Reprinted from THE PHYSICAL REVIEW, Vol. 88, No. 1, 139–140, October 1, 1952
Printed in U. S. A.

Production of Photomesons in Deuterium*

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(Received August 20, 1952)

THE reaction

$$\gamma+d\rightarrow\pi^-+p+p' \quad (1)$$

is being studied by detecting the meson in coincidence with a recoil proton. Since the deuteron is a loosely bound structure, it was expected that in a fair fraction of the cases the process should be characteristic of that for a neutron moving with the momentum distribution of the deuteron, the role of the proton being only that of a spectator. The present letter is a report of an investigation primarily of this "spectator process."

The experimental arrangement is shown in Fig. 1. 0.50-cm targets of D_2O and H_2O were irradiated by 310-Mev bremsstrahlung. Mesons emitted at $90\pm10°$ with an energy of 56 ± 9 Mev were identified by their specific ionization and range in a coincidence-anticoincidence telescope of three scintillators. The recoil protons were counted by a Na(Tl) crystal 6.55 g/cm² thick, a range corresponding to that of a 69-Mev proton. Their energy was measured with a pulse-height analyzer. The cross section for the process (1) was obtained as a function of both the proton energy and angle by making a D_2O-H_2O subtraction. The H_2O count was about 30 percent of that for the D_2O.

Figure 2 shows the angular distribution of the protons integrated over the energy spectrum. Curve A shows the distribution to be expected with our geometry for meson production from a free neutron at rest; curve B takes into account the internal momentum of the deuteron, assuming the zero-range wave function and no momentum transfer to the "spectator" proton. The cross section for meson production was assumed constant over the energy and angular intervals employed. The agreement of curve B with the experimental points is satisfactory, supporting the assumption of negligible momentum transfer to the "spectator" proton.

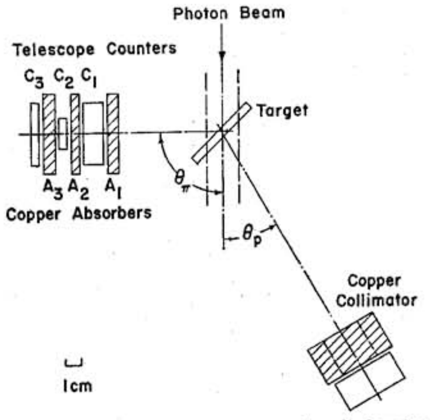


FIG. 1. Schematic diagram of the experimental arrangement.

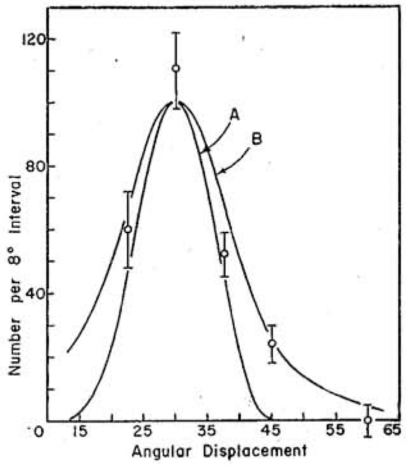
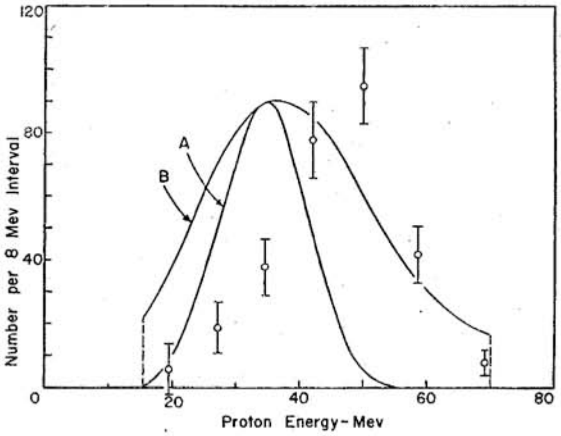


FIG. 2. Angular distribution of recoils counted in coincidence with a 56-Mev meson at 90°. See text for explanation of curves.

Figure 3 shows the energy spectrum of the recoil protons observed at $30°\pm6°$. Curves A and B were computed as for Fig. 2. The experimental points differ significantly from the theoretical curve in this case; they appear to be shifted from 10 to 15 Mev towards higher energy.

Considerable time has been spent in an effort to resolve this discrepancy. The proton counter was calibrated (1) by measure-



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ment of the Cs^{137} photoelectric peak at 0.67 Mev; (2) by measurement of pulses produced by cosmic-ray mesons at 9.5 Mev[1]; and (3) by extrapolation of the number-bias curve for an inhomogeneous beam of protons to the high energy cutoff at 69 Mev.[2] All these methods agreed to ±5 percent. Further checks were made by using different crystals for the proton counter and by direct range measurements on the protons.

