potential containing no spin-orbit coupling term. If we then assign a somewhat arbitrary value of $\sigma_{ce}=0.35$ b for the range in atomic weights between $A=50$ and $A=100$, the predictions shown in Fig. 3 for compound nucleus formation are generally low by less than 0.5 b. Assuming that the predictions are also correct to this extent in the region extending down to $A=30$, we obtain a value of $\sigma_{ce}\approx 1.0$ b for sulfur, and $\sigma_{ce}\approx 1.5$ b for potassium and calcium.

ACKNOWLEDGMENT

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Resonant Scattering of Gamma Rays from Nuclear Levels with a Linear Accelerator

F. D. SEWARD
Lawrence Radiation Laboratory, University of California, Livermore, California
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Several elements have been irradiated with a high-intensity bremsstrahlung beam and a search has been made for γ rays scattered from nuclear levels. A 6-in.×5-in.-diameter NaI(Tl) crystal was used as the detector. Resonant scattering was seen from Li^6, B^{11}, C^{12}, O^{16}, Mg, and Si. Pulse-height spectra for γ rays scattered from each of these are shown. Application of these spectra to previous experiments in which level widths and branching ratios were calculated is discussed. Levels in B^{11}, C^{12}, and O^{16} were observed which have not been seen with this technique previously.

INTRODUCTION

THE resonant scattering of gamma rays from nuclear levels has been observed by several techniques.[1] One method, which is the one used in the present study, is to place a sample of the scattering material in a high-energy bremsstrahlung beam. The bremsstrahlung spectrum is smooth and contains x rays of all energies up to the primary electron energy. If the scattering sample is viewed from the side, resonant-scattered gamma rays stand out from the background because they have a well-defined energy and because the cross section for the resonant process is quite large compared to that of nonresonant nuclear scattering and background effects.

In previous resonance fluorescence work of this type, mostly betatron work, a scattered photon spectrum has first been measured, and from this spectrum the presence of resonant-scattered γ rays and γ-ray branching ratios have been inferred. Scattered intensity measurements have then been made with good geometry, with and without an absorber in the incident beam, and the level widths calculated from this data.

In the experiment to be described an attempt was made to obtain scattered photon spectra with the best possible resolution. The linear accelerator provided a much more intense bremsstrahlung flux than betatrons of comparable energy. Scattered intensity and good geometry were sacrificed for resolution. Because of this and because of a slight energy fluctuation of the accelerator beam, no absorption measurements were undertaken. Since no absorption measurements were made and since the shape of the incident x-ray spectrum was not accurately known, level widths could not be calculated. However, the spectra obtained are better than those of previous work and some of the conclusions about branching ratios and level widths in Mg and Si are affected by the interpretation of these spectra.

This work then was intended to supplement previous measurements with better spectral data rather than to repeat the absorption measurements and level width calculations. It was also a survey to indicate other levels susceptible to this method of analysis. The following elements and compounds were used as scattering samples: Li^6H, Li^7, Be, B, B^{10}, C, H_2O, KF, NaCl, Mg, Al, Si, P, S, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, and Zn. For each sample the scattered gamma spectrum was studied to determine energies and intensities of any resonant-scattered γ rays. Prominent scattered γ rays were seen from Li^6, B, C, O, Mg, and Si. Resonant scattering from other samples was too small to be distinguished from the background.

EXPERIMENTAL TECHNIQUE

The Livermore linear accelerator[2] is a pulsed machine and for this experiment was operated with a pulse length of 1 to 2 μsec and a repetition rate of 100 pulses per second. Average beam currents of 10 to 20 μamp were used. Electron energies ranged from 13 to 20 Mev, and the energy spread of the beam in this range was $\sim$2 Mev.

Bremsstrahlung x rays were produced by the electron beam striking a 0.10-in. Ta target backed by 2 in. of Al.

[1] S. Devons, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press, Inc., New York, 1960), Part A, p. 533.

