuclei.

The pseudo-experimental results for the magnetic moments and M1 transition probabilities also compare very favorably with

TABLE VII. Binding energies (MeV) relative to the ground state of Ps^{40} . Column 2 lists the binding energies that result from an exact solution of the problem, column 3 the best fit to the binding energy on the assumption of the pure $f_{7/2}$ configuration, and column 4 lists the probability that in pseudo-nature the pure configuration $(d_{3/2})^4(f_{7/2})^{N-4}$ was actually present.

	Pseudo-experiment	$f_{7/2}$ theory	Percentage of $d^4 f^n$ in wave function
Ps^{41}	- 3.47	- 3.57	17.3
Ps^{42}	-11.66	-11.66	34.1
Ps^{43}	-16.83	-16.85	55.0
Ps^{44}	-26.56	-26.57	65.8
Ps^{45}	-33.46	-33.38	85.4
Ps^{46}	-44.62	-44.71	88.0
Ps^{47}	-53.13	-53.15	100.0
Ps^{48}	-65.66	-66.11	100.0

Fig. 24. Spectrum of pseudonium-43. "Pseudo-experiment" is the result of the exact calculation and " $f_{7/2}$ theory" is the least-squares fit based on the pure $f_{7/2}$ model for the levels.

TABLE VIII. The pseudo-experimental results for the quantity $(2I_f + 1)(4\pi/3)(\text{BM1})$ for M1 transitions in various pseudonium isotopes. The spins I_i and I_f of the initial and final states involved are in column 1. For the pure configuration, all the transition probabilities should vanish. For comparison, the single-particle estimate for the $f_{7/2} \rightarrow f_{7/2}$ transition is 37.64.

$I_i \rightarrow I_f$	Ps^{43}	Ps^{45}
$\frac{5}{2} \rightarrow \frac{7}{2}$	0.0006	0.0000
$\frac{3}{2} \rightarrow \frac{5}{2}$	0.0746	0.0050
$\frac{7}{2} \rightarrow \frac{9}{2}$	0.0013	0.0000
$\frac{9}{2} \rightarrow \frac{11}{2}$	0.6930	0.0107

$I_i \rightarrow I_f$	Ps^{44}
$5 \rightarrow 6$	0.0002
$4 \rightarrow 5$	0.0000

predictions based on the pure configuration $(d_{3/2})^4 (f_{7/2})^{N-4}$. For example, the magnetic moments of the $\frac{7}{2}^-$ ground states of the pseudonium nuclei are all predicted to be -1.913 nuclear magnetons. This is almost identical to the pseudo-experimental values which range from -1.895 to -1.913 nuclear magnetons. In the case of the transition probabilities, there is a selection rule that states that within the identical nucleon configuration j^n there can be no M1 transitions. The pseudo-experimental results also exhibit this selection rule as is shown in Table VIII. The worst violation

of the selection rule is the $\frac{9}{2}^- \rightarrow \frac{11}{2}^-$ transition in Ps^{43} , and even this is down by a factor of 54 from the single-particle estimate.

The fact that the pseudo-experimental magnetic moments and transition rates fit so well with the pure-configuration values depends on two facts. First, the particles excited out of the so-called closed $d_{3/2}$ shell are predominantly zero-coupled pair excitations, i. e. ,

$$\psi_J \approx \alpha (d_{3/2})_0^4 (f_{7/2})_J^{N-4} + \beta (d_{3/2})_0^2 (f_{7/2})_J^{N-2} + \gamma (f_{7/2})_J^N. \quad (2)$$

We now make use of the fact that the odd magnetic-multipole operators are quasi-spin scalars, and consequently their matrix elements are independent of nucleon number. From these two facts, it follows that the magnetic moments should be close to the Schmidt value and the M1 transition probabilities should exhibit the same selection rules as the pure configuration, since each individual component of Eq. (2) has these properties and there are no cross terms.

Turning to the E2 transition rates, there is a selection rule that states that when a single-particle level of identical nucleons is half full, E2 radiation can be emitted only in transitions that change the seniority by two units. Our pure-configuration model says that the $f_{7/2}$ shell is half filled at Ps^{44} and consequently the E2 transitions in this nucleus should take place only between states whose seniority differs by two units. The pseudo-experimental results for this case are shown in Table IX and again one observes a remarkable similarity between "pure-configuration theory" and pseudo-experiment.

Finally the pure-configuration assignment predicts that the only $\ell=3$ level populated in a (d,p) reaction using the even pseudonium nuclei as targets should be the ground state of the neighboring odd-mass nucleus. In all "experimental" cases, more than 98% of the transition strength goes to the ground state.

TABLE IX. The quantity $(2I_f + 1)(4\pi/5)(2/b^2)^2$ (BE2) for the various transitions in Ps^{44} . Column 2 gives the results of the exact calculation, while column 3 has the predictions of a pure $(d_{3/2})^4 (f_{7/2})^4$ configuration. The spin states involved in the transitions are listed in the first column with the seniorities of the levels written as superscripts.

