136.25 kev ($g_{7/2}$, 7/2)9/2; intrinsic excitation state at 482.0 kev ($d_{5/2}$, 5/2)5/2; intrinsic state at 615.0 kev ($d_{3/2}$, 1/2)1/2; first rotational state at 618.9 kev ($d_{3/2}$, 1/2)3/2 or intrinsic state. If the 618.9-kev level is a first rotational state, the small level spacing of 3.9 kev is striking but not uncommon for spin 1/2 ground states. The 476-kev line is probably a parity-change transition and might start from an odd-parity state at 958 kev which is fed by an allowed low-energy beta group from Hf^{181}. The spin assignment obtained by angular correlation measurements by Heer *et al.*[2] for some of the levels is in agreement with the present result although these authors have not taken into account the presence of the 136.86-kev line.[4]

The authors wish to thank Dr. J. W. M. DuMond for his interest in this work, Dr. S. A. Moszkowski for helpful discussions, and Mr. E. N. Hatch for aid in measurements with the gamma spectrometer.

1615 (1955)], are: the configuration in the spherical limit, the component of the angular momentum along the symmetry axis, and the nuclear spin.

[4] *Note added in proof.*—P. H. Stelson and F. K. McGowan (meeting of the Southeastern Section of the American Physical Society, March 29–31, 1956) have reported a 5/2+ and a ½+ spin for the 482- and the 615-kev state respectively from polarization experiments.

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Neutron Scattering at 2.45 Mev by a Time-of-Flight Method*

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Results have been obtained by a pulsed-beam time-of-flight method for the cross sections for excitation of various levels in many nuclides by inelastic scattering at 90 degrees. The incident neutrons had a mean energy of 2.45 Mev and a spread of plus and minus 100 kev. Detailed angular distributions are given for the neutrons of inelastic scattering, for the accompanying de-excitation gamma rays, and for the elastically scattered neutrons for iron, nickel, and titanium. Such results are also given for iron and titanium for a mean incident energy of 2.25 Mev. The angular distributions indicate that for these nuclides and excitations the statistical assumption is not applicable to states in the compound nucleus. Results on the spectrum of neutrons inelastically scattered by gold may be fitted over a limited range by an effective nuclear temperature of 0.3±0.03 Mev. The same temperature describes the data on uranium 238 after subtraction of a fission neutron spectrum.

INTRODUCTION

THE significance of inelastic neutron scattering for understanding the mechanism of nuclear reactions is well known.[1] In particular the question of whether the neutron interacts directly with an individual bound nucleon or forms a compound nucleus may be tested by determining whether the angular distribution of the inelastically scattered neutrons is sensitive to the energy of the incident neutron.[2]

On the basis of the compound nucleus assumption together with the assumption that the excited states in the compound nucleus interfere in a random manner it has been possible to relate the angular distribution of the inelastically scattered neutrons corresponding to excitation of a particular state in the residual nucleus to the spin and parity of the level excited.[3] Further, if the levels in the residual nucleus are spaced sufficiently closely again the angular distribution of the scattered neutrons may be predicted (isotropic), and the shape of the energy distribution of the inelastically scattered neutrons may also be predicted.[3,4] Finally, inelastic neutron scattering provides a tool for locating energy levels in the residual nucleus, particularly in heavy nuclei where the detection of de-excitation gamma rays is sometimes difficult because of the extra complexity of the spectrum due to cascading effects, and the high Coulomb barrier makes it difficult to use charged particles.

An important obstacle to detailed study of the foregoing problems has been the lack of a rapid and efficient means of studying neutron spectra. Results have been obtained for 14-Mev neutrons by using an associated-particle-time-of-flight[5] technique. However, 14 Mev is a primary energy for which $(n,2n)$ reactions are a complicating feature, and the difficulty of extending the associated particle method to lower energies is a serious limitation of the method.

Emulsion methods have been used with considerable

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

[1] D. C. Peaslee, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1955), Vol. 5, p. 99.

[2] Proceedings of Brookhaven Conference, January 24 to 26, 1955, Brookhaven National Laboratory Report BNL-331 (unpublished), particularly p. 85, comment of R. M. Eisberg.

[3] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952).

[4] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).

[5] G. K. O'Neill, Phys. Rev. **95**, 1235 (1954).

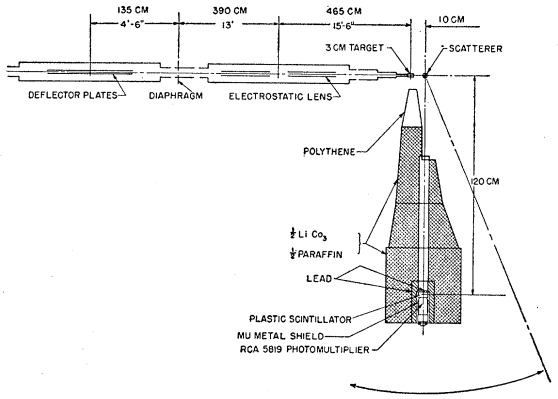

FIG. 1. Schematic diagram of the physical layout of the apparatus for measurement of neutron scattering by the pulsed-beam time-of-flight method.

success.[6] These methods have indeed been the most fruitful to date, but are objectionably slow. Thus the object underlying the development work on an improved apparatus has been the achievement of a system which is suitable for rapid data taking, is versatile, and compares with the resolution and accuracy of the emulsion technique. The method which has evolved depends on producing neutrons in bursts of millimicrosecond (hereafter abbreviated mμsec) duration by delivering the output of an electrostatic generator to a neutron-producing target in bursts of that duration. Details of the apparatus have already been given in several places.[7,8] In this paper only a general description of the apparatus will be given; emphasis will be on the results on inelastic scattering together with such data on the gamma rays of inelastic scattering and on elastic scattering as have been obtained incidentally to the data of primary interest.

