1.4 MeV, a $d_{5/2}$ resonance at about 2.4 MeV, and a $d_{3/2}$ resonance at about 6.5 MeV are all clearly evident. The $f_{7/2}$ phase shift is starting to go through a resonance at the maximum energy. There is no evidence for p resonances.

The $d_{5/2}$ and $s_{1/2}$ resonances presumably correspond to the ground and first excited states of F^{17}, both of these states having reduced widths which are large fractions of the Wigner limit. A $d_{3/2}$ single-particle level is experimentally observed at an incident proton energy of 4.67 MeV.[10] It is interesting to note that no prediction is made of a single-particle $p_{3/2}$ level similar to the one reported in O^{17} at an excitation of about 7.7 MeV by Baldinger *et al.*[11]

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Nuclear Resonant Scattering of Gamma Radiation of Variable Energy

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A variable-energy gamma-ray system is described. Monoenergetic gamma radiation undergoing Compton scattering produced this energy variability over a significant range. The parameters of the system are described.

Gamma radiation from a Co^{60} source of strength 1200 C was Compton scattered from a copper scatterer. The energy of the scattered radiation varies continuously from 1.33 MeV in the forward direction to 0.21 MeV at a scattering angle of 180°. The rays of mean energy 480 keV, corresponding to a mean scattering angle of 69.5°, were resonantly scattered by lithium. From a self-absorption experiment the mean life of the first excited state of Li^7 was found to be $(1.48 \pm 0.35) \times 10^{-13}$ sec.

I. INTRODUCTION

When inducing nuclear reactions by incident particles, energy variability has proved to be of immense value. In particular, the excitation of only a specific energy level, even when not far removed from neighboring levels, at least facilitates and at times makes possible, the determination of characteristics of the level concerned. For the study of photoreactions there are two main sources of gamma rays. In the first of these a decay from one specific nuclear level to another, gives rise to discrete energy gamma rays. The second source on the other hand is that of electron produced bremsstrahlung with a continuous range of energy values up to a maximum equal to the maximum electron energy. For the excitation of nuclear levels of specific energy, clearly neither source is ideal.

During the past decade gamma radiation has been successfully used for the measurement of widths (and, hence, lifetimes) of both bound and virtual nuclear states. In this period various techniques for nuclear resonant scattering and absorption of gamma radiation have developed rapidly.

In the earliest experiments, high temperature and ultracentrifuge methods were used. Subsequently, resonant scattering has been detected for gamma radiation which is Doppler broadened in energy as a result of preceding gamma or particle emission.[1] This applies to radiations emitted from both radioactive sources and in nuclear reactions of the type $(p,p'\gamma)$. The radiation widths of several bound states in various nuclei have been determined from such measurements. In some elegant experiments the gamma radiation emitted in proton capture reactions has been resonantly absorbed.[2] As a result of the proton capture the subsequent radiation is Doppler shifted in energy. This method is suitable for determining the radiation widths of highly excited states in nuclei. Recently, experiments have been reported in which the source of radiation is bremsstrahlung as produced by accelerated electrons.[3] Since the bremsstrahlung spectrum is continuous, all energy levels can be excited up to the maximum energy of the radiation incident on the scatterer. In this case resonant scattering can be observed provided that the level width is sufficiently large. This method has been used to study both low-energy and highly excited states of nuclei.

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[1] C. P. Swann, V. K. Rasmussen, and F. R. Metzger, Phys. Rev. **114**, 862 (1959).

[2] P. B. Smith and P. M. Endt, Phys. Rev. **110**, 397 (1958).

[3] E. C. Booth, Nucl. Phys. **19**, 426 (1960).

Cormack[4] has suggested another method for obtaining gamma rays of the correct energy for exciting nuclear states. He pointed out that by allowing monoenergetic gamma rays to undergo Compton scattering, a gamma-ray beam of energy variable over a definite range could be obtained. A variable-energy gamma source of this type has not yet been used to observe resonance fluorescence in nuclei. The practical difficulty in the application of this technique is clearly one of intensity. Any resonant scattering experiment will involve two successive scattering events. Calculations show that sources of several curies in strength are required. With multicurie sources of various radioactive elements now becoming readily available, the main obstacle in the successful application of Cormack's suggestion to resonant scattering has been removed.