$J_i^{V_i} \rightarrow J_f^{V_f}$	Pseudo-experiment	$f_{7/2}$ theory
$2^2 \rightarrow 0^0$	105.87	102.83
$2^2 \rightarrow 4^2$	4.63	0
$2^2 \rightarrow 4^4$	179.61	204.66
$2^4 \rightarrow 0^0$	0.02	0
$2^4 \rightarrow 4^2$	37.38	50.38
$2^4 \rightarrow 4^4$	0.11	0
$4^2 \rightarrow 5^4$	186.65	144.00
$4^4 \rightarrow 5^4$	0.14	0
$4^2 \rightarrow 6^2$	3.12	0
$4^4 \rightarrow 6^2$	196.12	246.87
$5^4 \rightarrow 6^2$	144.59	122.76
$8^4 \rightarrow 6^2$	227.02	249.76

The fact that the energies are insensitive to configuration mixing has been realized for many years (although the extremely large amount of mixing that can be tolerated is rather surprising). On the other hand, the gross insensitivity of the gamma-ray selection rules and other static and dynamic properties is probably due to the fact that we have dealt with an all-neutron nucleus, whose dominant excitations are zero-coupled pairs. In actual nuclei, the $1d_{3/2}$ and $1f_{7/2}$ levels are not degenerate; and in addition proton-neutron excitations can occur and these will give rise to other than zero-coupled pairs. Thus the situation

in real life is not likely to be as extreme as the model discussed here. However, an important point to be made is that many nuclear properties are almost completely insensitive to exciting zero-coupled pairs out of a so-called closed shell. The fact that this is so would mean that the effective interaction to be used in the usual shell-model calculations may be considerably different than the free nucleon-nucleon interaction.

[For example, the effective interaction that gives rise to the values of E_0 , E_2 , E_4 , and E_6 needed to fit the data contains an appreciable tensor and spin-orbit force, although none was present in Eq. (1).]

Finally, the fact that all the pseudo-experimental results fit so remarkably with the pure $f_{7/2}$ model—despite the inapplicability of the configuration—implies that the nuclear Hamiltonian may have some symmetry property which the shell model has so far missed. Since the nucleon-nucleon interaction of Eq. (1) was chosen to have properties similar to the free nucleon-nucleon interaction, it is possible that this new symmetry exists in actual nuclei and may provide a useful new tool in studies of nuclear structure.

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L. L. Lee, Jr. and R. H. Siemssen

Bull. Am. Phys. Soc. 10, 510 (26 April 1965)

ENERGY LEVELS IN Ca^{48} OBSERVED IN INELASTIC PROTON
SCATTERING (Project I-23)

A. Marinov and J. R. Erskine

Bull. Am. Phys. Soc. 10, 526 (26 April 1965)

ANGULAR DISTRIBUTIONS OF THE $\text{Mg}^{25}(\text{He}^3, \alpha)$ REACTION

C. Mayer-Böricke and D. Dehnhard (Project I-25)

Bull. Am. Phys. Soc. 10, 463 (26 April 1965)

YIELD CURVES FOR $\text{Mg}^{24}(\alpha, \gamma)\text{Si}^{28}$ (Project I-21)

L. Meyer-Schützmeister, Z. Vager, and R. E. Segel

Bull. Am. Phys. Soc. 10, 463 (26 April 1965)

* University of Sheffield.

[†] Northern Illinois University.

[†] Indiana University.

American Physical Society meeting, Washington, D. C., 26—29 April 1965 (cont'd.).

CORRELATIONS IN $\text{Ni}^{58}(\text{p}, \text{p}') \text{ YIELD CURVES}$. . . (Project I-29)

J. E. Monahan, A. J. Elwyn, R. E. Segel, L. L. Lee, Jr., L. Meyer-Schützmeister, Z. Vager, and P. P. Singh*
Bull. Am. Phys. Soc. 10, 495 (26 April 1965)

NEUTRON CROSS SECTIONS OF THE BORON ISOTOPES

F. P. Mooring and J. E. Monahan (Project I-16)
Bull. Am. Phys. Soc. 10, 513 (26 April 1965)

NEUTRON TIME-OF-FLIGHT ANALYZER WITH LARGE MEMORY CAPACITY AND VARIABLE CHANNEL WIDTH

C. C. Rockwood (Electronics), R. E. Coté, H. E. Jackson, and G. E. Thomas (Project I-1)
Bull. Am. Phys. Soc. 10, 500 (26 April 1965)

(d, p) REACTION ON Si^{28} , F^{19} , S^{32} , S^{34} , AND C^{12} . . . (Project I-27)

J. P. Schiffer, L. L. Lee, Jr., A. Marinov, and C. Mayer-Böricke
Bull. Am. Phys. Soc. 10, 510-511 (26 April 1965)

YIELD CURVES FROM $\text{B}^{10} + \text{p}$ (Project I-21)

R. E. Segel and P. P. Singh
Bull. Am. Phys. Soc. 10, 426 (26 April 1965)

He^3 SCATTERING FROM THE EVEN Ni ISOTOPES . . . (Project I-22)

R. H. Siemssen, T. H. Braid, D. Dehnhard, and B. Zeidman
Bull. Am. Phys. Soc. 10, 540 (26 April 1965)

STATES OF B^{10} FROM THE ELASTIC SCATTERING OF ALPHA PARTICLES BY Li^6 (Project I-21)

P. P. Singh and D. S. Gemmell
Bull. Am. Phys. Soc. 10, 538 (26 April 1965)

ELECTRON EMISSION FROM COPPER MONOCRYSTALS UNDER HIGH-ENERGY DEUTERON BOMBARDMENT . . . (Project II-25)

K. Swenson and M. Kaminsky
Bull. Am. Phys. Soc. 10, 432 (26 April 1965)

*Indiana University.

