271.7 ew 27 hr; 293.5, 299.6, 303.8 w 27 hr?; 332.6, 333.6 ew ?; 392.4 w ?; 414 ew ?; 458 vw 6 hr; 465, 473, 480 ew 6 hr?; 503, 508, 513 w 6 hr?; 582, 604, 618, 640 ew ?; 667, 687 w ?.

ACKNOWLEDGMENTS

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Note added in proof:—M. C. Michel (thesis, University of California, 1953) has recently made a time-of-flight analysis of the thallium isotopes. Independently he assigns the 1.8-hr activity to $A=198$ and also observes the 5.3-hr activity of Tl^{198} which is reported in our work.

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Large-Angle Scattering of Co^{60} Gamma Rays*†

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Measurements of the scattering of Co^{60} gamma rays from lead, tin, copper, and aluminum have been made at a mean angle of 135°. In addition to Compton scattering and annihilation radiation, some higher energy components are present. Elastic scattering was observed in each of these scatterers and the cross section for this process has been measured. Results are shown to be consistant with recent theoretical calculations on Rayleigh and Thomson scattering.

INTRODUCTION

INVESTIGATION of the large-angle scattering of gamma rays permits the measurement of scattering events other than Compton scattering. This is of low energy and can be discriminated against. Investigations of this type were made by Chao[1] and Gray and Tarrant[2] in a study of the scattering of ThC″ gamma-rays from lead and other scatterers, and first showed the presence of annihilation radiation from positrons produced in the scatterer.

Pollard and Alburger[3] employed this method in 1948 in an attempt to measure nuclear resonance scattering of Na^{24} gamma rays in magnesium. Their results showed no marked excess in intensity of gamma rays scattered from magnesium over those scattered from aluminum. However, measurements on scattering from magnesium, aluminum, lead, and mercury showed, in each case, an unidentified component of hard radiation having an absorption coefficient characteristic of the unmodified incident beam.

Moon[4] and Storruste[5] have made similar measurements on scattering from lead, copper, and aluminum. Moon has attempted to explain the results of Pollard and Alburger on the basis of interference between coherent scattering by bound electrons (Rayleigh scattering) and Thomson scattering from the nucleus. In addition, he has confirmed the calculations of Franz[6] on Rayleigh scattering at a mean angle of 115° and at an energy of 0.41 Mev, and Storruste has extended his measurements to other angles in the region from 60° to 150°.

More recently, Wilson[7] has measured this elastic scattering from lead at various angles in the energy regions near 1.3 Mev and 2.6 Mev in an attempt to find evidence of Delbrück scattering (potential scattering by virtual pair formation in the field of the nucleus).

With this background in mind, an investigation was undertaken of large-angle scattering of Co^{60} gamma rays, with particular attention paid to the elastic scattering. Knowledge of the cross sections for this process, and their dependence on the atomic number of the scatterer, would be useful in the interpretation of existing calculations on Rayleigh scattering and might provide additional evidence for the existence of Delbrück scattering or resonance scattering.

THEORY

In addition to Compton scattering and annihilation radiation, other scattering events are possible in the energy region of 1.3 Mev by the processes of bremsstrahlung, Thomson scattering, Rayleigh scattering,

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† Part of a dissertation presented to the Faculty of the Graduate School of Yale University, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.
[1] C. Y. Chao, Phys. Rev. **36**, 1519 (1930).
[2] L. H. Gray and G. T. P. Tarrant, Proc. Roy. Soc. (London) **136**, 662 (1932).
[3] E. C. Pollard and D. E. Alburger, Phys. Rev. **74**, 926 (1948).
[4] P. B. Moon, Proc. Phys. Soc. (London) **A63**, 1189 (1950).
[5] A. Storruste, Proc. Phys. Soc. (London) **A63**, 1197 (1950).
[6] W. Franz, Z. Physik **98**, 314 (1935).
[7] R. R. Wilson, Phys. Rev. **90**, 720 (1953).

