situation in a given electric field is not readily observed. By using pulse techniques and special experimental precautions, it has been possible to observe steady-state changes in the mobility of electrons in germanium samples.

As has been discussed in several publications,[1] the resistance of n-type germanium samples under relatively low field conditions can be modulated by hole emission from the end electrode. In the experiments which are being reported, precautions have been taken to minimize such modulation. Figure 1 shows the type of

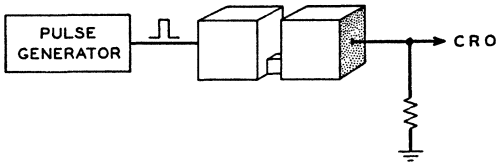

FIG. 1. Schematic diagram of germanium sample and its associated electrical circuit.

sample used and its associated electrical circuit. The resistance of the germanium arises from a small filament which is left after a large portion of the cross section of a block of germanium has been removed by a special cutting technique.[2] Large area electrodes make contact on the relatively massive ends of the block. Although fields as high as 4×10^4 v/cm are applied along the filament, the field at the ends never exceeds about 10 v/cm. With such low fields, the transit time for injected holes to reach the filament is much greater than the duration of a pulse. Hence they do not affect the observed conductivity of the filament. Also, the surfaces of the specimen were prepared to be as smooth as possible, since otherwise hole generation and attendant modulation appear to occur.

The voltage pulses used were obtained from a generator of low internal impedance, were quite flat-topped, and were of a duration of 0.1 μsec. The energy dissipated in the filament during a single pulse corresponded at most to an energy density of 2×10^7 ergs/cc. This produced, during a pulse, a temperature rise of less than one degree. Furthermore, the pulse repetition rate of 100 pps afforded ample time between pulses for this heat to diffuse to the massive ends. There was, therefore, no accumulative heating of the filament.

Current density—electric field characteristics for a typical n-type germanium sample are shown in Fig. 2. Similar characteristics, though not quite so marked, have been obtained with p-type germanium. It is seen that ohmic behavior exists up to a field of about 6×10^2 v/cm, beyond which there is a gradual transition approaching constant current. For fields below 2×10^4 v/cm the number of carriers is considered to remain constant. The constant resistivity portion of the characteristics corresponds, then, to regions of constant mobility. The essentially constant current portion, on the other hand, corresponds to a range in which the mobility varies as E^{-1}, and in which the drift velocity is constant and of the order of 10^7 cm/sec. Beyond a field of 2×10^4 v/cm the current pulses are no longer flat-topped, and it is believed that hole injection or generation occurs. With less carefully prepared surfaces similar increases in the number of carriers are evident at lower fields.

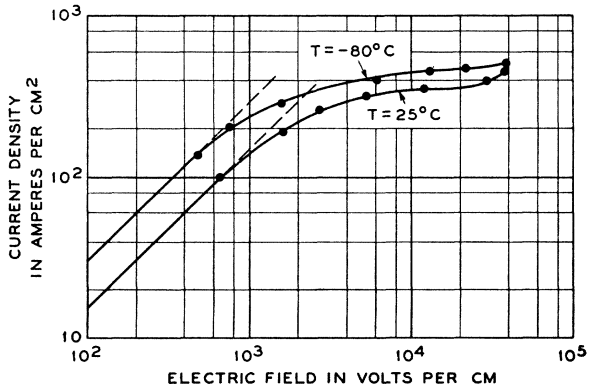

FIG. 2. Current density—electric field characteristic for a typical n-type germanium sample.

A theoretical analysis shows that if energy losses are due to acoustical phonons, the critical field at which Ohm's law should fail is about $c/\mu \doteq 150$ v/cm, where c is the velocity of longitudinal acoustic waves and μ the low field mobility. However, if energy losses due to "optical" modes[3] dominate, the critical field may be higher and a limiting drift velocity of about $(h\nu/m)^{\frac{1}{2}} \doteq 10^7$ cm/sec will arise, in good agreement with that observed. The data appear to represent the cumulative effect of both acoustical and optical scattering. At lower temperatures the acoustical modes should be the more important and a drift velocity $\doteq (c\mu E)^{\frac{1}{2}}$ is predicted. The apparent importance of the optical modes furnishes further evidence that the "effective mass" is not isotropic.[4]

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Experimental Evidence for the Three-Photon Annihilation of an Electron-Positron Pair*

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A DEVELOPMENT of recent origin in pair theory is the theoretical discovery of selection rules governing the annihilation of electron-positron pairs.[1–3] Calculations of the relative frequency of occurrence of the three-photon annihilation process as compared with the two-photon process have been made by Ore and Powell,[4] who obtain 1/370, and by Lifshitz,[5] who obtains 1/235.