American Physical Society meeting, Washington, D. C., 26—29 April 1965 (cont'd.).

p-WAVE NEUTRON RESONANCES IN U^{238} AT VERY LOW ENERGY (Project I-3)

G. E. Thomas and L. M. Bollinger

Bull. Am. Phys. Soc. 10, 513 (26 April 1965)

STUDY OF THE ISOBARIC-SPIN-FORBIDDEN REACTION $C^{12}(d, \alpha)B^{10}$ (1.74 MEV, $T = 1$) (Project I-21)

D. von Ehrenstein, L. Meyer-Schützmeister, and
R. G. Allas

Bull. Am. Phys. Soc. 10, 440 (26 April 1965)

(d, He^3) REACTION ON $1f_{7/2}$ NUCLEI (Project I-22)

B. Zeidman and T. H. Braid

Bull. Am. Phys. Soc. 10, 479 (26 April 1965)

American Physical Society meeting, Chicago, 28—30 October 1965.

NUCLEAR RESONANCE FLUORESCENCE IN Kr^{82} . . . (Unattached)

G. B. Beard

Bull. Am. Phys. Soc. 10, 1116-1117 (28 October 1965)

DECAY OF Co^{55} (Project I-9)

H. J. Fischbeck, F. T. Porter (Chemistry), M. S.
Freedman (Chemistry), F. Wagner, Jr. (Chemistry),
and H. H. Bolotin

Bull. Am. Phys. Soc. 10, 1116 (28 October 1965)

BLOCKING OF SCATTERED PROTONS IN SINGLE CRYSTALS

D. S. Gemmell and R. E. Holland (Project I-32)

Bull. Am. Phys. Soc. 10, 1122 (28 October 1965)

HFS OF THE 4F GROUND MULTIPLET OF V^{51} . . . (Project I-80)

L. S. Goodman and W. J. Childs

Bull. Am. Phys. Soc. 10, 1098 (28 October 1965)

LIFETIMES OF $d_{3/2} \rightarrow f_{7/2}$ TRANSITIONS IN Ca^{41} AND K^{39}

R. E. Holland and F. J. Lynch (Project I-14)

Bull. Am. Phys. Soc. 10, 1116 (28 October 1965)

American Physical Society meeting, Chicago, 28—30 October 1965 (cont'd.).

HIGH-RESOLUTION MEASUREMENTS OF RESONANCE NEUTRON
CAPTURE IN Pt^{195} (Project I-7)

H. E. Jackson and G. E. Thomas

Bull. Am. Phys. Soc. 10, 1108 (28 October 1965)

ELECTRON EMISSION FROM METAL MONOCRYSTALS UNDER
HIGH-ENERGY ION IMPACT (Project II-25)

M. Kaminsky

Bull. Am. Phys. Soc. 10, 1105 (28 October 1965)

IMPROVED TIMING WITH NaI(Tl) (Project I-14)

F. J. Lynch

Bull. Am. Phys. Soc. 10, 1100 (28 October 1965)

$\text{Si}^{28}(\alpha, \gamma)$ IN THE GIANT-RESONANCE REGION . . . (Project I-21)

L. Meyer-Schützmeister, Z. Vager, R. E. Segel, and
P. P. Singh

Bull. Am. Phys. Soc. 10, 1084 (28 October 1965)

GAMMA SPECTRA ARISING FROM (n, γ) REACTIONS IN
HAFNIUM (Project I-61)

A. I. Namenson, H. E. Jackson, and R. K. Smither

Bull. Am. Phys. Soc. 10, 1108 (28 October 1965)

MÖSSBAUER EFFECT IN CESIUM METAL (Project I-19)

G. J. Perlow, A. J. Boyle, and G. L. Montet (Solid State
Science)

Bull. Am. Phys. Soc. 10, 1112 (28 October 1965)

CHARGE RADII FROM COULOMB ENERGIES OF ANALOG
STATES (Project I-27)

J. P. Schiffer and K. W. Jones*

Bull. Am. Phys. Soc. 10, 1084 (28 October 1965)

ALPHA DECAY OF THE 5.16-MEV STATE IN B^{10} . . . (Project I-21)

R. E. Segel, P. P. Singh,† and M. A. Grace‡

Bull. Am. Phys. Soc. 10, 1115 (28 October 1965)

* Brookhaven National Laboratory.

† Indiana University.

‡ Oxford University.

American Physical Society meeting, Chicago, 28—30 October 1965 (cont'd.).