EXPERIMENTAL ARRANGEMENT

The large Los Alamos Van de Graaff accelerator has been fitted with a pair of electrostatic deflector plates (Fig. 1) located close to the point at which the beam emerges from the mass- and energy-analyzing magnet. Radio-frequency voltage of 3.7 Mc/sec is applied to the plates, causing the charged particle beam to be swept over a slit 4.5 feet away. The beam which goes through the slit is focused on the target 30 feet away by means of an electrostatic quadrupole lens. Thus, charged particles are delivered to the target twice per rf cycle on a duty cycle of a few percent, giving bursts of about 3 mμsec duration, with an average current of 0.5 μa. The target is 3 cm long filled with tritium to a pressure of 120 cm of Hg. Monoenergetic neutrons are made by the $T(p,n)He^3$ reaction. The neutrons are scattered by a cylindrical scatterer whose center is about 10 cm from the center of the target, and the scattered neutrons are observed by a shielded detector at a distance which may be varied. In these measurements the flight path was usually between 120 and 160 cm. The time of arrival of a neutron at the detector is measured relative to a pulse derived once per cycle from the rf voltage which drives the deflector plates. This time interval is converted to a pulse height, and the pulse height is measured by means of a 100 channel pulse-height analyzer.

The detector is a plastic scintillator furnished by the Pilot Chemical Company, Waltham, Massachusetts. It is one and one-half inches thick, two inches in diameter, and is cemented to a RCA-5819 photomultiplier. The relative efficiency of this detector is shown in Fig. 2 as a function of neutron energy for two biases. The upper bias corresponds to a total counting rate due to photomultiplier noise and cosmic rays of about three counts per second; the lower bias corresponds to a rate of six per second. At the lower bias the detector is usable down to an energy between 300 and 500 kev. The sensitivity curve of Fig. 2 was determined by measuring the yield of the $T(p,n)He^3$ reaction as a function of neutron energy, and comparing the result with the yield of the reaction as measured with a counter telescope and hydrogenous radiator.[9] This method was applicable to the region above 1.2-Mev neutron energy. Below this energy the comparison was made with the relative yield of the $T(p,n)He^3$ reaction as determined with a long counter.[10]

Most of the results to be reported were obtained at a proton energy of 3.50 Mev. Taking account of the energy loss in the target window, which was of nickel 0.15 thousands of an inch thick, and of the thickness of the gas target, the average energy of the neutrons at zero degrees was 2.475 Mev. Because of the finite angle subtended by the scatterer at the target and the dependence of the neutron energy on angle the average

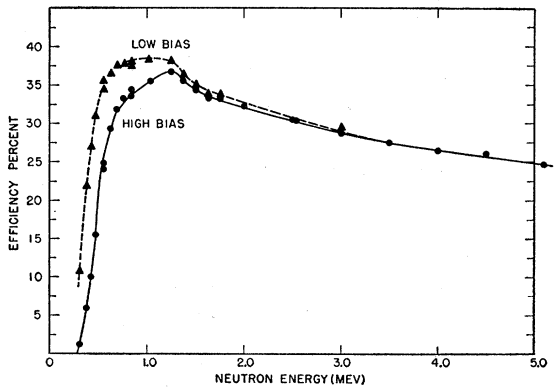

FIG. 2. Efficiency of the time-of-flight detector is shown as a function of neutron energy for two biases.

[6] E. R. Graves and L. Rosen, Phys. Rev. **89**, 343 (1953).
[7] L. Cranberg, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, Switzerland, 1955* (United Nations, New York, 1956), Vol. 4, Paper P/577.
[8] Weber, Johnstone, and Cranberg, Rev. Sci. Instr. **27**, 166 (1956).
[9] Haddad, Perry, and Smith (private communication).
[10] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).

energy of the neutrons incident on the scatterer was 2.45 Mev.

The most important factor in the energy spread was the target thickness, which amounted to 105 kev. The maximum angle subtended by the scatterer at the target was 15 degrees. This corresponds to a spread in energy of the incident neutrons of 70 kev. The straggling in the target window accounted for an estimated 30-kev spread, so that the spread in energy of the neutrons incident on the scatterer may be represented as a triangle whose base was approximately 200 kev wide.

The detector used in this work is sensitive to gamma rays as well as to neutrons, so that at the position of the time scale corresponding to the velocity of light there appears a line corresponding to the gamma rays of inelastic scattering and capture. The gamma ray, in combination with the elastic peak, proves to be useful in calibrating the time scale once the linearity of the time-to-pulse-height conversion has been established. Details of the technique for measuring the linearity of the conversion have been given elsewhere.[8] It suffices to note here that the accuracy with which a well resolved line may be located is about 0.5 mμsec, as determined from measurements on known lines.

The method of determining cross sections depends on a comparison with the n-p cross section as given previously[11] for the case of the 850-kev level in iron. In the following the cross section for iron is used as a sort of secondary standard, and all other cross sections

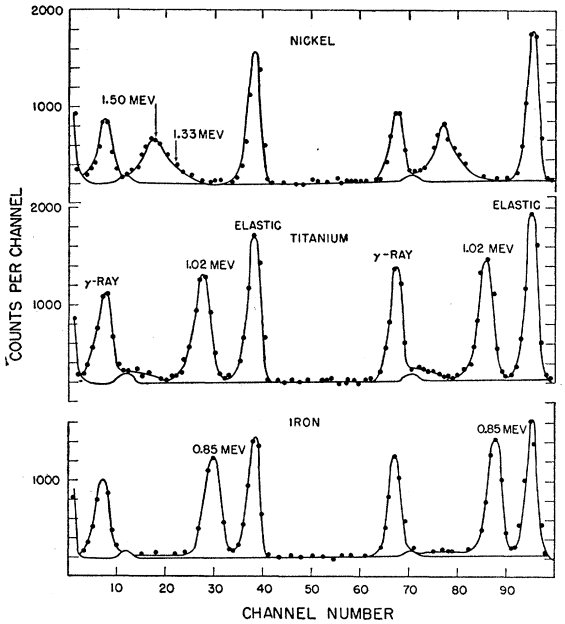

FIG. 3. Time spectra obtained at 90 degrees for neutron scattering at 2.45 Mev from nickel, iron, and titanium. The solid line under each spectrum is the background observed in the absence of the scatterer. The gamma rays, elastically scattered neutrons, and the principle groups of inelastically scattered neutrons are identified. A flight path of 1.5 meters was used.

[11] L. Cranberg and J. S. Levin, Phys. Rev. **100**, 434 (1955).