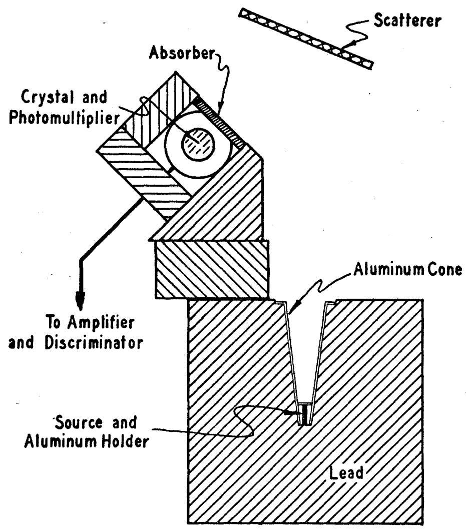

FIG. 1. Arrangement of apparatus for measurement of gamma-ray scattering at a mean angle of 135°.

resonance scattering, and Delbrück scattering. The last four can contribute to elastic scattering.

The classical scattering calculation of Thomson[8] is applicable to scattering from the nucleus in this energy region (by replacing the electronic charge e by Ze and the mass by the nuclear mass) since the rest energy of the heavy nucleus is large in comparison with the incident gamma-ray energy and relativistic effects can be neglected. The differential cross section is approximately proportional to Z^2 and is independent of the incident gamma-ray energy.

Franz[6] has calculated the cross section to be expected from Rayleigh scattering in the gamma-ray region for small scattering angles, and Moon[4] has given an extension of his results for the case of large angles. This calculation, computed on the basis of a Thomas-Fermi electronic charge distribution, predicts a Z^3 dependence for the scattering cross section and shows that the scattering is mainly in the forward direction. Levinger[9] discusses Bethe's interpretation of these form-factor calculations, showing that for values of the photon change in momentum greater than the characteristic momentum of a K electron, a better approximation would be obtained by using Dirac wave functions for K electrons. His calculations predict a somewhat lower cross section than Franz' and show that the scattering may be proportional to Z^8 or Z^{10} in the energy region of 1.3 Mev. It would thus be negligible in comparison to the Thomson scattering in the case of the lower atomic number scatterers. Levinger has described the approximations involved in these calculations and the relativistic corrections to be expected in this energy region, and Brown and Woodward[10] have discussed the effects of binding in the intermediate state.

The probability for the occurrence of resonance scattering by nuclear excitation depends on how near the incident gamma-ray energy is to that of an excited state. Levinger[11] has calculated the cross section to be expected when the incident energy is far enough from the nearest energy level so that the contribution to the scattering from it is small compared to the scattering from all other levels. (Twenty electron volts seems to be far enough.) In that case, he has concluded that, at 1.3 Mev, the scattering to be expected from resonance absorption is negligible compared to the Thomson scattering intensity.

Very little theoretical work has been done on potential scattering. Rohrlich and Gluckstern[12] have made an exact calculation of this scattering of 1.33-Mev gamma rays from lead at 0° and predict a differential cross section of 0.15 mb/sterad. Since the angular dependence is rather high, and the scattering is proportional to Z^4, it is doubtful if there is any substantial scattering at 135° in comparison with other processes such as those mentioned above.

APPARATUS

The scintillation spectrometer used in the energy measurements consisted of a large NaI(Tl) crystal mounted on an RCA type 5819 photomultiplier tube used in conjunction with a single-channel pulse-height analyzer. The instrument has been fully described in a previous paper.[13]

The Co^{60} source, with a strength of about five curies, was obtained in the form of a wire $\frac{1}{8}$ inch in diameter by $\frac{5}{8}$ inch long and was mounted in the center of a large lead cylinder 12 inches in diameter by 12 inches long, with a conical opening to define the beam dimensions. A diagram of this and the geometry used in the scattering measurements is shown in Fig. 1. Measurements were made at a mean angle of 135°.

Scatterers were cut from lead, tin, copper, and aluminum in the form of ellipses of such a thickness as to have, in each scatterer, the same number of electrons. These were supported on a thin aluminum stand whose effect on the scattering was negligible in comparison with the scatterers, but which was left in place during background measurements. All background measurements were made with the source in place but with scatterers removed.