LIFETIME OF THE 1.95-MEV LEVEL IN Ca^{41} . . . (Project I-33)

P. P. Singh, R. H. Siemssen, R. E. Segel, and S. I. Baker

Bull. Am. Phys. Soc. 10, 1115-1116 (28 October 1965)

GIANT RESONANCE IN $\text{Mg}^{26}(\alpha, \gamma)\text{Si}^{30}$ (Project I-21)

Z. Vager, L. Meyer-Schützmeister, R. E. Segel, and P. P. Singh

Bull. Am. Phys. Soc. 10, 1084 (28 October 1965)

DECAY OF 5.7-DAY Mn^{52} (Project I-9)

F. Wagner, Jr. (Chemistry), M. S. Freedman (Chemistry), F. T. Porter (Chemistry), and H. H. Bolotin

Bull. Am. Phys. Soc. 10, 1116 (28 October 1965)

STUDY OF $\text{Zn}^{66,68}(\text{He}^3, d)\text{Ga}^{67,69}$ REACTIONS . . . (Project I-27)

B. Zeidman, R. H. Siemssen, and L. L. Lee, Jr.

Bull. Am. Phys. Soc. 10, 1126 (28 October 1965)

ANL TOPICAL REPORT

SURVEY OF POLARIZED ION SOURCES IN EUROPE . . . (Project I-13)

D. C. Hess and D. von Ehrenstein

Argonne National Laboratory Topical Report ANL-7118
(November 1965)

STUDENT REPORTS

THE MEASUREMENT OF GAMMA-GAMMA DIRECTIONAL CORRELATIONS

R. W. Hadsell (Project I-37)

ACM student report to Cornell College (9 July 1965)

SEMICONDUCTOR JUNCTION DETECTORS (Unattached)

R. Henninger

Co-op student report to Northwestern University (March 1965)

CIRCUITS FOR USE WITH THE ATOMIC-BEAM MACHINE . . . (Project I-80)

G. Hoffman

Co-op student report to the Illinois Institute of Technology
(Spring 1965)

ELASTIC SCATTERING OF PROTONS BY Mg^{26} (Project I-31)

M. C. Mertz

Ph. D. Thesis, Illinois Institute of Technology (June 1965)

CALCULATION OF ABSOLUTE CROSS SECTIONS IN THE CENTER-
OF-MASS SYSTEM (Project I-27)

E. J. Moore

Co-op student report to the University of Detroit
(27 July 1965)

A 34-KG SUPERCONDUCTING MAGNET (Project I-19)

W. Platz

ACM student report to Ripon College (June 1965)

WORK REPORT (Project II-25)

K. Swenson

Co-op student report to the University of Michigan (June
1965)

A CONTROL EXPERIMENT TO VALIDATE MEASUREMENTS OF
HIGH-FREQUENCY ADMITTANCE OF HIGH-FREQUENCY PLASMAS

B. A. Tryba (Project IV-10)

ACM student report to Mundelein College (31 August 1965)

CALCULATION OF CONVERSION FACTORS FOR TRANSFORMING
FROM THE LABORATORY TO THE CENTER-OF-MASS SYSTEM

C. A. Walker (Project I-18)

Co-op student report to the University of Florida
(18 August 1965)

INFORMAL REPORTS

USERS' MANUAL FOR THE SPEAK-EASY PROGRAM . . . (Project V-60)

S. Cohen and M. Kraimer (Applied Mathematics)

Physics Division Informal Report PHY-1965A (September
1965)

A COMPUTER PROGRAM FOR AUTOMATIC DECOMPOSITION OF
SPECTRA FROM CHARGED-PARTICLE REACTIONS . . . (Project I-23)

P. Spink and J. R. Erskine

Physics Division Informal Report PHY-1965B (December
1965)

MONTE CARLO CALCULATION OF THE EFFICIENCY OF THE
COMPTON POLARIMETER IN DETECTING THE LINEAR POLARIZATION
OF GAMMA RAYS (Project I-41)

G. T. Wood

Physics Division Informal Report PHY-1965C (December
1965)

ADDITIONAL PAPERS ACCEPTED FOR PUBLICATION

HYPERTRITON WITH S' STATE AND THE Λ -N INTERACTION

A. R. Bodmer (Project V-56)

Phys. Rev.

THE MASS-SEVEN HYPERNUCLEI AND THE MASS-SIX NUCLEI

A. R. Bodmer and J. W. Murphy* (Project V-56)

Nucl. Phys.