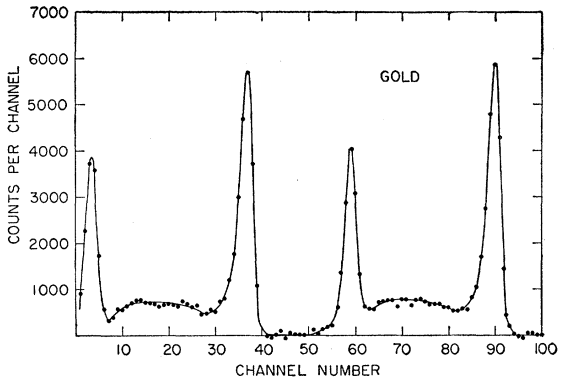

FIG. 4. Time spectrum obtained at 90 degrees for neutron scattering at 2.45 Mev from gold. The "sample out" background has been subtracted. The detector bias used to obtain this spectrum corresponds to the lower curve in Fig. 2, and the flight path was 1.2 meters.

have been determined relative to it, correcting for the energy dependence of the sensitivity of the detector by use of the curve in Fig. 2.

RESULTS

The data obtained fall into three general categories. First, a survey was made consisting of an examination of the spectra from each of about 50 elements at one scattering angle, ninety degrees. Second, a number of elements were selected for careful study as a function of angle to determine the angular distribution of the inelastically scattered neutrons which correspond to the excitation of a particular level. Third, for the case where effectively a continuum of levels is excited in the residual nucleus an examination was made of the shape of the spectrum of the inelastically scattered neutrons at 90 and at 160 degrees.

1. Survey

The elements included in the survey were essentially all those which were conveniently available in the required quantity, which was in the neighborhood of 1 mole. In most cases the samples were available in elemental form. The exceptions were N, F, and Cl, which were used in the form of melamine (CH_2N_2), CF_2, and CCl_4. Neither carbon nor hydrogen should affect the results for inelastic scattering at the angle and primary energy used in the survey.

Most of the samples were in the form of hollow cylinders 2 inches long, with an i.d. of $\frac{3}{8}$ inch and an o.d. of $\frac{3}{4}$ or 1 inch. The choice of o.d. was based on the desire to have samples of roughly equal transmission so that attenuation of the neutron beam and multiple scattering would be roughly the same in all the samples. The transmission of the samples was about 75%.

A Monte Carlo calculation was made of the scattering by the $\frac{3}{4}$-inch o.d. iron sample, which is typical of the samples used in the survey. This showed that, averaged over angle, the double elastically scattered

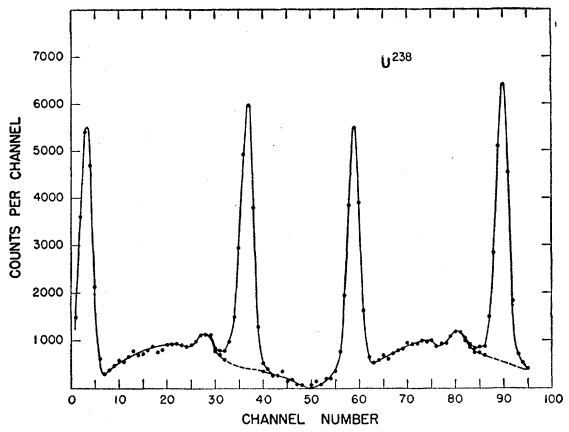

FIG. 5. Time spectrum obtained at 90 degrees for neutron scattering at 2.45 Mev from uranium 238. The "sample out" background has been subtracted; the detector bias corresponds to the lower curve in Fig. 2, and the flight path was 1.2 meters.

neutrons detected were 11% of the singly scattered neutrons, and that 25% of the inelastically scattered neutrons had experienced one additional elastic scattering. The calculation also showed that the method previously[11] used to correct for multiple scattering and beam attenuation to obtain cross sections for inelastic scattering was correct to about 3%.

The results of the survey fall into three general categories. First, in the case of nuclides up to about copper and including the magic nuclides, the spectra obtained are strongly structured, and most, if not all the levels which have been previously reported are observed if they are excited with sufficient strength. At the other extreme, and this is true in general for the heaviest, nonmagic elements, the only conspicuous structures are those which correspond to elastic scattering and to the gamma rays of inelastic scattering. In the time range corresponding to neutrons which have been scattered inelastically, only a structureless continuum is observed. In the intermediate range of nuclear masses, structures are observed superimposed on the continuum.

Figure 3 illustrates the time spectra obtained for iron, nickel, and titanium as examples of the first type of result. Time increases to the left in these figures, and the base line represents the spectrum observed without scatterer. Figure 4 shows the result for gold as an example of a continuum. Unexpectedly, the spectrum of U^{238} proved to fall in the intermediate category, and it is shown in Fig. 5. It will be noted that in each spectrum there is a duplicate presentation. This arises from the fact that only one fiducial pulse is generated per rf cycle whereas two neutron bursts occur in the target. In each case the elastically scattered neutrons and the gamma rays associated with inelastic scattering are clearly evident. Capture and other reactions contribute also to the gamma-ray peak, but usually not significantly.[12–14] In the case of U^{238}, since the energy of the primary neutrons is above the fission threshold, the fission gamma rays must be contributing to the height of the gamma-ray peak, and there is a continuum of fission neutrons which extends above the energy of the primary neutrons.

Table I gives a summary of the levels which have been observed and the cross sections for their excitation at 2.45 Mev. An asterisk indicates levels which have not been reported hitherto, or about which there has been considerable uncertainty. In general the accuracy of the energy assignment is less than that obtained by other methods,[13–15] as is the resolution, except for the heaviest nuclides.

Because of the expected density of levels for the medium weight and heavy nuclides at the excitation energy used here, and the added complication introduced in some cases by the isotopic composition, it is unlikely that any of the new levels reported is indeed a single level. The exception to this is probably Pb^{206}.

TABLE I. Levels excited at 2.45 Mev at 90°. An asterisk indicates levels which have not been reported hitherto, or about which there has been considerable uncertainty.