[2] N. Austin and S. Fultz, Rev. Sci. Instr. **30**, 284 (1959).

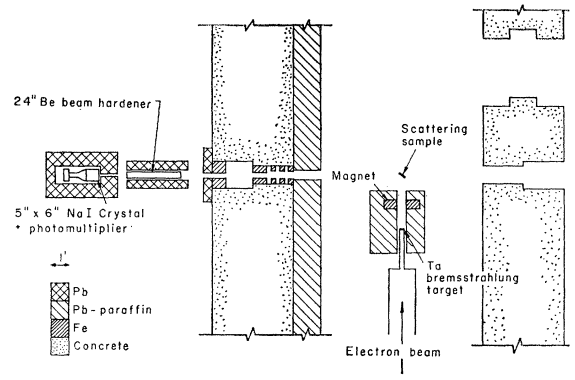

FIG. 1. Scale drawing of the scattering geometry. The x rays produced by the electron beam striking the Ta target are scattered from the scattering sample into the NaI crystal spectrometer.

The target had 1 ft of Pb-paraffin shielding around the sides and a permanent magnet (1 kgauss field) was used to sweep electrons from the x-ray beam. The experimental arrangement is shown in Fig. 1. Gamma rays scattered at an angle of 90° were detected by a 6-in.×5-in.-diam NaI(Tl) crystal. The crystal was contained in a Pb house with 6-in. walls and the γ rays were collimated to pass through the center of the crystal by a 1-in.-diam hole. Actually two setups were used to collect the data to be presented. One, as illustrated in Fig. 1, detected γ rays scattered to the left. In an attempt to reduce the scattering-sample-out background, the NaI detector was moved to the other side of the experimental area so it picked up γ rays scattered at 90° to the right. In this second setup the scattered γ rays passed through a hole in a 3-ft concrete wall (shown in Fig. 1), through another room 15 ft wide, through a hole in a 6-ft concrete wall, and into the detector. In each case Fe and Pb collimators were placed in these holes in the shield wall, so the scattering sample was the only material in a high radiation field seen by the detector. The detector was about three times as far from the scattering sample in this second arrangement; although the scattering-sample-out background was reduced, the reduction in scattered γ-ray flux was equally reduced, so no advantage was gained. A 24-in. Be beam hardener was used with the setup shown in Fig. 1. Only 18 in. of Be beam hardener was used when observing γ rays scattered to the right. The data shown in Figs. 2 and 3 were taken with the setup shown in Fig. 1, and all other spectra shown were taken with the second arrangement.

The NaI crystal was optically bonded to a DuMont 6364 photomultiplier, pulses from which went directly to a cable-driving preamplifier. Pulses were amplified and then sorted by an RIDL 200-channel pulse height analyzer. This analyzer was gated on for ~ 4 μsec each time the accelerator was pulsed. This duty cycle of 4×10^{-4} reduced the background caused by cosmic rays and natural radioactivity to a negligible level.

Three other types of background were encountered.

(1) Low-energy x rays were scattered from the sample in such number that the detector was swamped during each beam pulse. These x rays were eliminated with the Be beam hardener.

(2) Neutrons and x rays were scattered from the walls and collimators and were present even when the scattering sample was removed. This background is shown in Figs. 2 and 3. It has been subtracted from the other data by the following method: The bremsstrahlung beam was monitored by placing a detector ~ 3 ft behind the scattering sample. This detector consisted of a 2-in. diam$\times\frac{3}{4}$ in. thick plastic fluor and an FW 114 photodiode. This detector did not saturate in the high radiation fields produced during the beam pulse. The integrated current from the photodiode was taken as a measure of the total x-ray flux through the scattering sample for a given run. At each energy used, a scattering-sample-out run was made and the background measured. This background was then subtracted from the sample-in run, using the integrated diode current to normalize. Actually, data for each element consisted of several sample-in and sample-out runs. By comparing these runs made under identical conditions, the accuracy of the background subtraction is estimated as $\sim 10\%$. This uncertainty is caused by fluctuations in the energy of electrons from the accelerator. It was not uncommon to have the average energy of the beam change by ~ 0.5 Mev during a run.

