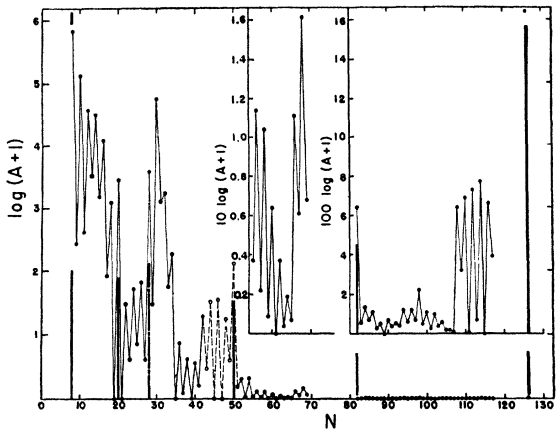

FIG. 2. The same as Fig. 1 except that the abundance is plotted as a function of the number of neutrons (isosteres). In the region of high N where the abundances are low a strikingly high relative abundance is indicated for $N=108$ to $N=116$.

In this communication only relations made more prominent by recent data are considered: many others are discussed in earlier papers.

The earliest suggestion (1915 to 1923) that certain proton and neutron numbers are related to high and low stability and abundance was made by the writer, but the first definite introduction of the concept of nuclear shells appears to be that of Bartlett.[5]

* From a paper on special numbers, presented as an introduction to the symposium on nuclear shells, New York Meeting of the American Physical Society (February 4, 1950).

[1] W. D. Harkins and E. D. Wilson, J. Am. Chem. Soc. **37**, 1367, 1383, 1396 (1915); Proc. Nat. Acad. Sci. **1**, 276 (1915); W. D. Harkins, Phil. Mag. **30**, 723 (1915). See also references 1–14, Phys. Rev. **76**, 989 (1949).

[2] Values collected by J. Greenstein as cited by G. P. Kuiper, *Atmospheres of the Earth and Planets* (University of Chicago Press, Chicago, 1949), p. 309. See also A. Unsöld, Zeits. f. Astrophys. **24**, 323 (1948); **21**, 1 (1941); L. H. Aller and D. H. Menzel, Astrophys. J. **102**, 239 (1945); D. H. Menzel—see Goldberg and Aller, *Atoms, Stars and Nebulae* (The Blakiston Company, Philadelphia, 1943).

[3] D. M. Goldschmidt, *Die Mengenverhältnisse der Elemente und der Atom-Arten* (Oslo, 1938).

[4] H. Brown, Rev. Mod. Phys. **21**, 625 (1949).

[5] J. H. Bartlett, Nature **130**, 165 (1932).

Yields of Photo-Neutrons with Calorimetrically Measured 320-Mev Bremsstrahlung*

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THE numbers of neutrons per erg of 320-Mev bremsstrahlung from samples hung in the beam six meters from the target were detected by a rhodium foil in a large paraffin block. Except for the calorimeter, the equipment and method were the same as those used with the 22-Mev betatron.[1] Corrections generally about 10 percent had to be made because of the distribution of beam intensity over the sample. A correction for the x-ray attenuation in the samples of heavy elements was never greater than 4.5 percent. This correction was not the calculated fractional loss of intensity due to absorption; rather, the correction was found by placing graphite detectors in front of and behind the sample and determining the relative activities. This empirical determination was necessary since degradation of high energy photons passing through the sample largely compensates for absorption of x-rays in the 20-Mev region where $\gamma-n$ processes occur. The rhodium-paraffin detector was calibrated with a known radium-beryllium source of neutrons. An uncertainty in all results described here is due to the unknown variation of efficiency of the detector for the neutron spectra from different elements and from the calibrating source.

For the calorimetric determination of x-ray intensity a collimated beam was absorbed in a lead block whose temperature was compared by thermocouples with that of a similar block not in the beam. The result was that our intermediate standard, a Victoreen 100r ionization chamber behind 0.125 in. of lead, indicated 7.8×10^{-4} joules/cm^2/r. Figure 1 shows the yields plotted with the yields[1] determined at 22 Mev for comparison. The numerical ordinates refer only to the 320-Mev yields.

