Letters to the Editor

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Total Neutron Cross Sections of Several Nuclei at 14 Mev*

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THE total neutron cross sections of polyethylene (for hydrogen), beryllium, carbon, titanium,[1] vanadium,[1] zirconium,[1] and lead were obtained from a good geometry transmission measurement using neutrons from the University of Pittsburgh cyclotron, made available through the courtesy of Dr. A. J. Allen. Neutrons in the energy range of 13 to 15 Mev were detected by allowing the neutron beam to impinge on a polyethylene radiator and then detecting recoil protons by passing them through a proportional counter telescope[2] made up of four counters in a triple coincidence, anticoincidence arrangement. Suitable aluminum absorbers were placed between the polyethylene foil and the front counter of the telescope and between the last two counters in order to determine the lower and upper energy limits, respectively, of the sensitive range of the counter telescope. The mean neutron energy was 13.9 Mev.

The samples whose neutron transmissions were measured were placed midway between the cyclotron target and the polyethylene foil of the neutron detector. The largest sample subtended a plane angle of 5° at the detector. Hence, it was necessary to correct each observed cross section for the effect of neutrons scattered elastically into the detector from the sample. This correction was calculated using the method of McMillan and Sewell.[3] Table I lists the observed cross sections, the elastic scattering corrections, and the corrected cross sections. The errors due to counting fluctuations are considered to be much greater than any others inherent in the method used, since the measured transmissions were corrected by measurement of stray neutrons scattered into the detector from the surroundings. Hence, the standard deviations listed with the corrected cross sections were calculated only on the basis of counting statistics.[4] The last column of Table I lists nuclear radii calculated from the corrected cross sections by the relation:

$$\sigma_t = 2\pi R^2.$$

The nuclear radii obtained from the present experiment are compared with those of Amaldi, *et al.*,[5] also measured at 14 Mev, in Fig. 1. The best fit to the data of Amaldi, *et al.*, is given by the straight line:

$$R = (1.3 + 1.37A^{\frac{1}{3}}) \times 10^{-13} \text{ cm},$$

which is plotted on Fig. 1. The carbon, titanium, and vanadium cross sections agree very well with the straight line. The beryllium radius is anomalously high; however, the beryllium cross section agrees well with the beryllium curve in Adair's[6] recent compilation of neutron cross sections. Interpolation of his curve of the beryllium cross section as a function of energy between 4 Mev and 40 Mev gives a value of the beryllium cross section at 14 Mev of about $1\frac{1}{4}$ barns. The measured value from the present experiment is 1.41±0.11 barns.

The zirconium and lead radii are apparently significantly smaller than the notion of constant nuclear density leads one to expect. Amaldi, *et al.*, also give a small value of the lead radius (9.00±0.13 $\times 10^{-13}$ cm). Furthermore, it is worth noting that the titanium, vanadium, and zirconium cross sections were all measured as part of one continuous data run, as were polyethylene and lead. It is concluded that the anomalously small zirconium and lead radii are indications of closed shell structure[7] of $_{40}Zr^{90}$ (48 percent abundant isotope) with 50 neutrons, and of $_{82}Pb^{208}$ (52 percent abundant isotope) with 126 neutrons or 82 protons.

TABLE I. Neutron total cross sections and nuclear radii.

Scatterer	Observed cross sect. (barns)	Scattering correction (% of obs.)	Corrected cross sect. (barns)	Standard deviation (barns)	Radius (10^{-13} cm)
Poly[a]	2.73	1.8	2.78	±0.09	···
H[a]	···	···	0.77	±0.04	···
Be	1.39	1.4	1.41	±0.11	4.73±0.21
C	1.23	0.8	1.24	±0.06	4.44±0.11
Ti	2.22	0.9	2.24	±0.29	5.98±0.36
V	2.49	1.2	2.52	±0.24	6.33±0.30
Zr	2.34	1.3	2.37	±0.35	6.14±0.45
Pb	4.80	3.5	4.97	±0.27	8.90±0.23

[a] The formula $(CH_2)_n$ was used for polyethylene in order to compute the hydrogen cross section: $\sigma_H = \frac{1}{2}(\sigma_{poly} - \sigma_C)$.

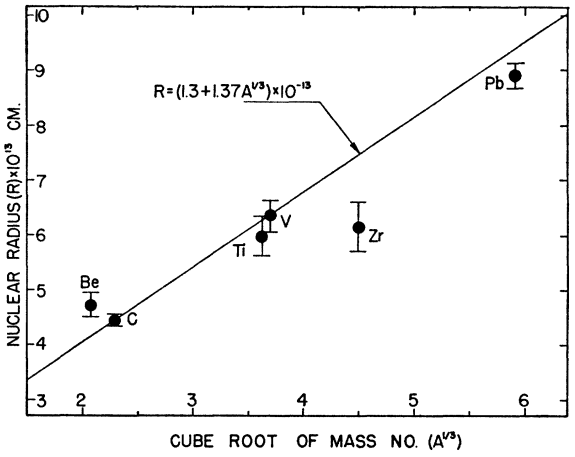

FIG. 1. Nuclear radius as a function of cube root of mass number. The straight line $R = (1.3 + 1.37A^{\frac{1}{3}}) \times 10^{-13}$ cm represents the best fit to the data of Amaldi, *et al.* The plotted points are calculated from the cross sections of the present experiment by the relation: $\sigma_t = 2\pi R^2$.

I wish to express my appreciation and thanks to Professor E. C. Creutz for suggesting this problem and for his continuing interest and advice.

* This work was supported in part by the ONR.
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[3] E. M. McMillan and D. C. Sewell, U. S. AEC publication MDDC-1558, unpublished.
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[5] Amaldi, Bocciarelli, Cacciapuoti, and Trabacchi, Nuovo Cimento **3**, 203 (1943).
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Mobilities of Electrons in High Electric Fields

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IN ordinary theories of electrical conductivity it is supposed that the electric field is so small that the energy given to the electrons can be transferred to the lattice with no great alteration in the energy distribution of the electrons. In the case of electrical breakdown such changes are considered, but the equilibrium

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

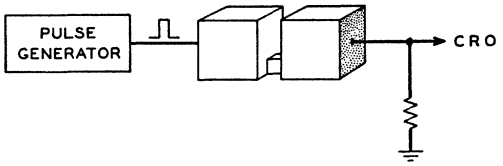

FIG. 1. Schematic diagram of germanium sample and its associated electrical circuit.

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.

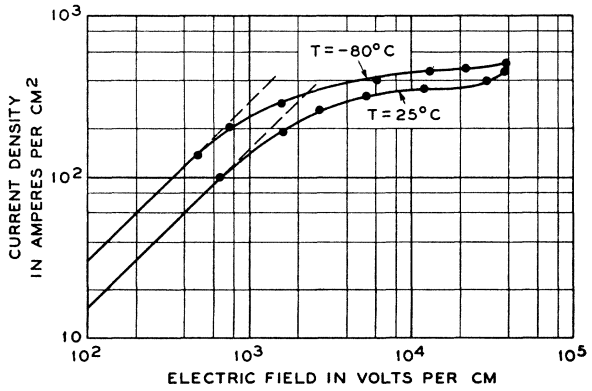

FIG. 2. Current density—electric field characteristic for a typical n-type germanium sample.

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