RESULTS

Figure 2 shows the spectra of radiation scattered from $\frac{3}{8}$ inch of lead, and equivalent thicknesses of tin

[8] J. J. Thomson, *Conduction of Electricity Through Gases* (Cambridge University Press, London, 1906).
[9] J. S. Levinger, Phys. Rev. **87**, 656 (1952).
[10] G. E. Brown and J. B. Woodward, Proc. Phys. Soc. (London) **A65**, 977 (1952).
[11] J. S. Levinger, Phys. Rev. **84**, 523 (1951).
[12] F. Rohrlich and R. L. Gluckstern, Phys. Rev. **86**, 1 (1952).
[13] T. D. Strickler and W. G. Wadey, Rev. Sci. Instr. **24**, 13 (1953).

and copper, using $\frac{3}{16}$ inch of lead absorber between scatterer and counter. Calibration curves are shown at pulse heights corresponding to energies of 0.51 Mev, 1.17 Mev, and 1.33 Mev. The Compton scattering peaks at 0.24 Mev, and the annihilation peaks are easily distinguishable. Pulses were observed with pulse heights up to 83 volts, corresponding to energies up to 1.33 Mev although the intensities were very low and cannot be seen in these curves.

Figure 3 shows an expanded portion of the curves in the energy region of 1.33 Mev of scattering from lead, tin, copper, and aluminum. These were run with $\frac{3}{8}$ inch of lead absorber between scatterer and counter to further discriminate against the Compton scattering. Vertical bars on the measured points indicate the statistical accuracies (standard deviations). The set of runs shown required about one week of running time on the spectrometer and the pulse height during this time was stable within a few percent. Calibration curves over the 1.33-Mev peak of Co^{60} were taken repeatedly during these runs as a check on the stability.

To eliminate the possibility that any substantial part of these curves was due to pileup of lower energy photons in the crystal, a spectrum of the direct radiation from a source of Cs^{137} was measured at a distance such as to give an over-all counting rate greater than that scattered from the scatterers. This spectrum, with a peak at 0.661 Mev, was found to fall off much more rapidly at higher energies than the scattered spectra.

To measure the cross sections for this apparant elastic scattering, a weak Co^{60} source of known intensity was placed in the center of the position of the scatterer and the spectrum measured again in the region of the 1.33-Mev peak. From the known strengths of the two Co^{60} sources, the ratio of the counting rates at the 1.33-Mev peaks, and the geometry of the system, the corresponding cross sections were calculated. The effect of absorption of the incident and scattered beam in the scatterer was accounted for using values for the absorption coefficients calculated from cross sections for Compton effect and photoelectric effect given by Heitler,[14] and for pair production given by Hirschfelder and Adams.[15]

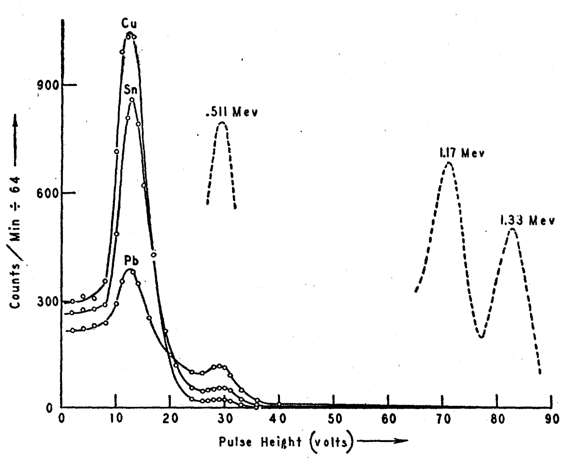

FIG. 2. Spectra of Co^{60} gamma rays scattered at 135° from lead, tin, and copper. Dotted curves show calibration lines from Co^{60} and Na^{22} at 0.51 Mev, 1.17 Mev, and 1.33 Mev.

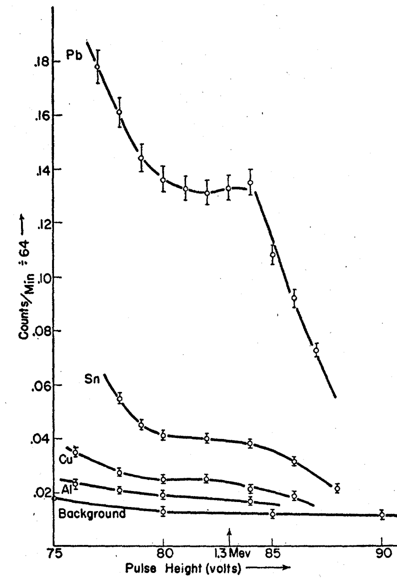

FIG. 3. Spectra in the energy region of 1.3 Mev of scattering from lead, tin, copper, and aluminum. Vertical lines on measured points indicate statistical accuracies.