An error in the definition of meson energy[3] could be produced if mesons were being scattered around the anticoincidence counter C_3. To check this point, experiments were performed with two different telescopes, in one of which C_3 had twice the area of the other. The results with the two telescopes were identical.

Assuming the angular distribution of recoils to be correctly given by curve B of Fig. 2, one can compute the differential cross section for the production of negative pions accompanied by correlated recoil protons. The value obtained is 10.8 ± 1.0 μb/sterad for production at 90° in the laboratory by 236-Mev photons. The error quoted is the standard statistical deviation. We have also determined the cross section for the production of negative pions without the requirement of a correlated recoil, using the π^-/π^+ ratios of Littauer and Walker[4] to separate the π^- and π^+ contributions in the telescope. The value so obtained is 11.8 ± 1.2 μb/sterad. The agreement between the two cross sections may be taken as evidence that the "spectator process" does indeed account for a substantial fraction of the meson production in the deuteron at the angles and energies here involved.

The correctness of the interpretation is, of course, still in doubt due to the failure to fit the energy distributions of the recoils. In closing, we might mention two possible explanations of this discrepancy which have been considered and found unsatisfactory. The first is that the low energy protons are preferentially removed by Coulomb scattering in the target. This is a small effect and there is a tendency for *scattering in* to cancel *scattering out*. The second is that the cross section for meson production might vary in such a way as to favor high energy recoils. Here the difficulty is that the photon energy in the c.m. system is defined within fairly narrow limits by the meson energy, regardless of the momentum state of the struck nucleon, and the cross section is unlikely to vary steeply enough within these limits.

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salt was replaced by a specimen cut from solid crystal, either hollow or having wall clearances.

As the existence of a helium II film in the tube connecting the capsule with the pumping system (up to 40 cm of its length in helium II bath when a membrane was not used, and 6 cm of its length in vacuum jacket when the diminished effect was observed) is a necessary condition for the appearance of the phenomenon, it could be perhaps considered as an extreme case of the fountain effect, producing cavitation of the helium II within the powder. The oscillations could then be explained by assuming consecutive coolings of the helium II film and warmings of the helium II in bulk, above the powder, with re-entries of the liquid into the colder powder.

In view of these observations, caution should be exercised with remote control experiments in assuming thermal equilibrium when a powdered paramagnetic salt is diluted with helium.

* This work was carried out under a grant from the National Research Council of Canada.

$p-n$ Junctions Produced by Growth Rate Variation

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(Received July 29, 1952)

MORE than a hundred uniformly spaced $p-n$ junctions have been produced in an ingot of germanium by periodically varying the rate of growth of the crystal from a properly doped melt. The amount of an impurity picked up by a growing crystal is determined by the segregation constant k,[1] which has been observed to depend upon the growth rate even when the accumulation of impurities ahead of the ingot is made negligible by thorough stirring of the melt.[2] The preparation of $p-n$ junctions by growth rate variation requires the presence of two opposite type impurities whose segregation constants vary at different rates with growth velocity.

Pronounced growth rate effects have been observed in the segregation of antimony during the solidification of ingots of germanium, as shown in Fig. 1. These data were obtained by conductivity measurements of a tri-crystal grown from a melt, using a bundle of three differently oriented seed crystals. Concentration of impurities in the melt ahead of the growing interface was made small by rotating the ingot at 200 rpm to provide thorough stirring.

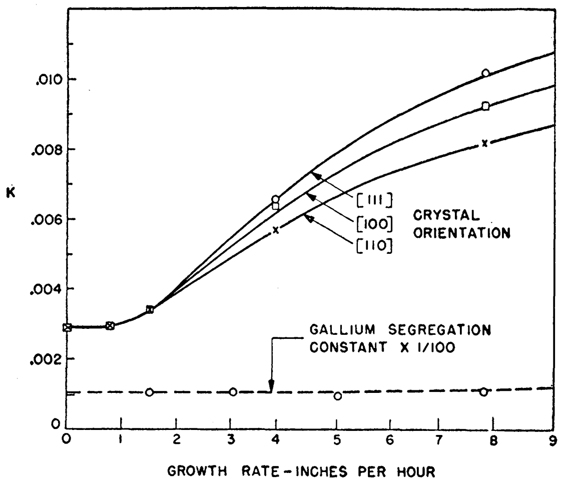

FIG. 1. Effect of growth rate upon the segregation of antimony during the growth of a germanium crystal.

