

decay of the milligram amounts of U^{233} used in the earlier investigations was too low to permit detection. However, gram quantities of U^{233} have since become available and with this larger amount of source material it has been possible to observe directly the Tl^{209} beta-particles.

The thallium was isolated by ether extraction from a solution of Ac^{225} obtained from a stock of U^{233} which had decayed for one year. The Ac^{225} was separated from the uranium by co-precipitation with lanthanum fluoride and was thoroughly purified by a procedure involving extraction of the Ac^{225} with a benzene solution of thenoyltrifluoroacetone to separate from radium and thorium isotopes,³ followed by addition of lead carrier and precipitation of lead sulfide to remove any extraneous lead, bismuth, or polonium activities.

Because of the short half-life of the thallium a method of rapid separation was necessary. The following procedure proved satisfactory. Ten milligrams of inactive thallium carrier and a small amount of bromine were added to 2 ml of 6N HCl containing the Ac^{225} . The solution was heated to oxidize the thallium to the extractable +3 state and the excess bromine boiled out. The solution was cooled, 2 ml of ether added and the mixture stirred for 30 sec. The ether phase was transferred to another vessel and stirred for several seconds with an equal volume of ether-saturated 6N HCl. After separation of the phases, the acid layer was drained through a stopcock and the washing repeated two or three times with fresh portions of acid. After the final wash the ether was transferred to a platinum dish and ignited. When the ether was consumed the platinum dish was rapidly cooled and placed immediately in the counter. The total time elapsed from start of the separation to start of counting was three to five minutes.

Decay of the thallium activity, which amounted to several thousand counts per minute initially, was followed at half-minute intervals. A small amount of long-lived activity, 20 to 30 counts/min. above the natural background, which remained after decay of the thallium was probably due to incomplete chemical separation. A typical decay curve is shown in Fig. 1. The half-life as determined by least-squares analysis of seven such decay curves was 2.20 min., with a probable error of ± 0.07 min.

An aluminum absorption curve of the Tl^{209} beta-particles (Fig. 2) was obtained by isolating a series of samples and following the

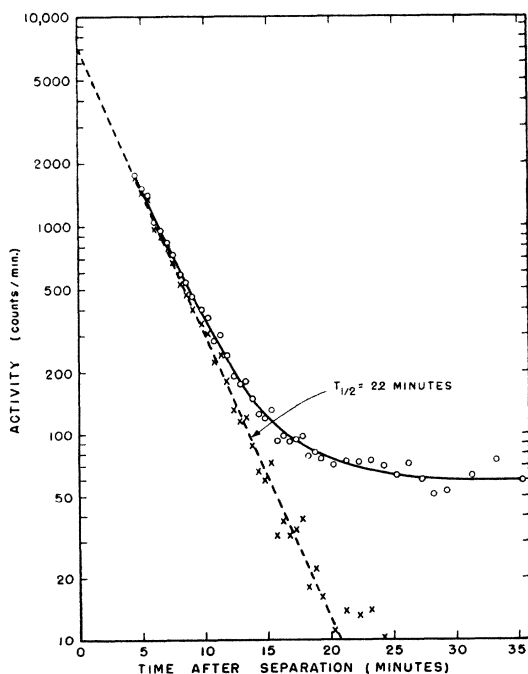


FIG. 1. Decay of Tl^{209} .

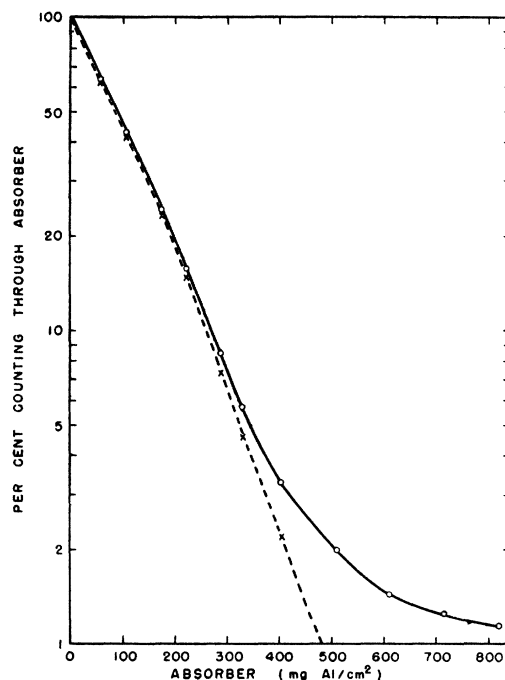


FIG. 2. Absorption of Tl^{209} beta-particles in aluminum. Feather range, ~ 825 mg Al/cm² corresponding to $E_{max} = 1.8$. Half-thickness ~ 80 mg Al/cm².

decay of each alternately with and without a given absorber. Each sample thus yielded one point on the absorption curve which was the ratio of the extrapolated counting rate at zero time with absorber to that without absorber. A Feather analysis⁴ of the absorption curve, after subtraction of the hard component, gave a value of about 825 mg of aluminum for the range, corresponding to a maximum energy of 1.8 Mev. The half-thickness was about 80 mg Al/cm².