This report describes a successful resonant scattering experiment using Compton-scattered gamma rays from a 1200-C source of Co^{60} to obtain gamma rays of the desired energy. The 480-keV level in Li^7 was excited, and the width, thereof, determined.

II. ENERGY VARIABILITY OF THE GAMMA RADIATION

There are three principal ways in which gamma radiation interacts with matter. These are the photoelectric effect, the Compton effect, and the pair production effect. To obtain energy variation over a significant range, only the Compton effect is of importance. Applying the laws of conservation of energy and momentum in the interaction of a gamma ray and a free electron, the following expression for the energy E of the Compton-scattered radiation is obtained:

$$1/E = 1/E_0 + (1-\cos\theta)/m_0c^2,$$

where E_0 is the energy of the radiation incident on the scatterer, m_0 is the rest mass of the electron, and θ is the angle in laboratory space between the initial and final directions of the photon. For the 1.33- and 1.17-MeV gamma rays from Co^{60}, a continuously variable energy is available from 1.33 to 0.21 MeV. This is illustrated in Fig. 1. It is interesting to note that for $E_0 \gg m_0c^2$ and $\theta = 180°$;

$$1/E \simeq 2/0.51 = 3.92 \text{ MeV}^{-1}.$$

Thus for large E_0, the energy of the scattered radiation is continuously variable from E_0 to about 0.26 MeV over an angular scan of 180°. On the other hand, for low-energy incident radiation, the energy of the scattered radiation varies more slowly over a smaller range.

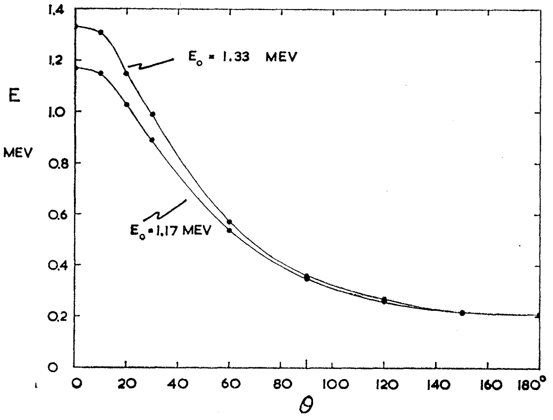

FIG. 1. Energy variation of gamma radiation undergoing Compton scattering.

The spread in energy ΔE due to a spread in scattering angle $\Delta\theta$ is given by

$$\Delta E = \frac{(E_0^2/m_0c^2)\sin\theta\Delta\theta}{[1+E_0(1-\cos\theta)/m_0c^2]^2}.$$

Figure 2 shows this energy variation per unit angle of the Compton-scattered radiation for the two gamma rays from Co^{60}.

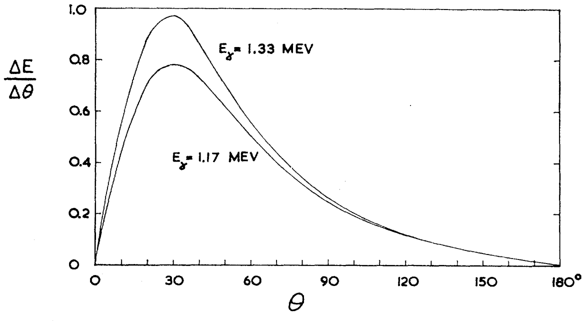

FIG. 2. The energy spread per unit angle (MeV per radian) of the Compton-scattered radiation as a function of scattering angle for the gamma rays from a Co^{60} source.

A further parameter of interest for the Compton process is the differential cross section. This is most conveniently obtained from tables. It appears that for $E_\gamma < 1$ MeV, the variation of the differential cross section with θ is small. For high-energy radiation this quantity is appreciably smaller in the backward than in the forward direction.

III. EXPERIMENTAL CONSIDERATIONS

A cobalt unit designed for clinical application, was used in this investigation. It consisted of a 1200-C Co^{60} source mounted at the center of a 15-in.-diam sphere composed of tungsten and lead. The beam of gamma radiation from the source was well collimated by an aperture of variable size. In order to counter balance the weight of the source shielding, a large lead disk, 30 in. in diameter and 3 in. thick at the center, is mounted 24 in. from the source aperture in the path of the emergent beam. This counterweight was the source of very intense back-scattered radiation which pro-

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[4] A. M. Cormack, Phys. Rev. 96, 716 (1954).

duced the greatest background contribution. It was not possible to remove this disk during experiments.

