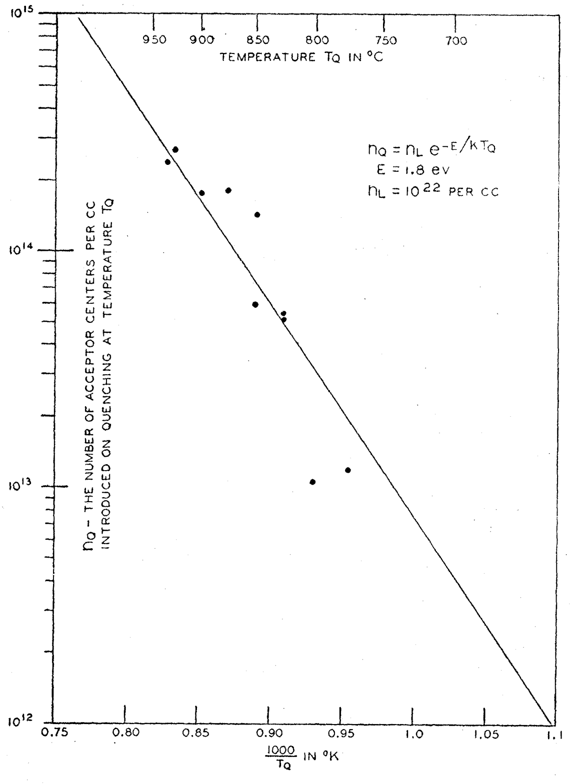


FIG. 1. Temperature dependence of acceptor concentration in quenched germanium samples.

where E is the activation energy for the production of an acceptor center and n_L is the maximum density of lattice sites that could be occupied by acceptors of this type. From theory,[7] n_L is approximately 10^{22} per cc for germanium. If the equilibrium state of the sample at temperature T_Q is essentially "frozen" by the rapid quench, the measured increase in acceptor center density should be very nearly equal to n_Q. In the limit of $T \rightarrow \infty$, the curve is made to pass through $n_Q = n_L$ as required theoretically. The activation energy is found to be 1.8 ev per center, which may be compared to the activation energy of 1.2 ev per center for the introduction of copper into the germanium lattice.[3]

If the thermally produced acceptor centers are due to some unknown chemical impurity, then Fig. 1 can be regarded as a plot of the temperature dependence of the solid solubility of this impurity in germanium. There are two ways in which impurities could enter a quenched sample. They could diffuse into the germanium during the quench, although no impurity whose diffusion in germanium has thus far been studied could diffuse uniformly from the surface in this short time. A more likely possibility is that an impurity has diffused into the germanium during the heating time, and that the rapid quench has essentially "frozen" this dispersed impurity which would otherwise "anneal" in the regular cooling cycle. This "annealing" might be similar to (though much faster than) that for copper in germanium. There is, as yet, insufficient evidence to distinguish lattice defects from chemical impurities.

Although the surface treatments described above permit the heating of a test sample to high temperature without resistivity change, there was always a decrease in body lifetime. For example, when a test sample with an original lifetime of 100μsec was heated for one minute at about 825°C, followed by the regular cooling cycle, the average body lifetime was reduced to 19μsec. It is known that recombination centers are formed by some chemical impurities[8] and by lattice imperfections.[9] In the heat treatments performed in these experiments, the cause of the recombination centers has not been ascertained. The preliminary experiments indicate that recombination centers diffuse in rapidly from the surface in a manner similar to copper. This suggests that, in this case, recombination centers may be a chemical impurity which has a marked effect on lifetime while making only a small contribution to the resistivity.

I would like to express appreciation to W. Shockley, M. Sparks, and G. C. Dacey for encouragement in these experiments.

---

[1] H. C. Theuerer and J. H. Scaff, Trans. Am. Inst. Mining Met. Engrs. **191**, 59 (1951); Fuller, Theuerer, and van Roosbroeck, Phys. Rev. **85**, 678 (1952).

[2] W. E. Taylor, Phys. Rev. **86**, 642 (1952); C. Goldberg, Phys. Rev. **88**, 920 (1952); L. Esaki, Phys. Rev. **89**, 1026 (1953).

[3] C. S. Fuller and J. D. Struthers, Phys. Rev. **87**, 526 (1952); W. P. Slichter and E. D. Kolb, Phys. Rev. **87**, 527 (1952).