ELECTRON-SPIN RELAXATION AND THE MÖSSBAUER EFFECT IN
FERRIC AMMONIUM SULPHATE (Project I-19)

A. J. F. Boyle and J. R. Gabriel (Solid State Science)

Phys. Letters (1 December 1965)

ELECTRONIC g FACTORS OF THE LOW LEVELS OF Ni I . . . (Project I-80)

W. J. Childs, M. S. Fred (Chemistry), and L. S. Goodman

Phys. Rev. (7 January 1966)

HFS OF THE 9161-cm^{-1} $^2D_{5/2}$ STATE OF Au^{197} AND THE NUCLEAR
ELECTRIC QUADRUPOLE MOMENT (Project I-80)

W. J. Childs and L. S. Goodman

Phys. Rev. (7 January 1966)

HYPERFINE STRUCTURE OF Ge^{73} IN THE 3P_1 AND 3P_2 ATOMIC
STATES AND THE NUCLEAR MAGNETIC DIPOLE MOMENT OF
 Ge^{71} (Project I-80)

W. J. Childs and L. S. Goodman

Phys. Rev. (7 January 1966)

A NOTE ON THE MEASUREMENT OF THE ENERGIES OF GAMMA
RAYS FROM DECAY OF Ga^{66} (Project I-57)

R. E. Coté, R. Guso (Special Materials & Services), S. Raboy,

R. A. Carrigan, Jr., † A. Gaigalas, † R. B. Sutton, † and

C. C. Trail †

Nucl. Phys.

* The University, Manchester, England.

† Carnegie Institute of Technology.

† Brooklyn College.

RELATIVISTIC COMBINATION OF INTERNAL AND SPIN SYMMETRIES
IN S-MATRIX FORMULATION (Project V-42)

H. Ekstein

Phys. Rev.

POLARIZATION AND DIFFERENTIAL CROSS SECTIONS IN THE
SMALL-ANGLE SCATTERING OF NEUTRONS BY URANIUM

A. J. Elwyn, J. E. Monahan, R. O. Lane, A. Langsdorf, Jr.,
and F. P. Mooring (Project I-18)

Phys. Rev. (18 February 1966)

ENERGY LEVELS IN Sc^{49} FROM $\text{Ca}^{48}(\text{He}^3, d)\text{Sc}^{49}$, AND OTHER
REACTIONS PROCEEDING FROM Ca^{48} (Project I-23)

J. R. Erskine, A. Marinov, and J. P. Schiffer

Phys. Rev. (18 February 1966)

INELASTIC ALPHA SCATTERING AND ASSOCIATED GAMMA RADIA-
TION. II (Project V-3)

D. R. Inglis

Phys. Rev.

THE DYNAMO MODEL, FIELD REVERSAL, AND POLAR WANDERING

D. R. Inglis (Unattached)

J. Geomagnetism and Geoelectricity (Japan)

MULTI-BARYONS AND MANY-BODY FORCES (Unattached)

K. Just

Nuovo Cimento

MEAN RESIDENCE TIMES OF ALKALI IONS ON POLYCRYSTALLINE
WOLFRAM SURFACES AS STUDIED WITH A PULSED-MOLECULAR-
BEAM MASS SPECTROMETER (Project II-22)

M. Kaminsky

Ann. Physik

THE ANGULAR MOMENTUM-DEPENDENCE OF THE NUCLEAR LEVEL
DENSITY (Project V-16)

D. W. Lang

Nucl. Phys.

MEASUREMENTS OF NEUTRON CROSS SECTIONS OF Fe, Al, AND
 CF_2 BY A RATIO METHOD (Project V-17)

A. Langsdorf, Jr., J. E. Monahan, R. O. Lane, and A. J. Elwyn

Phys. Rev. (18 February 1966)

PERSONNEL CHANGES IN THE ANL PHYSICS DIVISION

NEW MEMBERS OF THE DIVISION

Staff Members

Dr. Arnold R. Bodmer. [REDACTED]

[REDACTED]
[REDACTED]
[REDACTED]
[REDACTED]

Ph.D., Manchester, 1953. He has been a Resident Research Associate in the Physics Division since 18 October 1963. He became a permanent staff member on 1 September 1965 and will continue his work on theoretical nuclear structure and hypernuclei.

Dr. G. C. Morrison. [REDACTED]

[REDACTED]
[REDACTED]
[REDACTED] Ph.D., University of Glasgow, 1957. He joined the Physics Division on 27 May 1965 to work on nuclear reactions and nuclear structure at the Tandem.

Dr. G. T. Wood. [REDACTED]

[REDACTED]
[REDACTED]
[REDACTED] 1. [REDACTED]
[REDACTED] Ph.D., Washington University, St. Louis, 1956. He joined the Physics Division on 2 August 1965 and is working

on internal-conversion electron spectroscopy with a 6-gap "orange" beta-ray spectrometer.

Resident Research Associates

Dr. A. E. Blaugrund, Weizmann Institute of Science, Rehovoth, Israel.

Doppler-shift measurements of lifetimes of nuclear levels; investigation of the decay schemes of Cu isotopes; determination of the conversion coefficient and E3 component of the 13-keV transition in Sc^{45} . Came to Argonne on 31 August 1965.

Dr. James T. Cushing, Imperial College, England. Internal symmetries and analyticity. Came to Argonne on 7 September 1965.

Dr. Cecil F. Dam, Cornell College. Working with S. B. Burson on γ - γ angular correlations. He is also the ACM-ANL supervisor under the sponsorship of the Office of College and University Cooperation. Came to Argonne on 7 June 1965.

Dr. Ben Day. Investigation of the shell-model potential in the nuclear surface region by means of Brueckner theory. Came to Argonne on 13 September 1965.