The experimental arrangement is shown in Fig. 3. The first scatterer was a block of copper, 1 in. thick, and mounted a mean distance of 4 in. from the source aperture. From tables of absorption coefficients for gamma radiation in copper, it can be deduced that the contribution of the Compton effect in the total absorption coefficient for 1.25-MeV radiation is approximately 99%. Other materials, such as lead, for example, would also be suitable for the first scatterer. The average angle between the direction of the beam incident on the copper scatterer and the line joining the centers of the first and second scatterers was 69.5°, this being the angle calculated as correct for producing the desired energy.

The second scatterer was composed of natural lithium metal, 5 cm thick. This slab of lithium was sealed in a polythene envelope containing paraffin. It was placed at a distance of 26 in. from the first scatterer in order to get a sufficient thickness of lead shielding between the final detector and the cobalt source. The beam incident on the lithium scatterer was well collimated.

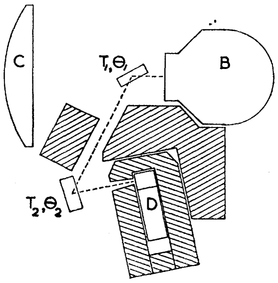

FIG. 3. Outline of the experimental arrangement, where the shaded areas represent lead shielding, T_1 the first scatterer (copper), T_2 the second scatterer (lithium or carbon), B the source container, C the counterweight, and D the scintillation detector.

The spread in energy of the γ-radiation incident on the second scatterer was about 70 keV. The radiation scattered from the lithium at an angle of 135° was detected by a scintillation counter consisting of a 3 in.×3 in. NaI(Tl) crystal mounted on a photomultiplier tube. The pulses from the counter were recorded by means of a 100-channel pulse-height analyzer.

The efficiency of the first scatterer can be improved by replacing the slab shape used here by a surface of revolution. For a given source strength this arrangement will give an appreciably greater intensity of gamma radiation of the required energy. This may be useful if a source of very high intensity is not available. To vary the energy of the scattered radiation, different scatterers would have to be used. Alternatively, if the first scatterer is of block form, the second scatterer could be of cylindrical shape. This would also ensure a greater intensity of resonantly scattered radiation.

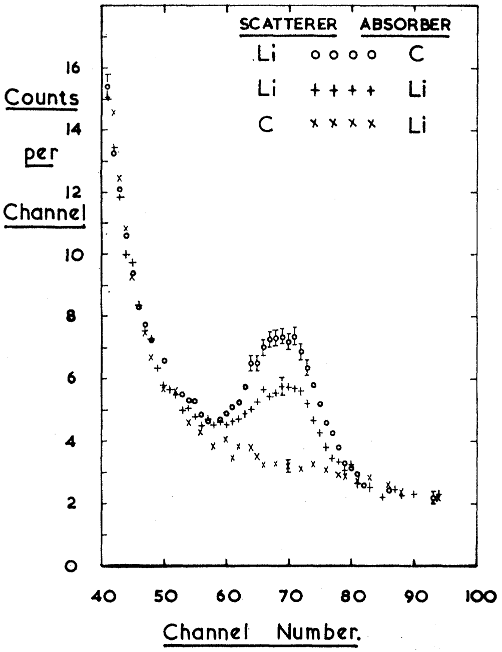

FIG. 4. Results for scattering from different combinations of lithium and carbon.

To obtain the width of the first excited state of lithium, a self-absorption experiment was performed. This technique has been used by several workers.[5] Two absorbers and two scatterers were used. The absorbers were located between the first (copper) scatterer and the second scatterer. The second scatterers were lithium and carbon and the absorbers were of the same materials. The absorbers were matched to give the same electronic attenuation. Measurements were made with the following combinations:

(1) lithium scatterer with carbon absorber;

(2) lithium scatterer with lithium absorber;

(3) carbon scatterer with lithium absorber.

Readings were taken with a particular scatterer and absorber for 35 min. Another combination of absorber and scatterer would then be introduced and readings taken for the next period. These cycles were repeated many times and sets of readings belonging to a particular combination of scatterer and absorber were added together.