(3) The third background originated in the scattering sample itself. It consisted of x rays with an almost exponential energy spectrum, increased with increasing Z, and masked any low-energy resonant-scattered γ rays which may have been present. The relative amount of this background was less for thinner samples, as is illustrated in Fig. 4, which shows pulse height spectra due to scattered γ rays for two thicknesses of C scattering sample. The two spectra have been normalized

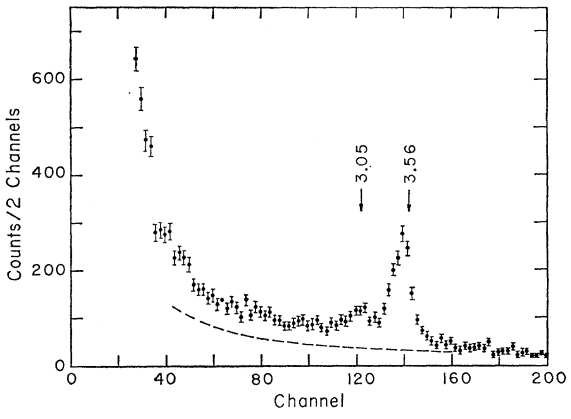

FIG. 2. Pulse-height spectrum for γ rays scattered from a Li^6H sample. The dashed line is the sample-out background. The rest of the counts are from resonant scattering from the 3.56-Mev level of Li^6 and from a sample-associated background. The horizontal energy scale was expanded compared to the other spectra to determine the spectrometer response to this γ ray.

to have the same 15.1-Mev resonant-scattered γ-ray intensity. The sample-out background has been subtracted. Poor statistics prevented drawing the 4.4-Mev line in the spectrum from the thicker sample. Because the two curves are normalized to the resonant-scattered 15.1-Mev line, which strongly absorbs in the sample, the low-energy part of the spectrum from the thicker sample is expected to be larger. The expected ratio[3] is 1.7. The observed ratio is 5. This third background, which changes nonlinearly with sample thickness, is thought to be due to bremsstrahlung from electrons created in the scattering sample by the incident x-ray beam. Samples were made as thin as possible to lower this background but thick enough to still give reasonable counting rates. Thicknesses of from $\frac{1}{8}$ to $\frac{1}{4}$ in. were used for the lighter elements, and 0.030-in.-thick sheets were used for the higher Z metals studied.

The NaI crystal and electronics were calibrated using the 4.43-Mev γ ray from a PoBe source and the 15.1-Mev resonant-scattered γ ray from C^{12}. This calibration was checked before and after each run with the PoBe source. Energies derived from this calibration are indicated on the pulse height spectra. Experimental uncertainty in the energies given by this calibration is ± 0.1 Mev. Some of the spectral line shapes are compared with response functions extrapolated from those given by Kockum and Starfelt (KS).[4] The NaI crystal and collimator used by KS were not exactly the same as for the present experiment. Nevertheless, their response functions seem to be quite applicable to our data. These extrapolated response functions are shown as solid lines in Figs. 3 and 5–8. Error bars on the experimental points represent counting statistics only.

For each scattering sample the electron beam energy

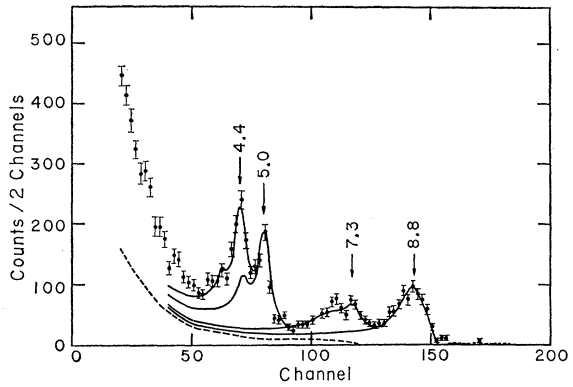

FIG. 3. Pulse-height spectrum for γ rays scattered from a natural B sample. The dashed line is the sample-out background. The solid lines are KS response functions for the indicated γ-ray energies.

