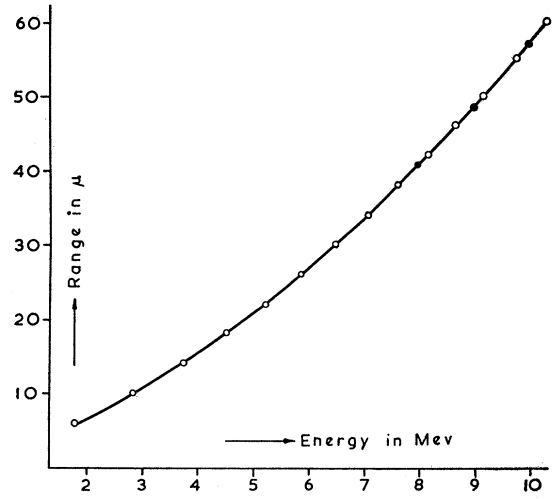

FIG. 1. Calculated range-energy curve for alpha-particles in dry Ilford C2 emulsions. The circles represent readings taken from Rotblat's (see reference 8) and the dots those taken from Catala's (see reference 9) experimental results.

tween the experimental points and the semi-empirical curve. In this figure some readings taken from the curve obtained by Catala and Gibson,[9] are also represented. These points also show very good agreement with the calculated values. Hence one may expect that range-energy relations in other types of emulsions are calculable with rather good accuracy.

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New Infrared Absorption Bands in *p*-Type Germanium

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TWO absorption bands have been discovered in the normally transparent region of the infrared in samples of germanium to which *p*-type impurities have been added. The extinction coefficient of a series of such samples of varying conductivity is shown in Fig. 1 as a function of wavelength. The absorption bands at 3.4 and 4.7 microns are clearly evident in all samples, the absorption at each wavelength being approximately proportional to the conductivity. The absorption bands at 15.5 and 19 microns have previously been reported.[1] These latter bands are clearly not due to the presence of the added impurities, as can be seen by comparison with the high purity sample also plotted in Fig. 1. They are probably associated with lattice vibrations.

A further experiment was performed to determine whether the new absorption bands were proportional to the number of acceptor centers present or to the number of free carriers. These were approximately equal to each other for the samples of Fig. 1. Several single crystals were grown which were scheduled to have a fairly uniform distribution of acceptor centers, but part way through the growth process donor impurity was added to the melt. The results from two such samples are shown in Fig. 2. Sample *A* was only partially compensated so that it remained *p*-type, while sample *B* was converted to an even lower resistivity *n*-type. The absorption bands are still present, although much reduced, in the partially

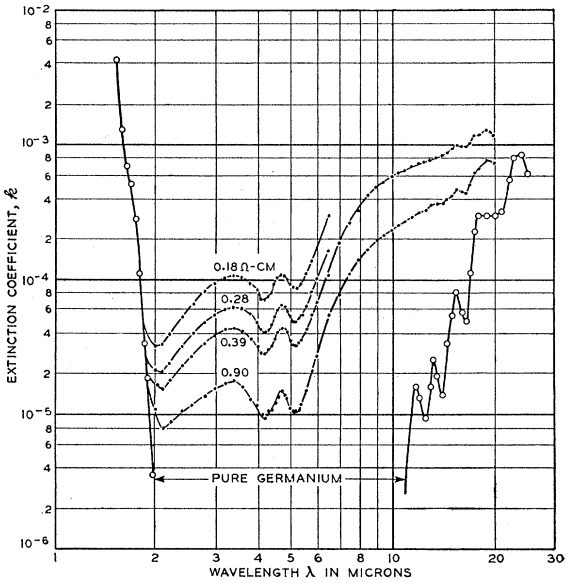

FIG. 1. Extinction coefficients of *p*-type germanium of various resistivities as a function of wavelength. These are compared with pure germanium (circled points).

compensated sample *A*, but entirely disappear in the sample converted to *n*-type. This leads us to conclude that the absorption is proportional to the concentration of free holes and not proportional to the concentration of the acceptor impurities.

Two possible mechanisms are conceived as consistent with the observations. First, the absorption bands may be caused by the presence of unknown impurities or lattice defects. These must be present in the different samples in approximately equal concentrations and must give energy levels which are within 0.1 ev of the filled band in order that the observed absorption be proportional to the number of free holes over the range of resistivities measured (0.1 ev is the approximate location of the Fermi level for the lowest resistivity *p*-type sample used). A second possible mechanism is absorption by the free holes themselves. This latter does not require constancy of the uncontrolled impurity concentration and thus seems more likely. In either event, the fact that we obtain absorption bands rather than continuous absorption suggests that the valence band of germanium has fine structure in the vicinity of 0.3 ev of its upper edge.

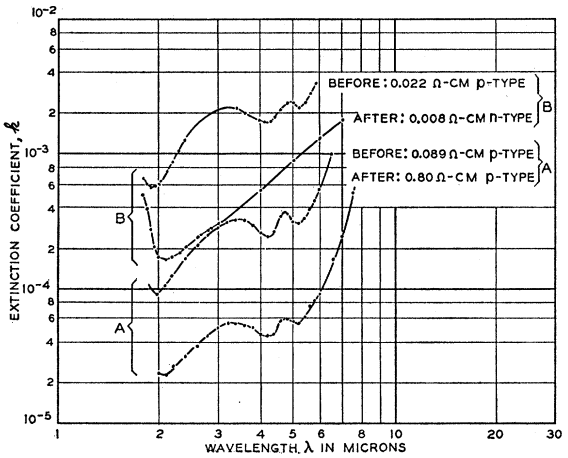

FIG. 2. Extinction coefficients for two germanium crystals containing acceptor centers both before and after donor centers have been added. Crystal *A* was partially compensated to give a higher resistivity *p*-type, while crystal *F* was converted to *n*-type.

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]

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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

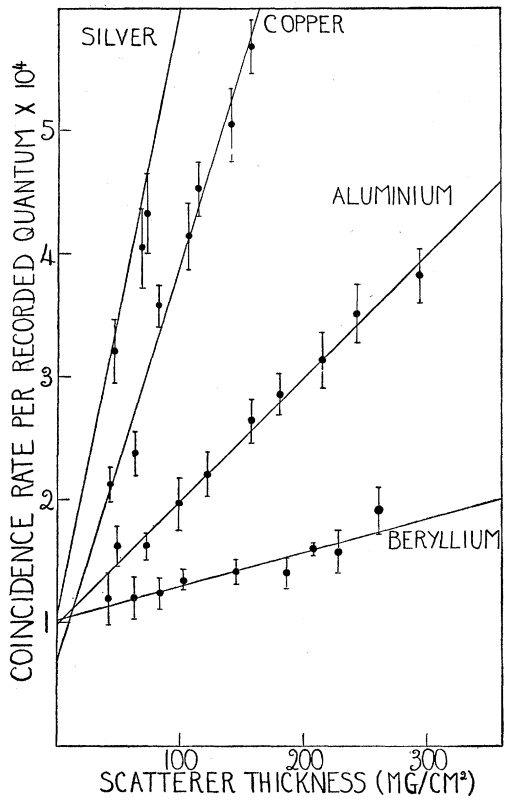

FIG. 1. Coincidence rate per recorded quantum *versus* scatterer thickness.

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.

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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