If we assume the absorption is by the free holes, then by dividing the absorption coefficient ($4\pi k/\lambda$) by the number of free carriers we can compute a cross section for capture of photons. At 3.4 microns this cross section for holes is $1.5A^2$, while for electrons it is only $0.13A^2$. These are both much larger than the cross section calculated from classical theory, which is of the order of $10^{-3}A^2$ for mobilities of the order of 1500 cm²/volt sec such as are found in these samples. Similar discrepancies with classical theory have previously been pointed out for *n*-type germanium[2] and *p*-type silicon.[2,3]

[1] R. C. Lord, Phys. Rev. **85**, 140 (1952).
[2] H. Y. Fan and M. Becker, *Proceedings of Reading Conference* (Butterworth Scientific Publications, London, 1951), pp. 132–147.
[3] H. B. Briggs, Phys. Rev. **77**, 727 (1950); M. Becker and H. Y. Fan, **76**, 1531 (1949).

The Double Compton Effect

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AN effect was predicted by Heitler and Nordheim[1] in which, in addition to the normal scattered quantum in the Compton process, one or more further quanta were produced, with decreasing order of probability. For two scattered quanta having comparable energies, and for incident quantum energies $\gg m_0c^2$, the ratio of the cross section to that of the normal Compton process $\sim 1/137$.

Co^{60} γ-rays from a 200-mC source were defined by a horizontal collimator designed to minimize scattering, secondary electrons being removed by a magnetic field. Effects due to coincident γ-rays from the source were negligible. The γ-rays fell on a foil placed perpendicular to the beam, scattered quanta being detected by two NaI(Tl) crystals $2\frac{3}{4}$ in. in diameter and just under 1 in. thick placed symmetrically in a plane just below, so that they were not struck by the incident beam. They accepted quanta with scattering angles between 45° and 145°, subtended a solid angle at the scatterer of ~4 percent sphere, and were shielded from each other by 20 g/cm² lead to eliminate cross-scattering.

From a preliminary experiment, in which the scatterer was a 170-mg/cm² naphthalene-anthracene crystal, it was found that all coincidences between the quantum counters due to the source were accompanied by the ejection of an electron from the scatterer.

The ratio of the quantum-quantum coincidence rate to the sum of the single quantum rates should be constant and independent of scatterer thickness for coincidences produced by a primary process. In addition to those from the double Compton effect, coincidences may also be produced by a normal Compton process in which the scattered electron suffers an inelastic nuclear collision in the material of the scatterer, resulting in a bremsstrahlung. The coincidence rate due to this secondary process is proportional to the square of the scatterer thickness, if this is fairly small compared with the electron range, and gives rise to a component in the coincidence rate per recorded quantum which varies linearly with scatterer thickness. The magnitude of the component depends on the atomic number of the scatterer.

Scatterers of thickness varying from 40–400 mg/cm² of Be, Al, Cu, and Ag were used. In each case, below ~200 mg/cm², the variation of coincidence rate per recorded quantum with thickness can be represented by the sum of a constant term, and a term varying linearly with thickness, as shown in Fig. 1. The magnitude of the constant term is independent of the atomic number of the scatterer, as it should be for an effect depending only on scattering from free electrons. The coefficient of the linear term $\propto Z^{2.24}$; the increase in the value of the exponent over that appropriate to bremsstrahlung production, $\propto Z^2$, being due possibly to the increased path length of electrons brought about by scattering.

To obtain a rough estimate of the relative cross sections for double and single Compton scattering, it will be assumed that one

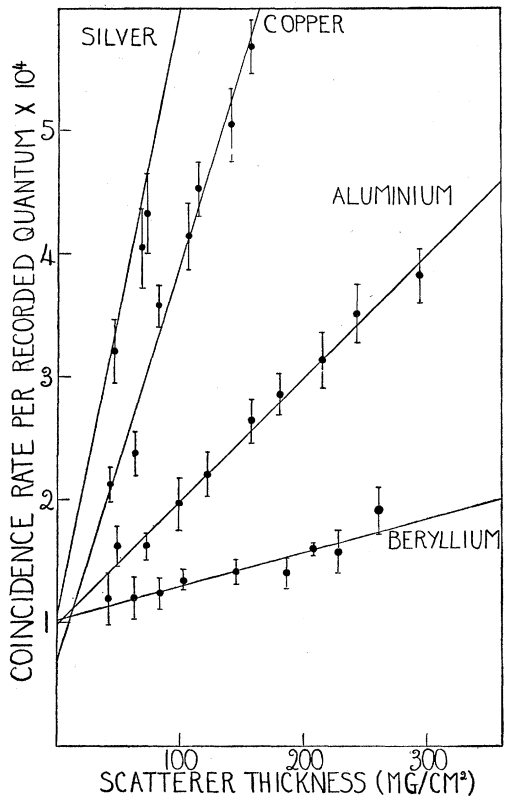

FIG. 1. Coincidence rate per recorded quantum *versus* scatterer thickness.