Element	Energy (Mev)	Cross section millibarns/sterad	Element	Energy (Mev)	Cross section millibarns/sterad
F	1.46±0.03	23±3	Zn	1.08±0.04	62±4
	1.55±0.03	23±3			
			As	0.78±0.04	27±6
Na	0.46±0.05	50±10		*1.25±0.03	47±8
				*1.63±0.02	21±3
Mg	1.38±0.03	24±2			
			Se	0.66±0.05	64±8
Al	1.03±0.03	20±2		*1.50±0.03	43±5
P	1.25±0.03	51±7	Zr	0.94±0.04	23±2
Ti^{48}	1.02±0.03	85±3	Mo	0.83±0.04	42±4
				1.56±0.03	52±4
V	0.92±0.03	16±1			
	1.63±0.03	18±2	Cd	0.64±0.05	40±5
				*1.36±0.03	31±4
Cr	1.49±0.03	48±3		*1.49±0.03	31±4
Mn	0.98±0.04	20±2	Sn	1.24±0.03	47±3
	1.29±0.03	11±1			
	1.53±0.03	12±2	Te	0.72±0.05	55±6
Fe^{56}	0.86±0.03	85±3	Pb^{206}	0.84±0.04	51±6
				1.44±0.03	44±6
Co	1.20±0.03	38±5		*1.74±0.02	32±5
	1.51±0.02	34±4			
	1.75±0.02	12±2	Bi	0.93±0.04	30±3
				1.65±0.03	34±4
$Ni^{60,58}$	1.33, 1.49	55±3			
			U^{238}	*1.18±0.03	10±3
Cu	0.98±0.04	38±5			
	1.46±0.03	32±4			
	*1.62±0.03	13±3			
	*1.74±0.02	9±2			
	1.90±0.02	7±2			

[12] Hughes, Garth, and Levin, Phys. Rev. **91**, 1423 (1953).
[13] Scherrer, Allison, and Faust, Phys. Rev. **96**, 386 (1954).
[14] R. B. Day, Phys. Rev. **102**, 767 (1956).
[15] Day, Johnsrud, and Lind, Bull. Am. Phys. Soc. Ser. II, 1, 56 (1956).

The sample used was radiogenic lead enriched in the 206 isotope to 88%. From the low level density to be expected in this magic nuclide, it is probable that a single level has been resolved at 1.74 Mev. The experimentally observed width is consistent with this interpretation. Observation of these neutron groups confirms the level structure inferred by Day *et al.*[15] from observations of the gamma rays of inelastic scattering. In the case of U^{238} it seems unlikely, both from general considerations of level density and the width of the observed peak, that a single level has been resolved. It is preferable to say that a group of levels centering about 1.18 Mev, having a spread of 150 kev or less, is excited with substantially higher cross section than adjacent levels. The possibility that this anomalous peak is due to the decay of a metastable fission product by gamma emission has been checked by observing the time spectrum as a function of flight path. These observations confirm the interpretation of the structure as being due to neutrons.

Table I includes only those levels for which a cross section could be assigned with fair accuracy. Some levels were observed, e.g., the 300-kev level in vanadium known from other work,[13] in such close proximity to the elastic peak that although they contributed a marked widening of the elastic line an accurate cross section could not be determined. The data obtained on 90 degree differential elastic scattering cross sections are being prepared for future publication.

2. Individual Levels

From the survey it appeared that for a detailed and fairly accurate study of the dependence of inelastic scattering on angle only a small number of levels were suitable. This results from the fact that only the first few levels are excited with appreciable cross section at an energy of 2.45 Mev. However, low-lying levels are difficult to resolve from elastically scattered neutrons, particularly at forward angles where the differential elastic scattering cross section is so much larger than the differential inelastic cross section. These considerations narrowed the choice to elements with a high first-excited state and a predominant isotope, and the first choices were iron, titanium, nickel, and chromium. These cover a narrow range in mass, are even-even in the predominant isotopes, and have first excited states which are 2 plus and ground states which are zero plus. Although no detailed calculations have been made, it may be expected that if the assumptions of the Hauser-Feshbach theory are satisfied then the inelastically scattered neutrons corresponding to excitation of the first level in these nuclei would have similar angular distributions.

In the course of the measurements on chromium, it was found that at forward angles a strong neutron group appeared. This proved to be due to hydrogen impurity, and in the absence of a better sample chromium had to be dropped from the list of elements which were examined closely. The samples used for these measurements were checked spectrochemically and found to have less than 1% of solid contaminant. For nickel and titanium the observed neutron spectra can indicate objectionable (more than 1 atomic percent) hydrogen contamination clearly, and none was observed. Hydrogen was less easily detected in iron by this method because of the position of the dominant level. On this account two scatterers were used: one was Armco grade, and the other was dry machined from a high-purity, vacuum-melted sample supplied by the National Research Corporation. No difference was observed in the results obtained with the two scatterers.

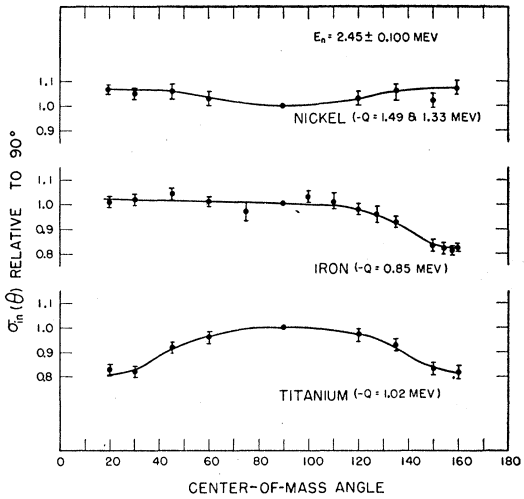

FIG. 6. Angular distribution of the inelastically scattered neutrons which correspond to the excitation of the 1.02-Mev level in Ti^{48}, the 850-kev level in Fe^{56}, and the 1.49- and 1.33-Mev levels in Ni^{58} and Ni^{60}, respectively. Results shown are relative to 90 degrees in the center-of-mass reference frame. The 90-degree isotopic cross sections, in barns/steradian, are as follows: Ti^{48}, 0.085±0.003; Fe^{56}, 0.085±0.003; and Ni^{58} and Ni^{60} combined 0.055±0.003.

Figure 6 shows the results obtained for the angular distributions of the inelastically scattered neutrons which excite the 1.02-Mev level in Ti^{48}, the 0.85-Mev level in Fe^{56}, and the levels in Ni^{58} and Ni^{60} which are known from other work[13] to be at 1.49 and 1.33 Mev, respectively. The latter two levels could not be resolved satisfactorily and the results hereafter quoted for nickel are the combined results for the two isotopes. The angular range covered is 20 to 160 degrees. The inelastic neutron yield is shown relative to 90 degrees; the 90-degree cross sections are given in the figure caption.