[4] This cleaning process was developed in collaboration with M. Sparks.

[5] Lark-Horovitz, Bleuler, Davis, and Tendam, Phys. Rev. **73**, 1256 (1948).

[6] Such defects have been observed in gold by J. W. Kauffman and J. S. Koehler, Phys. Rev. **88**, 194 (1952).

[7] N. F. Mott and R. W. Gurney, *Electron Processes in Ionic Crystals* (Oxford University Press, London, 1940), Chap. II.

[8] I am indebted to J. A. Burton for communication of these results prior to publication. They will be presented at the joint Am. Chem. Soc.-Am. Phys. Soc. Symposium on Impurity Phenomena on June 16, 1953 (to be published in J. Phys. Chem.).

[9] G. L. Pearson (private communication); also, W. Shockley, *Electrons and Holes in Semiconductors* (D. Van Nostrand Company, Inc., New York, 1950), p. 347.

Examples of Multiple Pion Production in n-p Collisions Observed at the Cosmotron*

W. B. FOWLER, R. P. SHUTT, A. M. THORNDIKE, AND W. L. WHITTEMORE
Brookhaven National Laboratory, Upton, New York

(Received June 11, 1953)

About 100 events attributed to π-meson production by neutrons in hydrogen have been photographed under conditions described in a previous communication.[1] Neutrons produced in a carbon target by the 2.2-Bev proton beam in the Cosmotron passed through appropriate collimators into a hydrogen-filled diffusion cloud chamber located in a field of 11 000 gauss. Two examples of creation of pairs of pions in the gas are shown in Figs. 1 and 2. Data on these events are given in Table I.

Track c in event A can be attributed to a proton from its momentum and estimated ionization density which are given in Table I. Tracks a and b, by the same method, must have been produced by particles much lighter than protons, most probably pions. (Masses of a and b are <400 and <240 electron masses, respectively.) The 6 angles fixing the directions of the 3 tracks with respect to the direction of travel of the incident neutrons were also determined by reprojecting the stereoscopic photographs in space. The resultant p_r of the transverse components of the three momenta is given in Table I. The fact that p_r is not zero also indicates that at least one neutral particle must be involved in addition to the charged ones, which is assumed to be a neutron. The two pions are then produced in the reaction $n+p=n+p+\pi^++\pi^-$.

TABLE I. Data on pion-pair events.

		Event A	Event B
Track a (negative charge)	Momentum (Mev/c)	474±50	980±70
	Estimated Ionization density	1 ×minimum	1 ×minimum
Track b (positive charge)	Momentum (Mev/c)	286±20	550±40
	Estimated Ionization density	1 ×minimum	1 ×minimum
Track c (positive charge)	Momentum (Mev/c)	835±50	1260±200
	Estimated Ionization density	1.5 to 2 ×minimum	2 to 3 ×minimum
Resultant transverse momentum, p_r (Mev/c)		268±20	50±60
Sum of forward momenta, p_z (Mev/c)		1260	2770
Sum of energies of charged particles (a,b,c), E_m (Mev)		1140	1950
Energy of incident neutron, E (Mev)		$2060\ {}^{+140}_{-250}$	1980±250