quantum has the normal distribution and the other is isotropically emitted and detected with 100 percent efficiency. This gives the double Compton cross section, integrated over the energy range 80–530 kev, to be 3×10^{-3} of the single Compton cross section. Mandl and Skyrme[2] have used the Feynman method to calculate the differential cross section where the two quanta are scattered at right angles to each other and to an incident quantum of energy 1 Mev, a case which approximates to the experimental one. Integrating over the energy range accepted by the discriminators and assuming 100 percent detection efficiency, a value for the coincidence rate per recorded quantum of 0.4×10^{-4} results. This is to be compared with the experimental value of 1.0×10^{-4}.

Thanks are due to Mr. W. H. Taylor and especially to Mr. G. A. Gard for able assistance in performing this experiment. Acknowledgment is made to the Director, Atomic Energy Research Establishment, England, for permission to publish this letter.

[1] W. Heitler and L. Nordheim, Physica **1**, 1059 (1934).
[2] F. Mandl and T. H. R. Skyrme (to be published).

Mobility of Electrons in Germanium

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IN the past, measurements of the Hall coefficient and conductivity of *n*-type germanium have yielded mobility values which, although increasing with time and presumably better crystals, were consistently lower than the drift mobility.[1] Measurements have now been made, at room temperature, on a number of new samples in various conductivity ranges which have yielded higher mobilities than any previously found. In the range of resistivity for which drift mobility values are available, these new values substantially agree with the drift mobility values measured

by Haynes.[2] The variation of mobility with impurity content observed in these new samples agrees quantitatively with the theoretically predicted variation due to impurity scattering.

The samples were prepared from single crystals of germanium that had previously undergone extensive purification.[3] Special precautions were taken to obtain a high degree of uniformity within the single crystal. The lower resistivities were obtained by adding arsenic. Slices were cut from these crystals and a suitable sample shape[4] was obtained by using a die driven by a magnetostrictive rod. The measured values of electron Hall mobility are plotted *vs* resistivity in Fig. 1. For the samples which are not near intrinsic, this is just the product of the Hall coefficient R and the conductivity σ. For the near intrinsic samples, electron Hall mobility was obtained by measuring $R\sigma$ over a range of temperatures and extrapolating along a $T^{-\frac{3}{2}}$ line.

The theoretical values shown in Fig. 1 were obtained from a theory based on the assumption that the surfaces of constant energy in the Brillouin zone are spherical. The lattice mobility, μ_L, which, of course, does not depend on impurity content, was taken as 3600, the best value from Haynes' measurements. The impurity

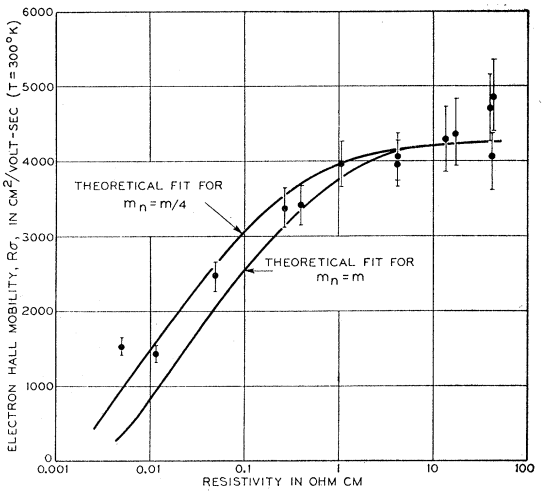

FIG. 1. Electron hole mobility in Ge as a function of resistivity.

mobility was computed from the theoretical formula[5]

$$\mu_I=\frac{8(2)^{\frac{1}{2}}\kappa^2(kT)^{\frac{3}{2}}}{\pi^{\frac{3}{2}}N_I e^3 m_n^{\frac{1}{2}}\ln[1+(3\kappa kT/e^2N_I^{\frac{1}{3}})^2]},$$

where κ is the dielectric constant, taken as 16.1, k Boltzmann's constant, T the absolute temperature, N_I the density of ionized impurities, e and m_n the charge and effective mass of the electron, respectively. N_I was taken equal to the density of conduction electrons. The calculations were done for m_n equal to the mass of a free electron, and one-quarter this value. The two mobilities were combined according to the exact formula,[6] the resulting integral being evaluated numerically.