If the bremsstrahlung spectrum is known, and if the effective photon energy for the disintegration is known, then the integral $\Pi=\int\sigma dE$ can be determined from these yields. For the case of deuterium the theoretical cross section can be used to estimate the yield for comparison with observation. Using the energy dependence of the deuterium cross section given by Bethe and Peierls with a maximum cross section of 24×10^{-28} cm^2, and using the theoretical spectrum used by the Berkeley synchroton group for a platinum target 0.020 in. thick, we calculate 6.3 neutrons/gram atom/erg/cm^2 averaged over all angles. We observe 6.9 neutrons/gram atom/erg/cm^2 after correcting the yield in the figure for the angular distribution and for the sensitivity of our apparatus as observed earlier.[1] Thus we observe 10 percent more than theory predicts. Another spectrum calculation for thin targets by Schiff[2] gives a theoretical yield 14 percent lower than is observed. Recent work of Almy and Diven with photo-disintegra-

TABLE I. Integrated cross sections, $\Pi=\int\sigma dE$.

Element	Assumed effective $h\nu$ (Mev)	Our values (Mev-barns)	Other determinations (Mev-barns)
C	30	0.11	0.14[a,b]
Cu	21	1.5	1.4[a,b]
U	16	11.	0.8[c]

[a] J. L. Lawson and M. L. Perlman, Phys. Rev. **74**, 1190 (1948).
[b] G. C. Baldwin and F. R. Elder, Phys. Rev. **78**, 76 (1950).
[c] G. C. Baldwin and G. S. Klaiber, Phys. Rev. **71**, 3 (1947).

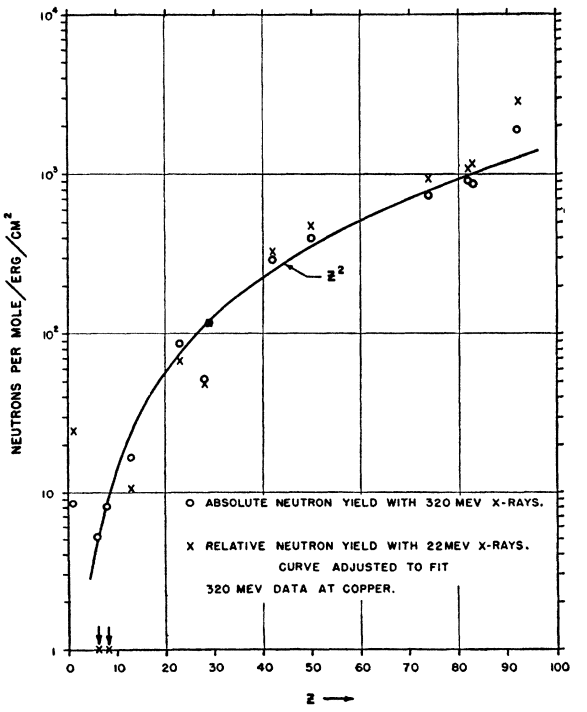

FIG. 1. Observed neutron yields at 320-Mev bremsstrahlung. The 22-Mev yield curve is adjusted to coincide at copper. The numerical ordinates refer only to the 320-Mev curve.

tions with the 22-Mev betatron has provided an ionization chamber calibration of the beam from that machine. Using their calibration and the previously observed yield at 22 Mev, we find that we observed 26 percent more than the theoretical yield. In this connection it should be noted that theoretically 90 percent of the yield from 320-Mev bremsstrahlung comes from the portion of the spectrum below 22 Mev. Thus the experiments at 320 Mev and at 22 Mev are measuring the photo-effect in the deuteron primarily in the same energy region. The great difference in the spectral shapes for these two energies is the reason for the relatively high yield for deuterium in the 22-Mev graph.

Table I shows some values of Π. Values of Π for the nine other elements can be computed from the yields in the graph, an assumption of $h\nu$, and a spectral shape. These integrals increase much faster than the theoretical Z dependence.[3,4]

Because of uncertain detector efficiency, one should hesitate to say that our type of experiment is good for determining Π in spite of the cases of agreement mentioned above. An unfavorable comparison is with Gaerttner's and Yeater's[5] results for oxygen. For the simple $(\gamma-n)$ disintegration we agree within 7 percent, but we are a factor of 4 below their value of Π which includes $(\gamma-p,n)$ and stars. Since these multiple disintegrations gave neutrons also, we should have detected some of them.

* Supported by the joint program of the ONR and AEC.
[1] G. A. Price and D. W. Kerst, Phys. Rev. **77**, 806 (1950).
[2] G. D. Adams, Phys. Rev. **74**, 1710 (1948).
[3] M. Goldhaber and E. Teller, Phys. Rev. **74**, 1046 (1948).
[4] J. S. Levinger and H. A. Bethe, Phys. Rev. **78**, 115 (1950).
[5] G. R. Gaerttner and M. L. Yeater, Phys. Rev. **77**, 714 (1950).