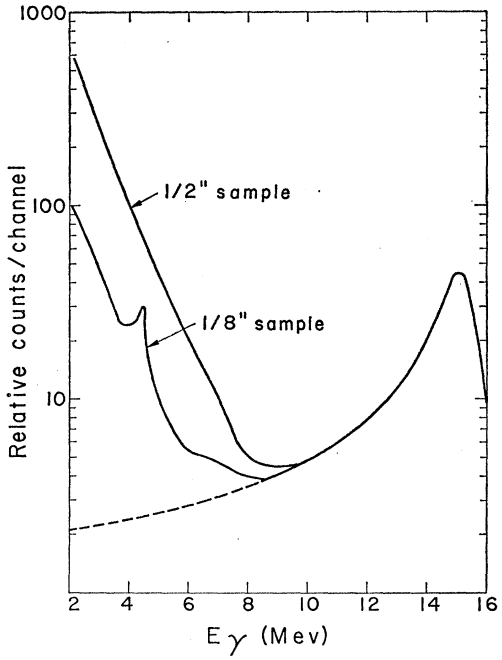

FIG. 4. Two pulse-height spectra for γ rays scattered from C samples of different thicknesses. The two spectra have been normalized to the resonant-scattered 15.1-Mev γ ray to illustrate the sample-associated background. The sample-out background has been subtracted from each spectrum. The dashed line is the 15.1-Mev response function tail.

was chosen high enough to give reasonable resonant scattering intensity but low enough to eliminate possible high-energy γ rays from $(\gamma,p\gamma)$ or $(\gamma,n\gamma)$ reactions in the sample. From 2 to 4 hours were required to collect the data for each sample with the exception of C which took about 8 hr of running time. The spectra presented are those in which a strongly scattered γ ray was seen. Scattering from all other samples was small. By "small" it is meant that any resonant-scattered γ rays were not strong enough to be distinguished from the backgrounds present. As mentioned before, the arrangement of the linear accelerator was not suitable for absorption experiments or precise threshold determination by variation of bremsstrahlung beam energy, so such measurements were not attempted. Others have made these studies on most of the resonant γ rays seen and hence proved that they were due to resonant excitation of a given nuclear level.

RESULTS

Li^6

The pulse height spectrum due to scattered γ rays from a Li^6H sample 3 in.$\times$3 in.$\times\frac{3}{4}$-in. thick is shown in Fig. 2. The sample-out background is given as a dotted line. Maximum bremsstrahlung energy was 17 Mev. A spectrum was first taken with less amplifier gain and no prominent γ rays were seen above 3.56 Mev. Both the full energy peak and a peak due to the

[3] Calculated assuming $\delta/\Gamma=0.6$, $\sigma_0=32.4$ barns, and using curves given by James Rainwater in *Encyclopedia of Physics* (Springer-Verlag, Berlin, 1957), Vol. XL, p. 380.

[4] J. Kockum and N. Starfelt, Nuclear Instr. and Methods 4, 171 (1959).