Dr. W. V. Prestwich, McMaster University, Hamilton, Ontario, Canada. Resonance capture and muonic x-ray experiments. Came to Argonne on 1 November 1965.

Dr. Esther L. Segel, Illinois Institute of Technology. Mössbauer analysis of meteorites. Returned to Argonne on 20 December 1965.

Resident Research Associates (Post-Doctoral)

Dr. Erhard Bieber, Physics Department, Technische Hochschule München, Germany. Decay of polarized neutrons. Came to Argonne on 1 November 1965.

Dr. Donald Blatchley, University of Iowa. Decay properties of polarized neutrons and neutron-capture gamma rays. Came to Argonne on 1 September 1965.

Dr. Gert Roepstorff, University of Hamburg, Germany. Relativistic dynamics, especially the study of three-particle scattering and bound states. Came to Argonne on 1 September 1965.

Dr. Dave Youngblood, Rice University. Charged-particle research on the Van de Graaff accelerators. Came to Argonne on 7 September 1965.

Resident Research Associates (Summer)

Dr. G. B. Beard, Wayne State University. A study of neutron-capture γ rays. Came to Argonne on 21 June 1965.

Dr. Patrick D. Doherty, Santa Clara University. Measurements of spatial asymmetries in the decay of polarized neutrons. Came to Argonne on 21 June 1965.

Dr. Tom Ehlert, Marquette University. Studies of relative electron-impact ionization cross sections. Came to Argonne on 24 May 1965.

Dr. Helmut J. Fischbeck, University of Michigan. Measurement of internal-conversion coefficients in Co^{55} . Came to Argonne on 3 May 1965.

Dr. Michael A. Grace, Oxford University. The Mössbauer effect in Fe^{57} . Came to Argonne on 26 August 1965.

Dr. Mazhar Hasan, Northern Illinois University. Theory of admittance of high-frequency gas discharges. Came to Argonne on 1 June 1965.

Dr. Chava Lifshitz, Hebrew University, Jerusalem. Photoionization and/or electron impact with energy selector. Came to Argonne on 30 June 1965.

Dr. Harry J. Lipkin, Weizmann Institute of Science, Rehovoth, Israel. Higher symmetries of elementary particles. Returned to Argonne on 2 July 1965.

Dr. Bernard Margolis, McGill University, Montreal, Quebec, Canada. Nuclear structure and reactions and also electron scattering. Came to Argonne on 1 July 1965.

Dr. P. P. Singh, Indiana University. Alpha capture in the E1 giant resonance. Returned to Argonne on 10 June 1965.

Dr. L. J. Tassie, Australian National University, Canberra, Australia.

Magnetic monopoles and electron scattering of nuclei.

Returned to Argonne on 1 July 1965.

Dr. Carroll C. Trail, Brooklyn College. Studies of muonic x rays.

Returned to Argonne on 21 June 1965.

University Users of the ANL Tandem

Mr. Bryce Bardin, Indiana University. Short nuclear lifetimes by Doppler-shift techniques. Work initiated on 29 October 1965.

Dr. Douglas Cline, University of Rochester. Decay scheme of Sc^{42} from the $\text{Ca}^{40}(\text{He}^3, \text{p}\gamma)\text{Sc}^{42}$ reaction. Work initiated on 3 August 1965.

Dr. Harry Gove, University of Rochester. Decay scheme of Sc^{42} from the $\text{Ca}^{40}(\text{He}^3, \text{p}\gamma)\text{Sc}^{42}$ reaction. Work initiated on 5 August 1965.

Mr. David W. Grissmer, Purdue University. Multiple Coulomb excitation and the reorientation effect. Work initiated on 22 October 1965.

Mr. John Kroepfl, Indiana University. Short nuclear lifetimes by Doppler-shift techniques. Work initiated on 29 October 1965.

Dr. Linwood L. Lee, State University of New York. Decay scheme of Sc^{42} from the $\text{Ca}^{40}(\text{He}^3, \text{p}\gamma)\text{Sc}^{42}$ reaction. Work initiated on 27 December 1965.

Mr. Murray Moinester, University of Rochester. Magnetic-spectrograph studies of (He^3, α) and (He^3, d) reactions. Work initiated on 24 June 1965.

Mr. Bruce A. Watson, Indiana University. Short nuclear lifetimes by Doppler-shift techniques. Work initiated on 29 October 1965.

Resident Student Associates (Thesis)

Mr. David Borlin, graduate student, Washington University. Working with T. H. Braid on elastic scattering from heavy elements and on (He^3, α) reactions. Came to Argonne on 18 October 1965 under the sponsorship of the National Science Foundation.

Mr. Richard E. Snyder, graduate student, Wayne State University. Working with S. Ruby on the Mössbauer effect in Sb^{121} . Came to Argonne on 8 September 1965.

Resident Student Associates (Summer)

Mr. Michael D. Crisp, graduate student, Washington University, St. Louis, Mo. Working with R. K. Smither on data analysis and construction of a control circuit for the bent-crystal spectrometer. Came to Argonne on 1 June 1965.

Mr. George Rieke, graduate student, Harvard University, Cambridge, Massachusetts. Working with G. J. Perlow on calculations on the feasibility of an experiment on time reversal. Came to Argonne on 21 June 1965.