It is clear that contrary to expectation the result for each of these elements is different, and for the case of iron there is a definite lack of symmetry about 90 degrees. The possibility that any of the differences may have been influenced by some sort of instrumental effect is precluded by the fact that the data for iron were very carefully checked for reproducibility over a period of several months, and the usual procedure for

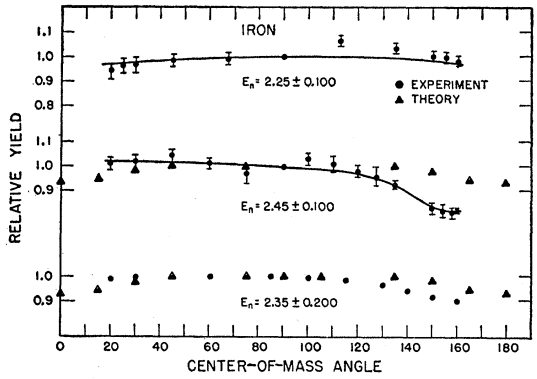

FIG. 7. Angular distributions of the inelastically scattered neutrons corresponding to excitation of the 850-kev level in Fe^{56} for incident energies of 2.25 and 2.45 Mev. Results shown are relative to 90 degrees in the center-of-mass system. The triangles represent the theoretical calculations of Emmerich normalized to the experimental data at 90 degrees. The bottom series of experimental points represents the average of the results for the two energies. The 90-degree isotopic cross section at 2.25 Mev is 0.080±0.004 barn/steradian.

taking the data for different elements was to run the various samples successively at a given angle. The only corrections to the raw data which were appreciable were corrections for the counting rate losses in the 100 channel pulse-height analyzer, and corrections for overlap of the tail of the elastic peak on the inelastic peak at the forward angles. Both of these corrections were greatest at the extreme forward angle. The counting rate loss correction amounted to a maximum of 15% and could be made to 1% by use of a discriminator whose upper and lower bounds were set to coincide with the range of pulse heights covered by the multichannel analyzer.

The correction for overlap was greatest for the case of iron because the level studied in that element lies lower than the levels studied in the other elements. The greatest correction for overlap was 12% and two methods of making the correction gave results which were consistent to better than 3%. In the first method the detector was turned to zero degrees and the line shape was obtained for the neutrons coming directly from the target. This method of determining the line shape should take care of all factors which contribute to the line shape for elastic scattering from a heavy element ($A>30$) except for two things: the effect of multiple scattering, and the effect of the larger energy spread in the primary neutron beam which the scatterer sees because it subtends a larger solid angle at the target than did the detector during the zero degree runs. These, however should have negligible effect on the correction. The other method of determining the detailed structure of the low-energy tail on the elastic line makes use of the fact that no level has yet been reported in nickel which is lower than 1.33 Mev. This suggests that the elastic peak for nickel is suitable for normalization purposes, and this method of normalization was also used.

No correction has been made in Fig. 6 for the effect of multiple scattering. By multiple scattering one means here the sequence of events "elastic-inelastic" and "inelastic-elastic" since in heavy elements these are energetically indistinguishable from single inelastic scattering. One expects that because elastic scattering is strongly forward in these measurements it will not strongly affect the angular distributions for inelastic scattering. This is particularly true also because of the small magnitude of the inelastic anisotropy expected and observed. This estimate of the situation was confirmed by the results obtained for an iron sample having a transmission of 60% compared to 75% for the sample used to obtained the data of Fig. 6. The relative yield at 160 degrees was reduced by not more than 3% from the value in Fig. 6.

The fact that the angular distributions obtained for the inelastically scattered neutrons in Fig. 6 were different from one another suggests either that the compound nucleus model fails to describe the situation adequately or that the levels in the compound state do not satisfy the requirement of the statistical theory. The most direct way of testing these alternatives is to check the dependence of the anisotropy on energy, since on the first alternative one expects little sensitivity to energy and on the second alternative the results should be energy-sensitive.[2] Accordingly the energy of the primary neutron beam was decreased by 200 kev, that is, by an amount equal to the spread in energy of the neutrons incident on the scatterer.

The results for iron at the lower energy are shown in Fig. 7 together with the result at the higher energy. It is clear that the angular distribution has changed appreciably, becoming essentially isotropic at the lower energy. Figure 7 also shows the results of a calculation of the angular distribution by Emmerich[16] on the basis of the Hauser-Feshbach theory using the

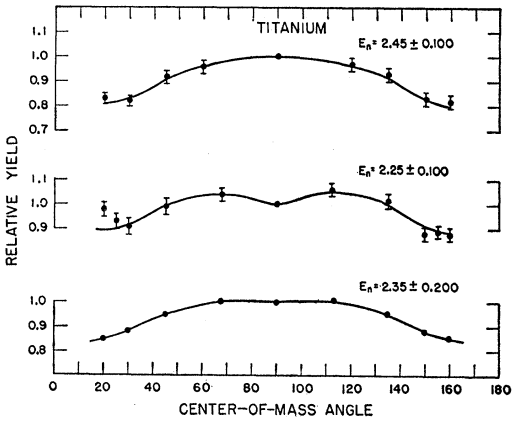

FIG. 8. Angular distributions of the inelastically scattered neutrons corresponding to excitation of the 1.02-Mev level in Ti^{48} for incident neutron energies of 2.25 and 2.45 Mev. The bottom curve is the average of the upper two curves. The 90-degree isotopic cross section at 2.25 Mev is 0.075±0.004 barn/steradian.

[16] W. S. Emmerich (private communication).

complex square-well parameters given in Fig. 11. The theoretical cross section at 90 degrees was about half the measured value. Theory and experiment have been normalized at 90 degrees in Fig. 7. The lowest sets of points in this figure show the result of averaging the data for the two energies and a repeat of the theoretical points. The discrepancy between theory and experiment has been noticeably reduced in the combined data.

Figure 8 shows the results for titanium for each of the two energies and for the two energies combined. The effect of energy change here is less marked than for iron, but there is a change with energy which is outside the errors of the measurements. No calculations have been made for this case. The data for nickel at the lower energy were not reliable because of overlap of the inelastically scattered neutrons on the gamma ray of the succeeding cycle.

From the observed neutron spectra for iron, nickel, and titanium and from what is known about the gamma rays from inelastic scattering and capture from other work[12–14] it is likely that about 90% of the gamma rays which are observed in the time spectrum correspond to de-excitation of the levels excited by the neutron groups which are observed to be predominant. For the case of iron this interpretation was further corroborated by the results of an absorption measurement on the gamma-ray line. A quarter of an inch thickness of lead was inserted midway between the scatterer and the detector and the effect on the height of the gamma-ray line was measured. The observed attenuation agreed within the 2% statistical uncertainty of the measurements with that calculated from the known attenuation coefficient of 850-kev gamma rays in lead.