Most p-type impurities such as Ga and In show much smaller changes in segregation constant. It follows that an ingot grown from a melt doped with the proper amount of antimony and either gallium or indium will be p-type when grown slowly and n-type when grown rapidly. By cycling the growth rate of an ingot, it is possible to produce a large number of uniform and evenly spaced $p-n$ junctions, each cycle producing two junctions having somewhat different characteristics. A wide variety of impurity distributions may be produced by changing the shape and amplitude of the growth cycles. In particular, this technique makes possible the growth of junctions having much smaller impurity concentration gradients than are produced by techniques previously reported.[3] Gradients less than 10^{-16} cm^{-4} are readily obtained and give rise to junctions having very low barrier capacities and high Zener breakdown voltages.

It is believed that the change in segregation constant with growth rate shown in Fig. 1 results largely from nonequilibrium conditions which prevail within the crystal near its growing surface. When the crystal is growing very slowly, the ratio of the impurity content in the solid to that in the liquid is given by the equilibrium segregation constant k_0. Because of the difference in binding energy at the surface of the crystal, it is to be expected that the composition of the surface layer of the crystal will be different from that in its interior. After each surface layer of the growing crystal is covered by a new layer, its composition will tend to approach the equilibrium value for the solid. If new layers are added too rapidly, however, the impurities have insufficient time to exchange with the surface, and material having a nonequilibrium composition will be grown.

The above mechanism leads to the following variation of segration constant with growth rate:

$$k=k_0+(k_s-k_0)\exp(-v_i/v).$$

Curves fitted to this equation are drawn through the experimental points in Fig. 1. The constant v_i is the growth rate for which the time interval between the deposition of successive layers to the crystal is equal to the relaxation time for the change in impurity content of a layer which has just been covered up. This time interval is comparable with the time required for antimony to diffuse a few angstroms in solid germanium as estimated from its measured diffusion constant.[4]

[1] R. N. Hall, Phys. Rev. **78**, 645 (1950).
[2] The dependence of segregation constant upon melt stirring was discussed by J. A. Burton and W. P. Slichter at the IRE and AIEE Conference on Semiconductor Device Research in June, 1952 (unpublished).
[3] Teal, Sparks, and Buehler, Phys. Rev. **81**, 637 (1951).
[4] W. C. Dunlap and D. E. Brown, Phys. Rev. **86**, 417 (1952).

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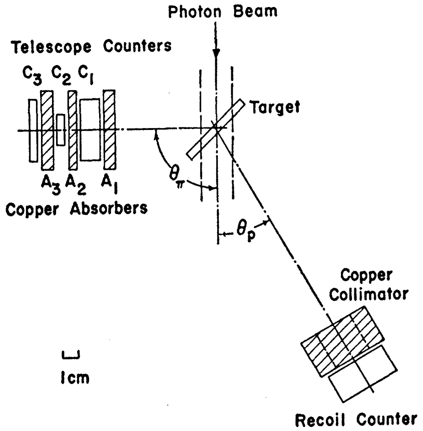

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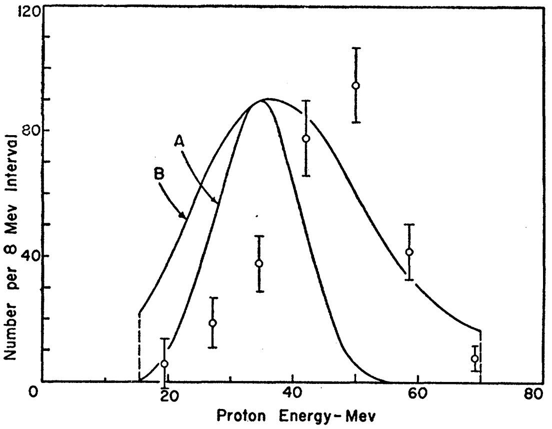

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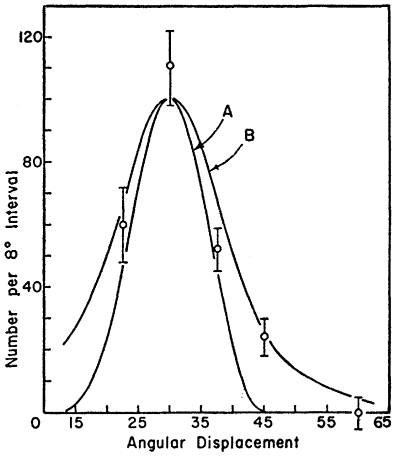

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An Anomaly in the Low Temperature Atomic Heat of Silver*

P. H. KEESOM AND N. PEARLMAN
Purdue University, Lafayette, Indiana

(Received July 21, 1952)

IN measurements of the atomic heat of the semiconductors Ge and Si at very low temperatures, the problem arose of distinguishing between two possible sources of deviations from a cubic dependence of the atomic heat on temperature: (a) electronic heat capacity (due to the presence of impurities); (b) polycrystal-