Several checks were made to confirm the validity of these cross section measurements. A spectrum was measured of a weak gamma-ray source of I^{131} extended over the dimensions of the scatterer, and this compared with that of the same source concentrated near the center. The effective decrease in counting rate due to the extended source was less than five percent. A sheet of photographic paper placed at the position of the scatterer and exposed to the gamma radiation of the strong source, showed an even irradiation over the entire face of the scatterer. Also, the strengths of the two sources were compared with a third source of intermediate strength using a Lauritsen electroscope and a number of pencil type ionization chambers, and the relative intensities (though not the absolute intensity) were thus determined within about fifteen percent.

These differential cross sections are listed in Table I along with the theoretical values for the coherent combination of Rayleigh scattering (using Bethe's form-factor calculation), and Thomson scattering. The experimental errors given in these measurements represent those introduced by inaccuracies in measurements of source strengths, effect of the extended source, pulse height instability, etc., as well as statistics

[14] W. Heitler, *The Quantum Theory of Radiation* (Oxford Univeristy Press, London, 1935).
[15] J. O. Hirschfelder and E. N. Adams, Phys. Rev. **73**, 863 (1948).

TABLE I. Differential elastic-scattering cross sections in millibarns/steradian.

	Pb	Sn	Cu	Al
Thomson	0.019	0.0080	0.0031	0.0007
Rayleigh	0.06	4.5×10^{-4}	3.2×10^{-6}	2×10^{-9}
Rayleigh plus Thomson	0.15	0.012	0.003	0.0007
Measured	0.12±0.04	0.015±0.006	0.004±0.002	0.0008±0.0004

in the counting rates. The largest of these in the case of lead was in the estimate of source strength.

DISCUSSION

Although for pure elastic scattering one would expect to measure a peak in the scattered spectrum at 1.33 Mev, it can be seen from the lead spectrum that no peak was observed. A definite change in slope, however, was recorded at this point which would seem to indicate that the elastic scattering was superimposed on a monotonically decreasing scattered component such as one might attribute to bremsstrahlung (from photoelectrons produced in the scatterer). Comparing the shape of the curve with the direct spectrum of Co^{60} gamma rays through $\frac{1}{2}$ inch of lead absorber, however, indicates that at 1.33 Mev the contribution of this component to the total scattering is probably small. The measured cross sections given in Table I, of course, include the effect of this component. This continuously decreasing component will be proportionally smaller than the elastic scattering in the case of the lighter elements because of the high Z dependence of the scattering at lower energy as pointed out below. This is confirmed by the measurements of Pollard and Alburger[3] which show considerable high-energy scattering (with a more continuous energy distribution) from lead, and much less from aluminum and magnesium—but all of it with an absorption coefficient equivalent to that of the incident beam. It is thus unnecessary to distinguish a peak in the scattered spectrum, since a measurement of the counting rate at the pulse height corresponding to the incident energy is sufficient to calculate a cross section with the accuracy shown above. Results are also in agreement with recent measurements made by Wilson[7] on elastic scattering from lead.

The continuous energy spectrum observed between 0.51 Mev and about 1.2 Mev (not shown in detail in the accompanying figures) appeared to be of some interest. Taking into consideration the thickness of the scatterers and the absorption coefficients at these energies, the measurements indicate that the Z dependence is very high in this region—proportional to Z^5 or more. If this radiation were due to bremsstrahlung from Compton electrons produced in the scatterer, one would expect the intensity to be dependent on Z^3. Consideration of the radiation from photoelectrons would partially explain this discrepancy. It is possible that other processes such as one-quantum annihilation of positrons would explain this high Z dependence but the explanation would require a more careful study than that attempted here.

The agreement between the measured cross sections and those calculated for Rayleigh and Thomson scattering may not be too significant, particularly in the case of the Rayleigh scattering. Considerations of the binding in the intermediate state and relativistic effects may be serious and the contributions of the potential scattering to the total elastic-scattering component is yet to be determined.

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