Data on the angular dependence of the gamma-ray line are therefore of interest and these are shown in Fig. 9 for a neutron energy of 2.45 Mev and in Fig. 10 for 2.25 Mev. These were obtained simultaneously with the data on the neutrons. In all cases these distributions are symmetric about 90 degrees, as indeed they must be since they represent transitions between unmixed

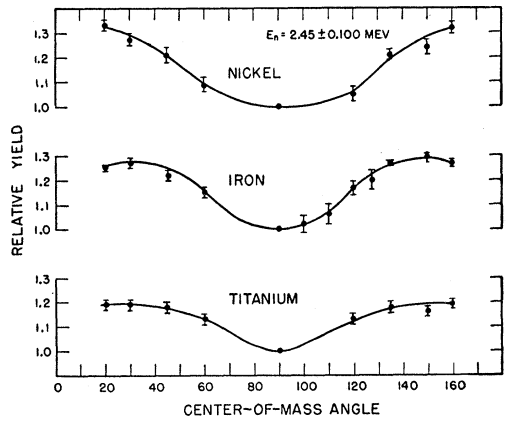

FIG. 9. Angular distributions of the yield relative to 90 degrees of gamma rays from iron, nickel, and titanium for a primary neutron energy of 2.45 Mev.

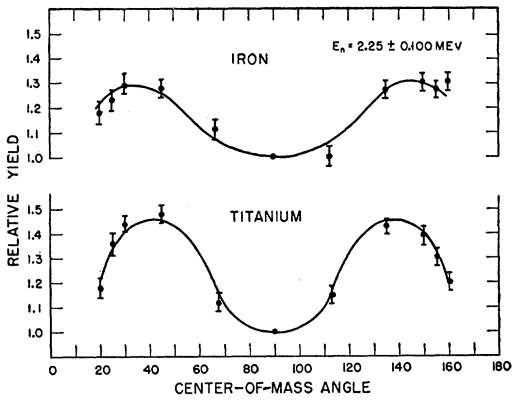

FIG. 10. Angular distributions of the yield relative to 90 degrees of gamma rays from iron and titanium for a primary neutron energy of 2.25 Mev.

states of definite spin and parity. This symmetry should not be influenced by multiple scattering.

The effect of multiple scattering on the anisotropy of these results should not be large for reasons similar to those given above for the inelastically scattered neutrons. By multiple scattering one means here mainly "elastic-inelastic" neutron events and "inelastic-Compton" events, where "Compton" refers to the scattering of gamma rays due to Compton effect. The maximum anisotropy observed with the iron scatterer with 60% transmission was only 4% less than for the 75% transmission sample.

The gamma-ray results also exhibit a sensitivity to nuclide and energy in circumstances in which such a result is unexpected if the assumptions of the statistical theory are applicable. It is nevertheless of interest to compare the general features of the results with the predictions of the theory for one case. The applicable theory here again is based on the Hauser-Feshbach theory[3] for the inelastically scattered neutrons. This, combined with a formalism due to Satchler,[17] has been used by Van Loef and Lind[18] to calculate the angular distribution of the gamma rays. The result given in Fig. 11 has been calculated by Emmerich[16] for iron at 2.5-Mev neutron energy. The neutron interaction is calculated on the basis of the optical model using the complex square-well parameters given in the figure. Values of $l \leq 2$ have been considered. It is clear that the calculated anisotropy is about twice that which is observed, although the general shape is similar to those measured.

At the same time that the foregoing data were obtained the yields of the elastically scattered neutrons were obtained as a function of angle. These data are shown for the two energies of the measurements for iron and titanium in Fig. 12. The results for nickel have also been obtained at 2.45-Mev energy and are very similar to those shown in Fig. 12. Compared to iron

[17] G. R. Satchler, Phys. Rev. **94**, 1306 (1954).
[18] J. J. Van Loef and D. A. Lind, Phys. Rev. **101**, 103 (1956).

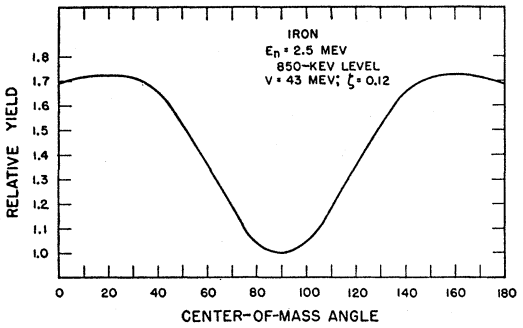

FIG. 11. Angular distribution of the yield relative to 90 degrees of the 850-kev gamma rays arising from inelastic scattering in Fe^{56} by neutrons of 2.5-Mev energy, as calculated by Emmerich. The complex square-well parameters used in the calculation are given in the figure.

the zero and 180 degree peaks are slightly reduced in intensity relative to the 90-degree yield; that is, the nickel data are slightly more isotropic, just as the iron result is slightly more isotropic than the titanium result. The data for iron at 2.45 Mev are in good agreement with those obtained by Walt and Beyster[19] at 2.50 Mev.

The similarity of the curves for the elastic scattering from these three elements is what one expects from the optical model.[20] On the other hand, the sharp drop for iron in the magnitude of the elastic scattering cross section for a 200-kev energy change shows that the compound elastic scattering is not negligible. The integral of the differential elastic scattering over solid angle gives 2.71 barns for iron at 2.45 Mev and 2.05 barns at 2.25 Mev. Combining these results with the integral of the differential inelastic scattering for iron gives a total cross section of 3.65±0.2 barns at 2.45 Mev and 2.95±0.2 barns at 2.25 Mev. This compares with 3.52±0.1 barns and 3.05±0.1 barns for the two energies as determined by a transmission measurement under the same conditions of target and bombarding proton energy as were used for the scattering data. This agreement of the calculated and directly measured total cross sections indicates that systematic errors in the differential measurements and the corrections thereto are within the estimated errors.

The results at the two energies as well as the results for different but similar nuclides at one energy strongly suggest that for the range of primary neutron energy and mass number considered here the compound nucleus concept may be an appropriate one, but the requirements of the statistical assumption regarding the levels in the compound state are not satisfied.