The three-photon annihilation radiation was detected with three scintillation counters arranged symmetrically about the source of radiation and connected in triple coincidence. The coincidence circuit resolving time was 5×10^{-7} sec without genuine coincidence loss.

Cu^{64}, enclosed by aluminum of sufficient thickness to stop all particle radiation, was used as the source of annihilation radiation. Of all the positron emitters considered Cu^{64} was found to satisfy best the conditions imposed on the choice of source. All of the work reported was done with spectroscopically pure copper obtained from the Johnson-Matthey Company, Ltd., London.[6] Turnings from the copper rod, made with a carboloy tool, were sent to Oak Ridge for irradiation with slow neutrons.

Anthracene and naphthalene crystals were used. The maximum efficiencies attained were 8.5 percent for the anthracene crystals and 6.5 percent for the naphthalene crystals for 0.51 Mev photons. In each case the efficiency was about one-half the maximum attainable, as calculated from the Klein-Nishina formula. The range of solid angles used in separate runs extended from 0.534 to 0.740 steradian. Initial singles rates extended from 1.94×10^3/sec to 2.62×10^3/sec. The runs varied in duration from a minimum of 7 to a maximum of 15 hours.

Chief emphasis was placed on the measurement of the ratio of the cross sections. Two supporting experiments were also carried out. In one, measurements were made with the source out of the plane of the counter crystals; and, in the other, lead absorption

measurements were made on the three-photon annihilation radiation.

The ratio of the cross sections for the two-photon and three-photon annihilation processes, respectively, was obtained from the expression,

$$\sigma_2/\sigma_3 = N_2 f_3(\epsilon_{0.33})^3/N_3 f_2(\epsilon_{0.51})^2,$$

where N_2 and N_3 are the genuine doubles and genuine triples per single, respectively; f_3 is the fraction of all three photon sets intercepted by the three counters; f_2 is the fraction of all two-photon sets intercepted by two symmetrically spaced counters; $\epsilon_{0.33}$ and $\epsilon_{0.51}$ are the intrinsic efficiencies of the detectors for 0.33-Mev and 0.51-Mev photons, respectively.

Random accidentals arising from the two-photon annihilation process accounted for the largest portion of the spurious triples rate. The total triples rate was also corrected for accidentals of the second kind and those spurious triples arising as a result of the scattering of the two-photon annihilation radiation in the aluminum converter. The effect on the spurious triples rate of bremsstrahlung radiation emitted by the positron in slowing down was considered and found to be negligible.

Care was taken to eliminate spurious triples arising from counter-to-counter scattering. The sides of the crystals as well as the photo-multipliers were protected by $\frac{1}{16}$-in. lead sheet. In addition, a baffle system of $\frac{1}{4}$-in. lead sheet was arranged so that one counter could not "see" another counter.

Aluminum foil of such thickness as to stop even the most energetic electron recoil from the aluminum converter was put on the face of each crystal.

When equal weights were assigned to fourteen separate runs, the mean of the ratio of the cross sections was found to be

$$\sigma_2/\sigma_3 = (2.0\pm0.4)\times10^2, \quad \epsilon_{0.33}=\epsilon_{0.51};$$
$$\sigma_2/\sigma_3 = (3.3\pm0.7)\times10^2, \quad \epsilon_{0.33}=1.18\epsilon_{0.51},$$

depending on the assumption made concerning the efficiency of the detector for 0.33-Mev gamma-radiation relative to the efficiency for the 0.51-Mev radiation, the latter being determined by coincidence-counting of the two-photon annihilation radiation.

There are two reasonable assumptions for extrapolation of the value to $\epsilon_{0.33}$ from the measured efficiency $\epsilon_{0.51}$. In the first, $\epsilon_{0.33}=1.18\epsilon_{0.51}$, the efficiency varies directly as the Compton cross section, Compton scattering being the only process of importance for light materials in this energy range. In the second assumption, $\epsilon_{0.33}=\epsilon_{0.51}$, the increased "absorption" for the 0.33-Mev gamma-rays is compensated for by the greater ease with which the larger pulses from the 0.51-Mev gamma-radiation are detected.