The Resistivity and Hall Effect of Germanium at Low Temperatures*

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June 8, 1950

THE theory of the electrical properties of germanium is based on the impurity semiconductor model.[1] The impurity donor and acceptor states are considered localized energy states. Conduction of electricity takes place by electrons in the conduction band or by holes in the filled band. Below room temperature, the contribution of intrinsic electrons and holes can usually be neglected, and conduction is due to only one kind of carrier, either electrons or holes. The activation energies for the impurity states are usually small but finite. As the temperature is reduced the concentration of electrons in the conduction band (or holes in the filled band) decreases rapidly with temperature. The resistivity and the Hall coefficient, which are inversely proportional to the concentration of carriers, therefore increase indefinitely as the temperature is lowered. Measurements of the resistivity and the Hall effect at low temperatures have been carried out to check the above prediction.

Germanium samples with different kinds of impurities and different concentrations were used. Measurements were carried out over a continuous temperature range from room temperature down to liquid helium temperatures. The results were found to be essentially independent of, (a) magnetic field variation between 1000 and 5000 gauss, (b) change by a factor of 10 in the electric field along the direction of flow of the sample current, (c) whether the potential leads to the sample were soldered on with tin or were pressure contacts onto rhodium-plated spots on the sample, (d) whether the sample surface is ground or etched, and (e) whether measurements were taken with increasing temperature or with decreasing temperature. The magnetic field, as measured at room temperature, is not expected to be influenced by the cryostat parts and the solder in the neighborhood of the sample at any temperature.

The resistivity and the Hall curves for some typical samples are shown in Figs. 1 and 2. It is seen that the resistivity and the Hall coefficient do not increase indefinitely as the temperature is reduced, as predicted by the usual theory. Instead, the Hall coefficient for every one of the samples investigated goes through a maximum at low temperatures, while the resistivity approaches a saturation value. This anomaly in the resistivity and the Hall effect calls for a modification of the usual theory of an impurity semiconductor, and will be dealt with separately.[2]

In the temperature region above that at which this anomaly occurs experiment and the usual theory agree satisfactorily. The activation energies for the different samples can be obtained from the slopes of the linear portions of the Hall curves. This activation energy is found to be of the order of 10 millivolts. It is lower for a higher impurity content. Sample SB-5 shows an almost flat Hall curve from room temperature down to 2°K. This may mean a complete overlapping of the impurity states with the conduction band; that is, zero activation energy. Or, it may mean that the mobilities in the conduction and the donor bands are approximately equal.

Owing to this low activation energy the exhaustion range, within which nearly all of the electrons are excited from the impurity states into the conduction band, extends from room temperature

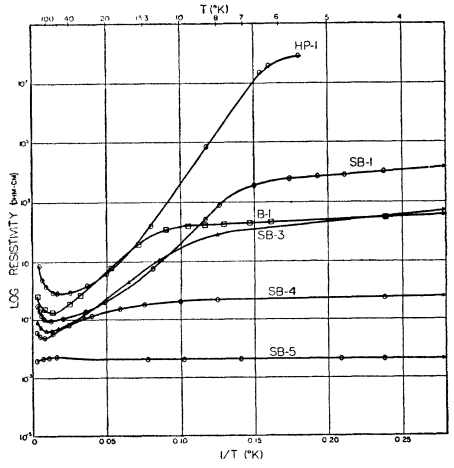

FIG. 1. Resistivity *vs.* $1/T$ for various germanium alloys: HP-1 is a high purity N-type sample; SB-1, SB-3, SB-4, SB-5 are N-type samples with antimony impurities; B-1 is a P-type sample with gallium and arsenic impurities. The impurities in the B-1 sample were introduced by neutron bombardment.

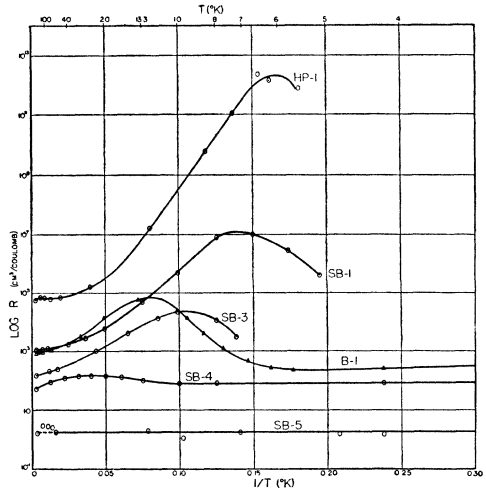

FIG. 2. Hall coefficient *vs.* $1/T$ for various germanium alloys. (See caption of Fig. 1 for description of samples.) For the higher resistance samples, the Hall coefficient at low temperatures became too small to be measured.