Only in one case (iron at 2.45 Mev) is there clear

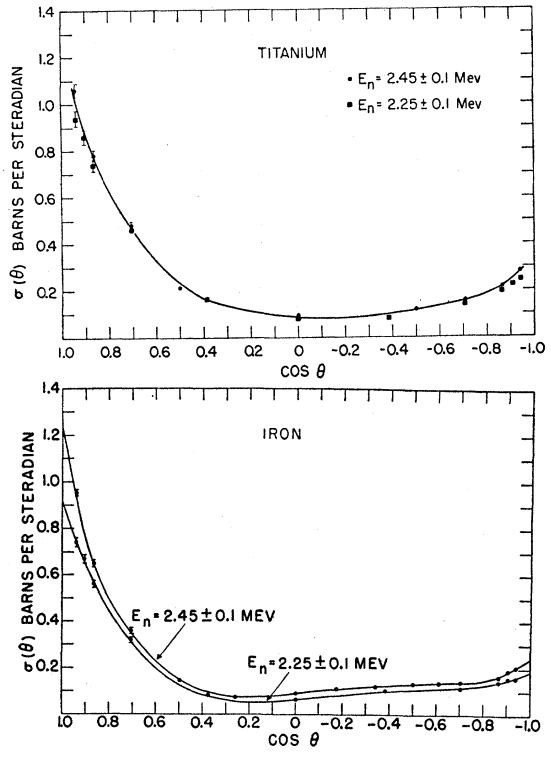

FIG. 12. Differential elastic scattering cross sections measured for iron and titanium at 2.25 and 2.45 Mev as a function of the cosine of the center-of-mass angle.

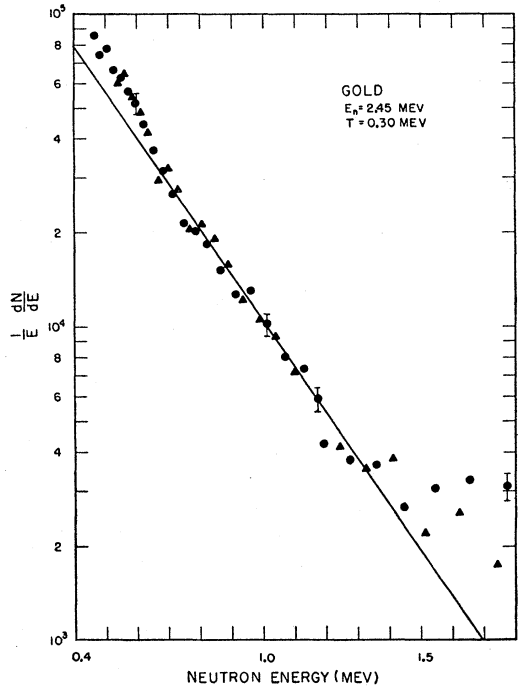

FIG. 13. Analysis of the spectral data obtained on gold. The function $E^{-1}dN/dE$ is shown plotted on an arbitrary logarithmic scale against the energy E of the scattered neutrons. The quantity dN/dE is the number of 90° scattered neutrons per unit energy interval as derived from the time spectra. The points shown as dots and triangles represent separately the data from each of the two cycles in the presentation of Fig. 4.

[19] M. Walt and J. R. Beyster (private communication).

[20] Feshbach, Porter, and Weisskopf, Phys. Rev. **96**, 448 (1954).

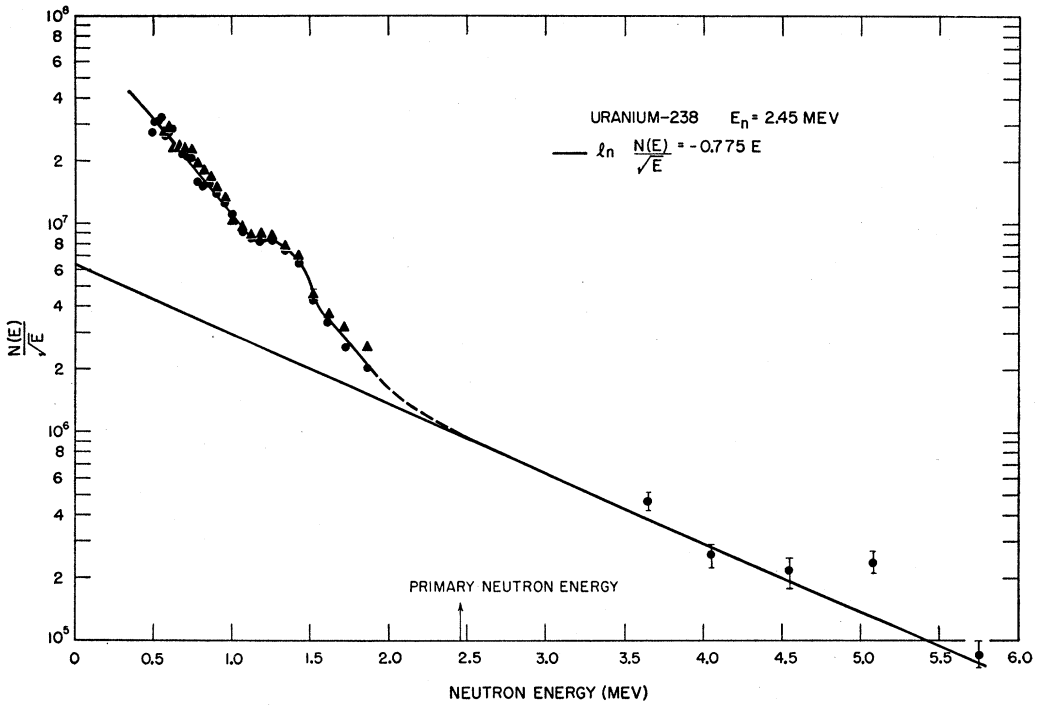

FIG. 14. Analysis of the spectral data obtained on U^{238}. The function $E^{-\frac{1}{2}}N(E)$ is shown plotted on an arbitrary logarithmic scale against the energy of the neutrons detected. The quantity $N(E)$ is the number of neutrons detected per unit energy interval as derived from the time spectra. The dashed portion of the curve represents the region of extrapolation under the elastic peak. The dots and triangles represent separately the data from each of the two cycles in the presentation of Fig. 5.

indication of net interference effects in the inelastic scattering. The four other inelastic angular distributions are consistent with symmetry about 90 degrees. In the context of the nuclide- and energy-sensitivity of the results, the observed symmetry may be regarded as due to chance or to the absence of interference effects rather than to their being randomized. Further data are needed to settle this question.