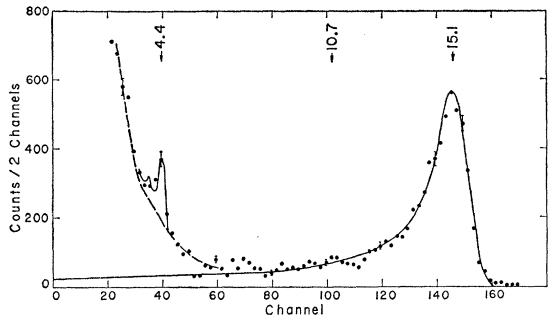

FIG. 5. Pulse-height spectrum for γ rays scattered from a C sample. Sample-out background has been subtracted. The solid lines are KS response functions for 4.4- and 15.1-Mev γ rays. The dashed line is an estimate of the sample-associated background.

escape of one annihilation quantum from the NaI crystal are visible. These peaks are superimposed on the sample-out background and the sample-associated background which both rise sharply at lower energy. The 3.56-Mev γ ray has been shown by Cohen and Tobin[5] to be resonant-scattered from the second excited state of Li^6. The spectrum is presented here to illustrate the response of the detector in this energy region and the spectral shape of the backgrounds.

B^{11}

Figure 3 shows the pulse height spectrum for γ rays scattered from a natural B sample. The sample was pressed from B powder into a disk $\frac{1}{4}$ in. thick by 3 in. in diameter. Thickness of the target was 0.84 g/cm^2. Maximum bremsstrahlung energy was 13 Mev. Four resonant-scattered γ rays were seen. When a 95% B^{10} sample was substituted for the natural B, no scattered γ rays could be distinguished from the background. The dashed curve is the sample-out background. The solid lines are response functions extrapolated from the work of KS. The two low-energy lines have been studied previously by this technique[6] and are from the 4.46- and 5.03-Mev levels of B^{11}. The two higher energy lines are taken to be resonant-scattered from the 7.30- and the 8.93-Mev levels of B^{11} since they are the only levels in this energy region which have high branching ratios for decay directly to the ground state.[7] The energies indicated in Fig. 3 were derived from the PoBe source calibration and are the positions of the peaks of the response functions. They agree within experimental uncertainty with the above level assignments. The sample-associated background obscured any lower energy scattered γ rays which may have been present. Thresholds for the (γ,p) and (γ,n) reactions in B^{11} are 11.4 and 11.2 Mev. Hence residual nuclei from these reactions cannot be the source of any of these lines.

[5] L. Cohen and R. A. Tobin, Nuclear Phys. **14**, 243 (1959).
[6] L. Cohen, R. A. Tobin, and J. McElhinney, Phys. Rev. **114**, 590 (1959).
[7] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 96 (1959).

C^{12}

The resonant scattering of photons from the 1+, 15.1-Mev level of C^{12} has been extensively studied by this technique.[8–10] Most of the transitions from this level go directly to the ground state. Any branching through the first excited state gives rise to 10.7- and 4.43-Mev γ rays. Pulse height spectra of previous experiments[8–10] have indicated the presence of this 10.7-Mev line. The fraction of γ transitions through the first-excited state has been given in each case as essentially ≤ 0.1. Charged particle experiments give this fraction as[11] 0.031 ± 0.006 and[12] 0.04 ± 0.01.

Figure 5 shows the pulse height spectrum due to scattered γ rays from a C target $\frac{1}{8}$ in. thick. Sample-out background has been subtracted. Maximum bremsstrahlung energy was 19 Mev. Two peaks corresponding to 4.43- and 15.1-Mev γ rays are seen. The 10.7-Mev γ ray, if present, is indistinguishable from the tail of the crystal response to the 15.1-Mev γ ray. The KS response functions drawn seem to fit the spectrum well and have been used to calculate the number of γ rays scattered into the detector. Using the areas under these response functions and correcting for crystal efficiency and 18 in. of Be beam hardener, the relative number of γ rays scattered at 90° was calculated as: 15.1 Mev, 1.00; 4.43 Mev, 0.31 ± 0.07; 10.7 Mev, ≤ 0.02.