Student Aides (ACM)

Mr. Douglas Bayer, Knox College. Working with W. A. Chupka on mass spectrometric study of collision-induced dissociation. Came to ANL on 12 July 1965.

Miss Nancy M. Uss, Knox College. Working with A. J. Hatch on the use of Langmuir dc probes in high-frequency discharge plasmas. Came to ANL on 12 July 1965.

Co-op Technicians

Mr. R. Michael Barnett, Antioch College, Yellow Springs, Ohio. Working with S. Ruby on the Mössbauer effect in Sb. Came to ANL on 20 September 1965.

Mr. Douglas Carpenter, Antioch College, Yellow Springs, Ohio. Working with L. Meyer-Schützmeister on angular correlation on the reaction $\text{Mg}^{24}(\text{He}^3, \alpha\gamma)\text{Mg}^{23}$. Came to ANL on 27 September 1965.

Mr. Linden Davis, Northwestern University, Evanston, Illinois. Working with J. P. Schiffer on data reduction for charged-particle experiments. Came to ANL on 14 June 1965.

Mr. Roger A. Hale, University of Illinois, Chicago Circle Campus. Working with J. P. Schiffer on an analysis of background counts from spectra obtained from the multichannel analyzers. Came to ANL on 27 December 1965.

Miss Priscilla Magalhaes, University of South Florida, Tampa. Working with R. O. Lane on data processing for the neutron polarization experiment. Came to ANL on 30 August 1965.

Mr. Edward J. Moore, University of Detroit. Working with J. P. Schiffer on data reduction for charged-particle experiments. Came to ANL on 24 May 1965.

Student Aides (Summer)

Mr. Thomas W. Burrows, University of California, Berkeley. Working with J. R. Erskine on charged-particle reactions in $\text{Th}^{230}(\text{d}, \text{p})\text{Th}^{231}$, $\text{U}^{234}(\text{d}, \text{p})\text{U}^{235}$, and $\text{Pu}^{240}(\text{d}, \text{p})\text{Pu}^{241}$ with the more recent theories of the deformed nucleus. Came to ANL on 15 June 1965.

Mr. Paul S. Eastman, St. Olaf College, Northfield, Minnesota. Working with M. Kaminsky on secondary electron emission from Al and Cu monocrystals under high-energy ion impact. Came to ANL on 1 June 1965.

Mr. Michael R. Gardner, Reed College, Portland, Oregon. Working with R. E. Segel on experiments on radiative capture of p, α, γ etc. at the tandem Van de Graaff. Came to ANL on 8 June 1965.

Mr. Leonard Olson, University of Illinois. Working with F. J. Lynch on programming for ASI computation of crystal planes involved in blocking of particles scattered from lattice sites. Came to ANL on 10 June 1965.

Mr. Richard Ostermeier, University of Illinois, Chicago Circle Campus.

Working with D. S. Gemmell on phase-shift analysis of elastic scattering of alpha particles from Li^6 . Came to ANL on 15 June 1965.

Mr. David Wineland, Harvard University, Cambridge, Massachusetts.

Working with L. L. Lee, Jr., on analysis of nuclear-reaction data. Came to ANL on 17 June 1965.

Technicians

Mr. Odessa J. Clayton joined the Physics Division on 19 May 1965 to work with T. H. Braid.

Mr. Jeffrey Franklin joined the Physics Division on 28 June 1965 to work with R. E. Segel.

Mr. Andrew C. Jorgensen joined the Physics Division on 21 June 1965 to work with J. R. Wallace.

Mr. Larry Marek joined the Physics Division on 13 December 1965 to work with J. R. Wallace.

Mr. Walter L. Schubert joined the Physics Division on 20 September 1965 to work with D. S. Gemmell.

Secretaries

Mrs. Marjorie Schmidt returned to the Physics Division on 26 July 1965 as secretary to B wing.

Miss Karen Thayer joined the Physics Division on 14 June 1965 as secretary to F wing and to assist in B wing.

Clerk

Mrs. Jacqueline Smith joined the Physics Division on 1 September 1965 to work with C. Egglar.

PROMOTION

Mr. Charles W. Schmidt, who has been with the Physics Division since 1 September 1964 as a technician working with D. C. Hess and D. von Ehrenstein, has been promoted to a scientific assistant on 8 November 1965.

LEAVES OF ABSENCE

Dr. Joseph Berkowitz left ANL on 1 September 1965 on a Guggenheim fellowship for one year at the Physikalisches Institut der Universität, Freiburg, W. Germany for mass-spectrometric investigations to clarify the theory of unimolecular decay processes.

Dr. S. B. Bårson left ANL on 15 August 1965 for one year at the Institute for Nuclear Research, Amsterdam, Netherlands for a spectroscopic investigation of the excited states of selected odd-odd nuclei.

Dr. Stanley Cohen left ANL on 5 September 1965 for one year at the Japanese Atomic Energy Research Institute and the Institute for Nuclear Studies of the University of Tokyo on a grant from the National Science Foundation for theoretical studies of nuclear structure.