¹ Hagemann, Katzin, Studier, Seaborg, and Ghiorso, Phys. Rev. **72**, 252 (1947); Phys. Rev. **79**, 435 (1950), this issue.

² English, Cranshaw, Demers, Harvey, Hincks, Jelley, and May, Phys. Rev. **72**, 253 (1947).

³ F. Hagemann, J. Am. Chem. Soc. **72**, 768 (1950).

⁴ N. Feather, Proc. Camb. Phil. Soc. **34**, 599 (1938); L. E. Glendenin, Nucleonics **2**, 12 (1948).

Resistivity of Semiconductors Containing Both Acceptors and Donors*

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THE resistivity of impurity semiconductors has previously been explained¹ by the addition of ρ_L , resistivity caused by scattering by lattice ions, and ρ_I , resistivity due to scattering by impurity ions. Since the mean free path associated with lattice scattering² is inversely proportional to temperature,

$$\rho = AT^{3/2}/n, \quad (1)$$

where A is a constant characteristic of the material and n is the density of conduction electrons or holes. By assuming that carriers are subject to Rutherford scattering by impurity ions, it has been shown³ that

$$\rho_I = 9 \times 10^{11} \pi^{3/2} e^2 m^{1/2} 2^{-7/2} \kappa^{-2} (kT)^{-3/2} (N_S/n) \times \ln \{1 + 36 \kappa^2 d^2 (kT)^2 e^{-4}\}, \quad (2)$$

where κ = dielectric constant, e and m electron charge and mass, and d one-half the average distance between the N_S scattering ions per unit volume.

Above 100°K the measured resistivities of most germanium samples agree very well with values calculated as the sum of $\rho_L + \rho_I$, with N_S set equal to n in calculating ρ_I . For samples of high impurity content ($>10^{18}$ cm $^{-3}$) the measured resistivity agrees with the values calculated taking $N_S = n$, down to temperatures as low as 4°K, provided that Eq. (2) is modified by using quantum statistics.¹ For samples having smaller impurity content, the measured resistivity² curve at low temperatures rises more rapidly with falling temperature than does the curve calculated in the manner described. At low temperatures, ρ_L becomes increasingly negligible compared to ρ_I , and so one cannot look to ρ_L behavior for explanation. The deviations cannot be explained as due to grain boundary effects because single crystal and polycrystalline samples show the same behavior. The observed resistivity behavior is such as would arise if N_S becomes increasingly large compared to n as T decreases. This would happen if N_S remains approximately constant while n falls off rapidly with decreasing temperature.

A germanium sample of either N - or P -type usually contains impurities of the opposite type in smaller concentration. Let N_N represent the maximum density of ionized donor levels and N_P the maximum density of ionized acceptor levels. For an N -type sample, $N_N > N_P$ and the N_P acceptor levels are filled with electrons from the donor levels, even at 0°K. These electrons are "frozen" in the acceptor levels and are not available for conduction at any temperature. At 0°K, with $n=0$, there are $N_0 = 2N_P$ scattering centers present. As T rises, n electrons are excited to the conduction band from donor levels, creating an additional n positive impurity ions. The concentration of scatterers may be taken as

$$N_S = n + N_0 = n + 2N_P, \quad (3)$$

where n has a temperature dependence found from the measured Hall coefficient, increasing from zero at 0°K to $N_N - N_P$ at exhaustion. At very low temperatures $N_S \approx N_0$ and thus independent of temperature. An analogous model applies to P -type samples.

In calculating the resistivity by use of Eqs (2) and (3), the number N_0 is so chosen as to give agreement of the calculated and measured resistivities at an arbitrarily chosen low temperature.