If the bottom of the conduction band is not degenerate, theory indicates that the ratio of Hall mobility to drift mobility should vary from 1.18, for very pure samples, to 1.93, for very impure ones. Using the published values of this ratio,[7] one can convert the mobility values calculated as described to Hall mobility. The results are shown in Fig. 1. For the very pure samples, 1.18×3600 lies within the range of experimental Hall mobilities, as expected if the energy surfaces are spherical. The excellence of the fit for $m_n=m/4$ would seem to be definite evidence for an effective mass of this order of magnitude. A more precise calculation of the impurity scattering might, however, modify the theoretical impurity mobility sufficiently to affect this estimate of the effective mass considerably. Other evidence for such a value of effective mass comes from data on density of conduction electrons *vs* temperature in germanium, which are best fitted by an effective mass of about this size. Beyond an impurity density of $10^{18}/\text{cm}^3$ a good fit cannot be expected, because the assumptions on which (1) is based are not well justified.

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[1] For discussion and references, see W. Shockley, *Electrons and Holes in Semiconductors*, (D. Van Nostrand Company, Inc., New York, 1950). Also G. L. Pearson (private communication).

[2] J. R. Haynes and W. Shockley, Phys. Rev. **81**, 835 (1951).

[3] These crystals were supplied by W. W. Bradley and K. M. Olsen of Bell Laboratories.

[4] G. L. Pearson and H. Suhl, Phys. Rev. **83**, 768 (1951). A similar sample is shown in Fig. 2 of this paper.

[5] E. M. Conwell and V. F. Weisskopf, Phys. Rev. **77**, 388 (1950).

[6] See, for example, reference 1, p. 276.

[7] V. A. Johnson and K. Lark-Horovitz, Phys. Rev. **82**, 977 (1951) and H. Jones, Phys. Rev. **81**, 149 (1951).

K-Shell Conversion Coefficient of Ce^{141}

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THE K-shell internal conversion coefficient of the 141-kev transition in Pr^{141} has been measured with a NaI scintillation spectrometer. It has also been possible to assign a classification to this transition.

Ce^{141} is known[1] to decay by β^- emission to Pr^{141}. The β^- spectrum of 442-kev end point is followed by a 141-kev gamma-ray.

The response of a $1\frac{1}{2}$-in. diameter by 1-in. NaI crystal to the K x-ray and 141-kev gamma-ray is shown in Fig. 1. The pulse-height

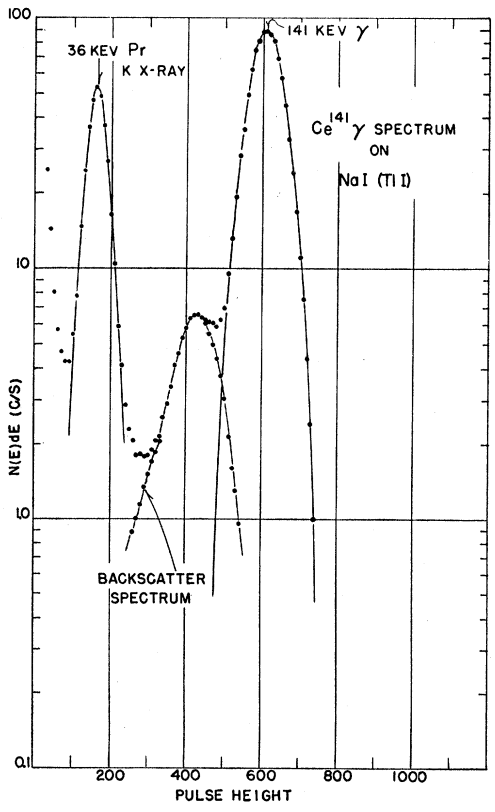

FIG. 1. Spectrum of the γ-radiation of Ce^{141}.

spectrum has been resolved into the gamma-ray, x-ray, and Compton backscatter from a graded shield surrounding the detector. The response of the crystal to scattered radiation was obtained through the use of a "shadow shield" which cut off the