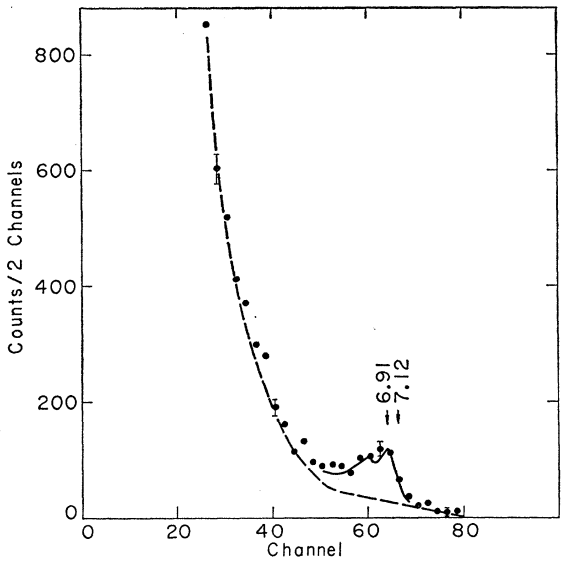

FIG. 6. Pulse-height spectrum for γ rays scattered from a H_2O sample. Sample-out background has been subtracted. The solid line is a KS response function for a 6.9-Mev γ ray. The dashed line is an estimate of the sample-associated background.

[8] E. Hayward and E. G. Fuller, Phys. Rev. **106**, 991 (1957).
[9] E. L. Garwin, Phys. Rev. **114**, 143 (1959).
[10] A. Bussière de Nercy and M. Langevin, J. phys. radium **21**, 293 (1960).
[11] E. Almqvist, D. A. Bromley, A. J. Ferguson, H. E. Gove, and A. E. Litherland, Phys. Rev. **114**, 1040 (1959).
[12] D. E. Alburger and R. E. Pixley, Phys. Rev. **119**, 1970 (1960).

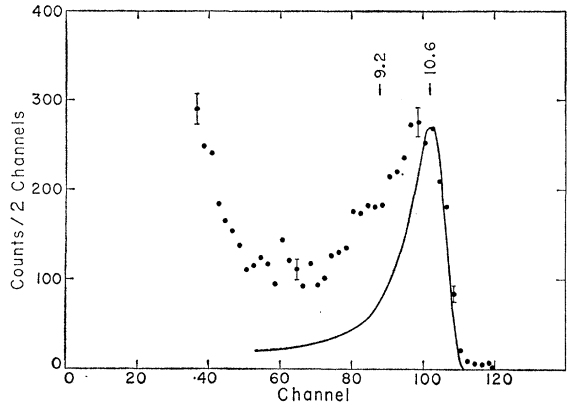

FIG. 7. Pulse-height spectrum for γ rays scattered from a Mg sample. Sample-out background has been subtracted. The solid line is a KS response function for a 10.6-Mev γ ray.

Such a large relative number of 4.4-Mev γ rays seemed to indicate resonant scattering directly from the 4.43-Mev level. To see if this was so, the following calculation was made: Level widths are known for the 4.43-Mev[13] and 15.1-Mev[9] levels of C^{12} and for the 3.56-Mev level of Li^6 (reference 5). Using these level parameters, the data of Figs. 2 and 5, some preliminary data for Li^6 and C^{12}, and allowing for self-absorption in the scattering sample, attentuation in the beam hardener, etc., the relative numbers of 3.56- and 15.1-Mev photons in the incident bremsstrahlung were roughly computed. Using this to estimate the shape of the incident x-ray spectrum, the relative number of 4.43-Mev photons to 15.1-Mev photons incident on the C target was estimated to be 20 ± 8. These two transitions are $E2$ and $M1$, respectively, and the angular distribution of scattered γ rays is as given by Garwin.[9] After correcting for the different angular distributions, the expected relative number of 4.43-Mev photons scattered at 90° was calculated to be 0.15 ± 0.08. Uncertainty in the calculated ratio is largely in level width data and in the estimated shape of the incident bremsstrahlung beam. Uncertainty in the observed ratio is mostly in the background subtraction.