It has also been suggested[21] that these data may be interpreted in terms of resonances in the excitation of collective modes of nuclear motion, in accordance with a model recently proposed by Brink.[22] More detailed calculations on this model are necessary before its implications for this problem will be clear.

3. Continuous Spectra

To test the applicability of the Hauser-Feshbach theory to heavy elements, where the statistical assumption may be applicable to the residual nucleus as well as to the compound state, it is pertinent to examine the spectrum of inelastically scattered neutrons and the angular dependence of the spectrum for an element such as gold. Uranium-238 has also been examined in some detail for its practical interest.

Two gold samples were run, one with dimensions 2 inches long, 1 inch o.d., and $\frac{3}{8}$ inch i.d.; the other of the same dimensions except that the o.d. was only $\frac{3}{4}$ inch. The purpose here was to check on the sensitivity of the result to multiple scattering. Runs were made at 90 degrees and 160 degrees. The results for the inelastic scattering were the same in all cases indicating the angular distribution was isotropic to about 10%, and that the shape of the observed distribution was not significantly affected by multiple scattering.

The 90 degree spectrum obtained is shown in Fig. 4 and is shown plotted in Fig. 13 in a way which tests the applicability of the nuclear temperature concept[4–6] to the residual nucleus. In the conversion of the raw data, which were a function of time, to the correct spectrum as a function of energy the resolution function used was that previously arrived at for the elastic peak. The result of the analysis proved to be insensitive to the width of this resolution function. It is clear that for the highest and lowest energy neutrons there is a significant discrepancy from the line in Fig. 13 which corresponds to an effective temperature of 0.3 ± 0.03 Mev. This effective temperature does however describe the data over much of the energy range.

It will be noted that the data shown in Fig. 13 for the two parts of the rf cycle do not coincide although they have the same shape. This is due to an instrumental effect and arises from the inequality of the neutron fluxes produced in the target in the two parts of the cycle. This inequality is evidenced in the elastic

[21] D. M. Chase and L. Wilets (private communication).
[22] D. M. Brink, Proc. Phys. Soc. (London) **A68**, 994 (1955).

and gamma-ray peaks as well as in the yield of inelastic neutrons. It will be noted also in the data to be given on U^{238}, and has no significant bearing on the results.

For U^{238} the data was obtained using a sample whose size was the same as that of the smaller gold sample above. The raw data are shown in Fig. 5, and in Fig. 14 are given the results of an analysis whose object is to resolve the spectrum into the components of neutrons which are due to inelastic scattering and those which are due to fission.

Thus far there are no data on the fission neutrons from U^{238}, but there are data available on the spectrum of fission neutrons for the case of U^{235} which has been caused to fission by thermal neutrons. This has been studied extensively and is well known.[23] Over the range[24] 0.18 to 9.0 Mev this spectrum is described by the function $E^{\frac{1}{2}}e^{-0.775E}$. This is the function which is shown plotted as a straight line in the semilogarithmic plot of Fig. 14. The line has been normalized to fit the observed neutron spectrum above the energy of the primary neutrons, where the contribution must be due entirely to fission. If one assumes that below 2.5 Mev the fission spectrum follows the empirical formula given above, then a resolution of the spectrum into fission and inelastic components is possible. Subtracting the fission neutrons and taking account of another factor of $E^{\frac{1}{2}}$, one may test the possibility of describing the data in terms of an effective temperature. The result of this analysis is that, except for the strong structure previously noted corresponding to levels in the vicinity of 1.18 Mev, an effective temperature of 0.3 Mev fits the data reasonably well. The uncertainty in this temperature is 10%.

The inelastic data on gold and uranium have also been fitted to a function of the form[4] $E\exp\{2[a(E_0-E)]^{\frac{1}{2}}\}$, where E_0 is the primary energy, but the fit is not improved.

It is not clear at this time to what extent the nuclear temperature concept describes nuclear excitations in the energy range considered here. A more extensive investigation of this matter is contemplated.

[23] B. Watt, Phys. Rev. **87**, 1037 (1952).
[24] Rosen, Frye, Nereson, and Cranberg (to be published); also Los Alamos Report LA-1916 (unpublished).

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Decay of Co^{58}†

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Co^{58} decays not only to the first but also to the second excited state of Fe^{58}. Both of these states in Fe^{58} possess spin 2, even parity, and the transition between them is a mixture of $E2$ and $M1$, with a mixing ratio $\delta(E2/M1)=+2.2\pm0.3$. The intensities of the 1.62-Mev and 0.81-Mev gamma rays originating from the second excited state (relative to the main 0.81-Mev transition) are 0.005 ± 0.001 and 0.016 ± 0.005, respectively.

INTRODUCTION

COBALT-58 belongs to the relatively small class of nuclei which can be investigated by nuclear alignment techniques.[1] Such work, in order to be of value, requires a detailed knowledge of the nuclear decay scheme. In the case of Co^{58}, the interpretation of the alignment experiments[2,3] is based on the decay scheme proposed by Deutsch and co-workers.[4,5] According to Deutsch, Co^{58} decays by K capture and positron emission entirely into the first excited state of Fe^{58}, and from there into the ground state by emitting a single gamma ray of 0.81-Mev energy. The alignment experiments confirm this scheme and, in addition, yield a consistent spin and parity assignment.

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* Research Fellow under the U. S. Exchange Program; on leave from the University of Milan, and from the Istituto Nazionale di Fisica Nucleare, Milan, Italy.
[1] See, e.g., Blin-Stoyle, Grace, and Halban, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North Holland Publishing Company, Amsterdam, 1955), p. 600 ff.
[2] Daniels, Grace, Halban, Kurti, and Robinson, Phil. Mag. **43**, 1297 (1952).
[3] Bishop, Daniels, Goldschmidt, Halban, Kurti, and Robinson, Phys. Rev. **88**, 1432 (1952).
[4] M. Deutsch and L. G. Elliott, Phys. Rev. **65**, 211 (1944).
[5] Good, Peaslee, and Deutsch, Phys. Rev. **69**, 313 (1946).