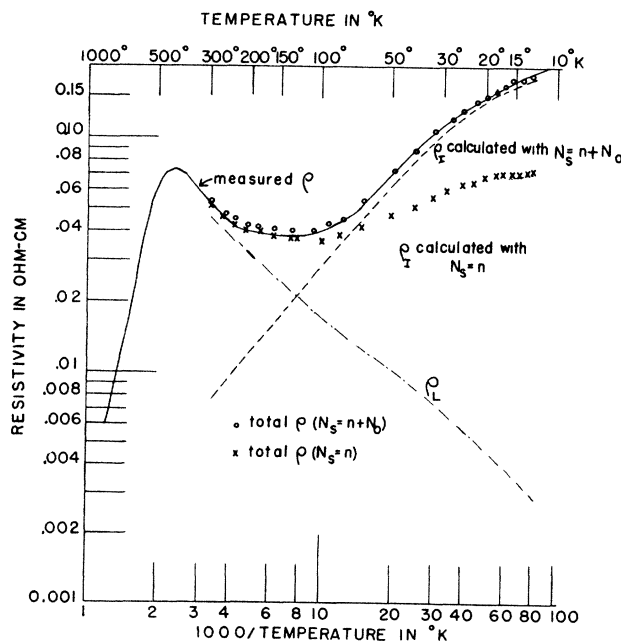


FIG. 1. Analysis of low temperature resistivity curve for germanium sample 33N (N -type, antimony added). N , impurity ion density at exhaustion $= 1.0 \times 10^{17}$ cm $^{-3}$. Agreement between theory and experiment is obtained by taking $N_0 = 2.4 \times 10^{16}$ cm $^{-3}$.

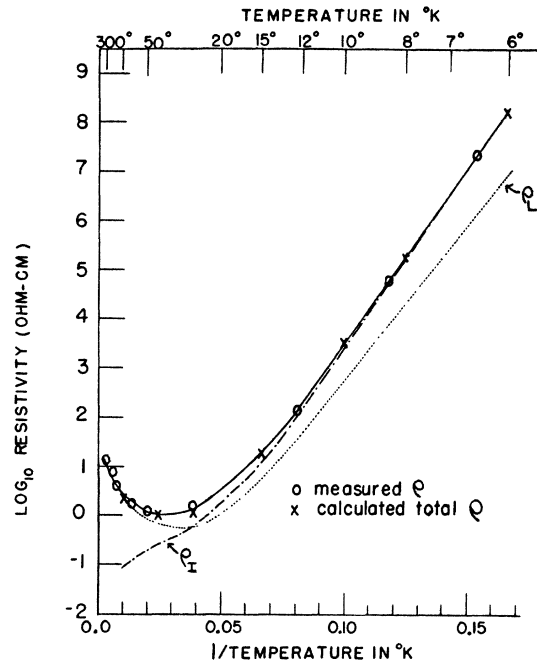


FIG. 2. Analysis of low temperature resistivity curve for germanium sample 43W-81 (high purity N -type). N , impurity ion density at exhaustion, $= 1.16 \times 10^{14}$ cm $^{-3}$. Number of scattering centers at 0°K, $N_0 = 1.04 \times 10^{14}$ cm $^{-3}$.

This N_0 is used in computing ρ_I from Eq. (2) throughout the impurity range. Figures 1 and 2 show, for two N -type samples of different impurity densities, the discrepancies appearing when N_S is taken as n and the good agreement obtained by considering the additional N_0 scattering ions. It is generally found for high resistivity samples that N_0 is of the same order of magnitude as the carrier concentration in the exhaustion range.

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¹ K. Lark-Horowitz and V. A. Johnson, Phys. Rev. **69**, 258 (1946); K. Lark-Horowitz (unpublished work).

² A. Sommerfeld and H. Bethe, *Handbuch d. Physik* (1933), Vol. 24, No. 2, p. 560.

³ E. Conwell and V. F. Weisskopf, Phys. Rev. **69**, 258 (1946); **77**, 388 (1950).

⁴ V. A. Johnson and K. Lark-Horowitz, Phys. Rev. **374**, 909 (1947); **72**, 531 (1947).

⁵ C. S. Hung and J. R. Gliessman (to be published).

Note on the Revision of the Hyperfine Structure of the Spectrum of Mercury

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OWING to an unfortunate misreading of the literature, a reference was given in an erroneous manner in our earlier Letter¹ on this subject. The last row of Table I should be omitted. The sentence from line 4 below the table commencing with "The value of . . ." to line 7, ending with ". . . the last row," should be omitted. The portion of the sentence of lines 8 and 9 below the table reading "not only different from that obtained by the nuclear absorption method, but is also" should be omitted.

A recent more accurate study has necessitated a change in the numerical values given in columns 2 and 7 of the last row but one of Table I from -182.3 and -2.86 ± 0.05 to -175.4 and -2.756 ± 0.017 , respectively. The conclusion is not altered by these changes.

¹ K. Murakawa, Phys. Rev. **78**, 480 (1950).