Positive results were also obtained in the auxiliary experiments. The number of genuine triple coincidences obtained with the source out of the plane of the crystals was zero within the error of the experiment. The absorption experiment gave evidence that the three-photon annihilation radiation was softer than the two-photon annihilation radiation.

Work is continuing on the problem. The measurements are to be repeated with more efficient detectors and with a coincident circuit having a resolving time $<5\times10^{-8}$ sec. As an additional check on the existence of the effect it is planned to use Na^{22} as a source of positrons and to measure the quadruple coincidence rate in four counters.

I wish to thank Professor C. G. Montgomery for his constant encouragement and interest in this investigation. I am also indebted to Dr. Aadne Ore for valuable discussions.

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‡ Assisted by the joint program of the ONR and AEC.

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[6] We are indebted to Professor C. T. Lane for this copper.

Detection of X-Rays by Means of NaI(Tl) Scintillation Counters*

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In connection with proposed research on nuclear isomerism we have been interested in investigating the possibility of detecting individual x-ray quanta by means of scintillation detectors. Using NaI(Tl) crystals[1] with uncooled RCA 5819 photo-multiplier tubes, we have been able to detect individual x-ray quanta in the range of 5- to 80-kev energy with an efficiency approaching 100 percent. X-rays of 2-kev energy have been detected with an efficiency between 50 and 80 percent.

The x-rays used in this experiment were produced as follows. In the range of 15 to 80 kev by monochromatizing x-rays from an Mo target with a Bragg single-crystal spectrometer; in the range of 5 to 20 kev by using the fluorescent radiation of various elements excited by Mo x-rays; at 2 kev by using the continuous radiation from a V target, filtered by the Be window of the x-ray tube and the oil covering the NaI crystal.

The NaI crystals were cleaved under oil into $\frac{1}{2}$ in. to $\frac{1}{4}$ in. parallelopipeds and used according to a technique previously described.[1] A thin (0.0005 in.) Al reflector was set over the crystal. In the detection of low energy x-rays a hole was cut into the reflector to allow the entrance of the x-rays.

With this arrangement we have found, from the widths of the pulse height distributions, 1.0 to 1.5 photo-electrons emitted from the photo-cathode of the 5819 tube for each kilo-electron-volt dissipated in the crystal. This figure agrees with previous estimates.[1] With 8-kev fluorescent x-rays from Cu, for example, we have observed the pulse height distribution shown in Fig. 1a, the width of which corresponds to approximately 12 photo-electrons on the average from the photo-cathode. Since all of the x-rays are absorbed in the crystal and since there seem to be hardly any pulses of zero pulse height, we can be quite sure that each 8-kev x-ray quantum results in a detectable pulse and hence the detection efficiency is close to 100 percent. This follows also from

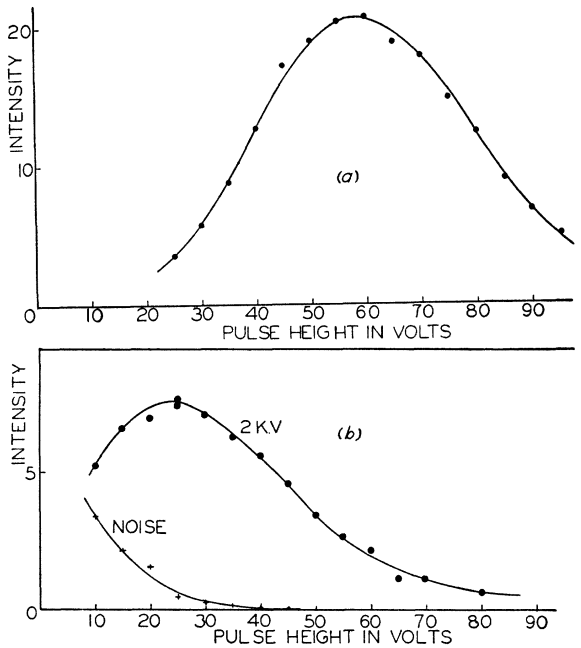

FIG. 1(a). Pulse height distribution due to 8-kev fluorescent x-rays from Cu (1.5-volt channel width). (b). Pulse height distribution due to 2-kev x-rays and due to photo-multiplier noise.