These numbers are crude but the rough agreement indicates that most of the 4.43-Mev γ rays seen are scattered directly from the first excited state of C^{12}. No estimate of the branching ratio through this state can be made from observation of this 4.43-Mev line. The fact that no 10.7-Mev line was seen does not disagree with a 0.03-γ ray branching through the first excited state. It is not certain that the tails of the KS response functions are correct for this spectrometer. If the tail of the 15.1-Mev response function in Fig. 3 were two-thirds as high as drawn, the relative 90° 10.7-Mev γ-ray intensity would be 0.05 ± 0.02. Higher ratios than this are unlikely.

[13] V. K. Rasmussen, F. R. Metzger, and C. P. Swann, Phys. Rev. **110**, 154 (1958).

O^{16}

Water was used for the O^{16} target. An Al holder with 0.00025-in. Mylar windows was used to hold a $4\times6\times\frac{1}{4}$-in. water sample. Several runs were made with and without water in the sample holder. Figure 6 shows the water-in runs with the normalized water-out runs subtracted, using 16-Mev electrons. Data have been fitted with an estimated sample-associated background and a KS response function for a single γ ray of energy 6.9 ± 0.1 Mev. This γ ray does not come from a $(\gamma,p\gamma)$ reaction as do the 5.3- and 6.3-Mev γ rays seen in an experiment done with higher energy bremsstrahlung.[14] The widths of the 6.91- and 7.12-Mev levels have both been measured as ~0.06 ev,[15] so for a thin target such as this, one expects a contribution from both levels. The data of Fig. 6 do not exclude a contribution from the 7.12-Mev level, but the major contribution seems to come from scattering from the 6.91-Mev state.

Mg

The spectrum in Fig. 7 was taken with a $\frac{1}{8}$-in.-thick natural Mg scattering sample and bremsstrahlung of 16 Mev maximum energy. The response function drawn has been fitted to the high energy edge of the rather broad peak; it corresponds to a γ-ray energy of 10.6 ± 0.1 Mev. Since the response function does not fit the observed data, it indicates that other high energy γ rays are present. These are probably from resonance fluorescence of the Mg isotopes, although high energy γ rays from $Mg^{25}(\gamma,n\gamma)Mg^{24}$ are possible.

There is some disagreement in the energy of this line as observed by others. More than one resonant-scattered γ ray in this energy region might account for the disagreement. Threshold determinations by variation of betatron energy yielded 10.5 ± 0.14 Mev for

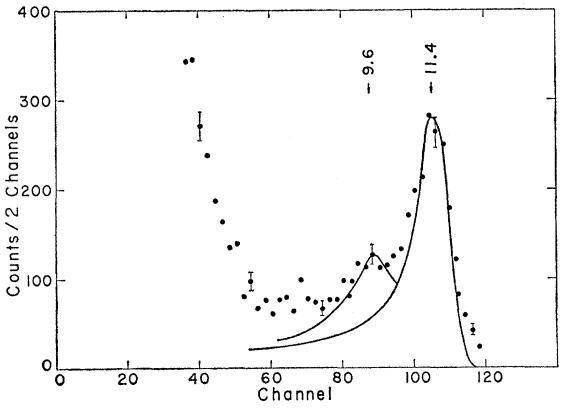

FIG. 8. Pulse-height spectrum for γ rays scattered from a Si sample. Sample-out background has been subtracted. Solid lines are KS response functions for 9.6- and 11.4-Mev γ rays.

[14] A. S. Penfold and E. L. Garwin, Phys. Rev. **116**, 120 (1959).
[15] C. P. Swann and F. R. Metzger, Phys. Rev. **108**, 982 (1957).