IV. RESULTS

Figure 4 indicates the results obtained during 15 h of measurement with different combinations of scatterers and absorbers. The lithium absorber, apart from causing electronic attenuation, also selectively absorbs the radiation in the region of 480 keV. The strong attenuation of the peak when the lithium absorber is present, is evident. The background is to a large extent due to the radiation scattered from the lead counterweight in the path of the beam from the cobalt source.

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[5] F. R. Metzger, Phys. Rev. **110**, 123 (1958).

The level width is extracted from these results in the following way:

The yield of γ rays resonantly scattered from a thick target is given by Metzger[5] as

$$Y=\pi^{1/2}N(E_r)\Delta k\int_0^a \left\{\sum_{m=0}^{\infty} \frac{(-kx)^m}{m!(m+1)^{1/2}}\right\} \exp(-\mu_1 x)dx,$$

where $N(E_r)$ is the number of γ rays per unit energy interval in the region of resonance, Δ is the Doppler width of the level, μ_1 is the total electronic absorption coefficient of the scatterer, a is the thickness of the scatterer, and

$$k=\frac{n(2J_e+1)\Gamma\lambda^2}{4(2J_g+1)\pi^{1/2}\Delta}.$$

In this expression for k, Γ is the level width, λ is the wavelength of the radiation, n is the number of nuclei per cm^3, and J_e and J_g are the spins of the excited and ground states, respectively. The integration is usually done numerically.

In an absorption experiment the yield Y_a of resonantly scattered quanta is obtained by carrying out the integration of the above expression between the limits d and $d+a$, where d is the thickness of the absorber. The ratio Y/Y_a is independent of $N(E_r)$.

From the expression of Ofer *et al.*,[6] in this experiment Δ can be calculated as 1.44 eV. From the experimental results, Y/Y_a was found to be 1.76, and Γ was subsequently calculated to be 4.42×10^{-3} eV. This corresponds to a mean lifetime for the 480-keV state of

$$\tau=(1.48\pm0.35)\times10^{-13}\text{ sec.}$$

The error assigned to this result is mainly statistical.

This level in Li^7 has been measured by several workers. By resonant scattering of bremsstrahlung, the following results were found:

Booth[3] (absorption method)	$(1.4\ \pm0.7\ )\times10^{-13}$ sec
Booth[3] (scattering method)	$(1.0\ \pm0.5\ )\times10^{-13}$ sec
Beckman and Sandström[7]	$(1.1\ \pm0.3\ )\times10^{-13}$ sec
Mouton, Sellschop, and Keddy[8]	$(1.25\pm0.06)\times10^{-13}$ sec.

By scattering Doppler-broadened γ rays from the reaction Li$^7(p,p')$Li^{7*}, Swann *et al.*[1] found

$$\tau=(1.15\pm0.14)\times10^{-13}\text{ sec (absorption method);}$$

$$\tau=(1.09\pm0.07)\times10^{-13}\text{ sec (scattering method).}$$

The result from the present measurements is, therefore, in agreement with previously measured values.

V. DISCUSSION

By the successful detection of the resonant scattering of gamma rays from the 0.48-MeV level of Li^7, the use of Compton scattering to obtain radiation of variable and sufficiently defined energy from a monoenergetic source has been demonstrated. This technique will permit the excitation of other nuclear levels, using gamma rays from any sources of sufficient strength. If high-energy gamma sources of sufficient intensity become available, this method will be as versatile as the bremsstrahlung method. It has the distinct advantage that the background problem is less serious than in the case of bremsstrahlung. Also, this method enables individual levels in a nucleus to be excited. With bremsstrahlung all levels up to the maximum energy of the spectrum are excited simultaneously. This introduces obvious complications when levels are closely spaced. Much of the photonuclear work to date has been done with bremsstrahlung. In this type of reaction study, a gamma source with small energy spread and of variable energy should be most valuable.

ACKNOWLEDGMENTS

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[6] S. Ofer and A. Schwarzschild, Phys. Rev. **116**, 725 (1959).

[7] O. Beckman and R. Sandström, Nucl. Phys. **5**, 595 (1958).

[8] W. L. Mouton, J. P. F. Sellschop, and R. J. Keddy, Phys. Rev. **128**, 2745 (1962).