Dr. Harold E. Jackson left ANL on 1 October 1965 for one year at the Center for Nuclear Studies, Saclay, France to study neutron-induced nuclear reactions by means of an electron linac.

Dr. Richard S. Preston left ANL on 1 September 1965 for a year at A. E. R. E. , Harwell, England, to work with the Mössbauer group on investigation of Mössbauer spectra of magnetic materials in the vicinity of their magnetic ordering temperatures.

PART-TIME APPOINTMENTS

Dr. Arnold R. Bodmer started teaching part time at the University of Illinois, Chicago Circle Campus, on 1 September 1965.

Dr. David R. Inglis taught a course at the University of Chicago from 4 October 1965 through 18 December 1965.

Dr. Malcolm H. Macfarlane started teaching part time at the University of Illinois, Urbana, on 16 September 1965 and will continue through 31 January 1966.

DEPARTURES

Dr. A. J. F. Boyle, resident research associate from the University of Western Australia has been at Argonne since 1 January 1965. He has collaborated with G. J. Perlow on the Mössbauer effect in Cs^{133} , electron spin relaxation, and the Mössbauer effect. He terminated at ANL on 30 June 1965 to return to the Physics Department, University of Western Australia, Nedlands, Western Australia.

Mr. Merle T. Burgy has been on the staff of the ANL Physics Division since 1946. He has worked on the polarization of neutrons, on the neutron-proton scattering amplitude, on the cross sections for stopping heavy ions in gases (Project I-15), on the spin-momentum correlation in the beta decay of polarized Li^8 nuclei (Project I-121), and on the symmetry properties of the decay of polarized neutrons (Project I-123). He terminated at ANL on 17 November 1965.

Mr. Louis J. Chiricotti, technician, has been in the Physics Division since 19 June 1962. He terminated on 13 December 1965.

Mr. Richard S. Cox, resident student associate (thesis) from Northwestern University has been at Argonne since 1 February 1965. He has collaborated with L. L. Lee, Jr., and J. P. Schiffer on analysis of (d,p) and (d,n) reactions. He terminated at ANL on 9 April 1965 to return to Northwestern University.

Mr. Teymoor Gedayloo, resident research associate from Lawrence College has been at Argonne since 1 July 1963. He has collaborated with S. B. Burson on beta-ray spectroscopy and he has been the supervisor of the ACM students. He terminated at ANL on 20 August 1965 to go to the California State Polytechnic College, San Luis Obispo.

Dr. Morton Hamermesh has been at Argonne since June 1948. He has worked on neutron polarization, accelerator design, Mössbauer effect, symmetry principles, and the neutron-electron interaction. He terminated at ANL on 1 July 1965 to become chairman of the Physics Department at the University of Minnesota, Minneapolis, Minnesota.

Dr. Harnam S. Hans, resident research associate from Texas A and M University has been at Argonne since 16 September 1963. He has worked on resonance scattering of neutron-capture gamma rays with the chopper group. He terminated at ANL on 28 May 1965 to go to the Kurukshetra University, Kurukshetra, Punjab, India.

Dr. Juergen Heberle has been on the staff of the ANL Physics Division since August 1957. He has worked on intense magnetic fields produced by superconducting magnets and on the Mössbauer effect. He terminated at ANL on 2 September 1965 to go to Clark University, Worcester, Massachusetts.

Dr. Linwood L. Lee, Jr., has been on the staff of the ANL Physics Division since 1 November 1954. He has studied nuclear structure with the tandem and 4.5-MeV Van de Graaff generators. He terminated at ANL on 31 August 1965 to go to the Physics Department, State University of New York at Stony Brook.

Mrs. Judy Maier, clerk, has been in the Physics Division since 4 May 1964. She terminated on 7 September 1965.

Dr. Amnon Marinov, resident research associate (post-doctoral) from the Hebrew University, Jerusalem, Israel, has been at Argonne since 5 June 1963. He has done research at the 12-MeV Tandem Van de Graaff and at the 4.5-MeV Van de Graaff. He terminated at ANL on 30 September 1965 to return to the Hebrew University in Jerusalem.

Dr. Sol Raboy has been on the staff of the ANL Physics Division since October 1951. He has worked on nuclear properties by muonic x-rays, capture gamma rays, and angular correlation. He terminated at ANL on 27 August 1965 to go to Harpur College, State University of New York, Binghamton, New York.

Mr. James Smith, technician, has been in the Physics Division since 26 September 1963. He terminated on 7 September 1965.

Mrs. Jeanette Vendel, secretary to F wing, has been in the Physics Division since 11 November 1963. She terminated on 17 May 1965.

Transfers

Mr. Robert Petersen, technician in Physics since 1958, transferred to the Chemistry cyclotron on 8 September 1965.

Mrs. Paulette Spink, technician in Physics since 16 September 1963,
transferred to High-Energy Physics on 23 August 1965.

Mr. Albert Vandergust, technician in Physics since 1958, transferred
to the Metallurgy Division on 25 October 1965.

Mrs. Catherine Yack, secretary since 1958, transferred to the
Radiological Physics Division on 19 July 1965.