Langevin and de Nercy[16] and 10.15±0.006 Mev for Tobin.[17] De Nercy and Langevin[10] conclude from the angular distributions of these γ rays that the peak consists of two γ rays, one directly to the ground state and one to the first excited state of Mg^{24}. Relative intensities of these two γ rays are given as $\frac{3}{5}$ and $\frac{2}{5}$, respectively. This interpretation does not agree with the spectrum of Fig. 7, for which the detector resolution was good enough to separate the two γ rays if present in these intensities (as, for example, in the Si^{28} data).

Si

A $\frac{1}{8}$-in.-thick sample of powdered Si in a Mylar holder produced the spectrum of Fig. 8, for which 16-Mev electrons were used. Response functions have been drawn corresponding to two γ rays of energy 11.4±0.1 and 9.6 Mev. Both of these γ rays are too high in energy to come from $(\gamma,n\gamma)$ or $(\gamma,p\gamma)$ reactions in the Si isotopes. It is assumed that they are both from resonant excitation of Si^{28}. The 11.4-Mev γ-ray energy agrees well with the results of Tobin,[17] and the 9.6-Mev γ ray is assumed to be a transition to the first-excited state at 1.78 Mev. If it is assumed that the transitions are (0–1–0) and (0–1–2) and that the 9.4-Mev γ ray is also dipole, then angular distributions of these two resonant-scattered γ rays are $1+\cos^2\theta$ and $1+(1/13)\times\cos^2\theta$, respectively, and the ratio of decays to the first-excited state to decays to the ground state is 0.19±0.04. As in the case of Mg, this contradicts an experiment in which it is concluded from the angular distribution of these two unresolved γ rays that this ratio is 0.6.[18]

ACKNOWLEDGMENTS

It was a pleasure to work with Dr. H. W. Koch during the first part of this experiment. The author is indebted to him both for suggesting that the accelerator be used for an experiment of this type and for much help with the experimental setup; to R. Shafer and C. Jupiter, who provided valuable assistance in data-taking; to F. Fulton, who made several targets by pressing powdered B and Si in molds; and to Dr. S. Fultz, who made accelerator time available. The work was done under the auspices of the U. S. Atomic Energy Commission.

[16] M. Langevin and A. Bussière de Nercy, J. phys. radium 20, 831 (1959).
[17] R. A. Tobin, Phys. Rev. 120, 175 (1960).
[18] A. Bussière de Nercy, J. phys. radium 22, 119 (1961).

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Magnetic Octupole Moments of Axially Symmetric Deformed Nuclei*†

S. A. WILLIAMS
Physics Department, Rensselaer Polytechnic Institute, Troy, New York
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The magnetic octupole moments of twenty odd-A nuclei whose energy levels are reasonably well described by the axially-symmetric collective model in strong coupling have been calculated. With but two exceptions, the predicted moments are of the same magnitude as or larger than the moments measured for seven nuclei. The model parameters have been determined by fitting the measured values of the lower moments and transition probabilities. The assumption has been made that the orbital gyromagnetic ratio for the odd nucleon is that of a free particle. Then from the total gyromagnetic ratio of the particle, which was determined from the measured magnetic dipole moment and $M1$ transition probabilities, the spin gyromagnetic ratio, g_s, was determined. With but one exception g_s was found to have a value between the free particle and pure Dirac particle values.

INTRODUCTION

THE magnetic dipole and electric quadrupole moments of most nuclei have been measured and reasonably well understood for some length of time. More recently, better measurements of hyperfine structure and reinterpretation of old data have yielded the magnetic octupole moments of seven nuclei.

The extreme single-particle model calculation of the octupole moments has been done by Schwartz[1] and predicts limits similar in nature to the Schmidt limits for the magnetic dipole moments. (See Figs. 1 and 2). The uniform or Margenau-Wigner (M-W) limits can also be used in connection with this model. One may note however, that although the Schmidt limits reasonably well describe the observed dipole moments, the Schwartz limits (or even the M-W limits) do not characterize the octupole moments well. With the exception of the two chlorine isotopes, all the measured

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[1] C. Schwartz, Phys. Rev. 97, 380 (1955).