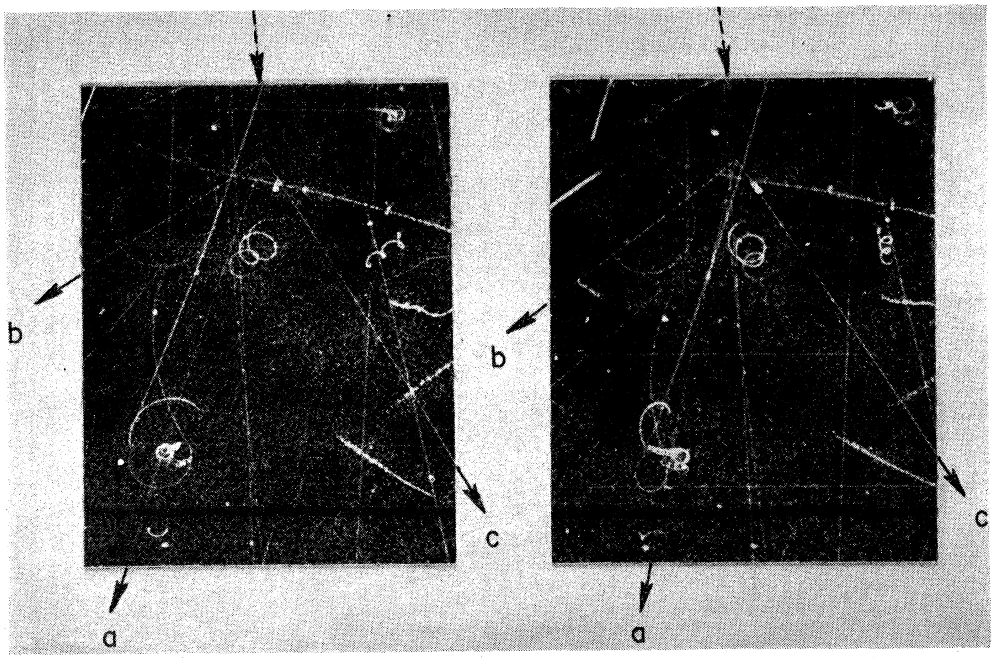


FIG. 1. Stereoscopic photograph of event *A*. Neutron enters in direction of broken arrow. Track *a* is identified as a π^-, track *b* as a π^+, track *c* as a proton. Horizontal black line is sweeping field electrode. Tracks pass underneath electrode.

From the sum p_z of the forward components of the momenta, the sum of the energies E_m of the charged particles (including all kinetic energies and the pion rest energies), and p_r one can calculate the energy E of the incident neutron, the indicated errors having been determined from the uncertainties of the momentum and angle measurements.

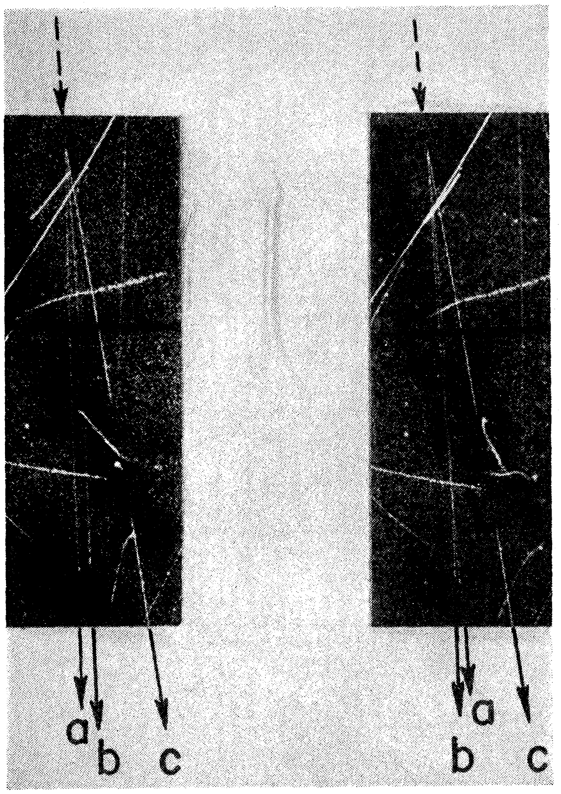


FIG. 2. Stereoscopic photograph of event *B*. Neutron enters in direction of broken arrow. Track *a* is a π^-, track *b* a π^+, track *c* a deuteron.

The energy available for meson creation in the center-of-mass system of incoming neutron and proton is 830 Mev. One can compute that the total energies of π^+ and π^- in the center-of-mass system are 320 and 300 Mev, respectively. Thus only 210 Mev remain for the nucleons in the c.m. system. This indicates the existence of very highly excited states of the nucleons after the collision. There is no obvious angular correlation between the outgoing nucleons and mesons in the c.m. system.

Track *c* in event *B* (Fig. 2) is of interest because of its large momentum and high estimated ionization density which are consistent only with a deuteron track. Track *b* must again be a particle much lighter than a proton, presumably a π^+ (mass <450 electron masses). We interpret this event as following the reaction $n+p=d+\pi^++\pi^-$. As required for this reaction, p_r is zero within the given errors which are mostly caused by uncertainties in the rather small angles involved here. p_z must here be equal to the momentum of the incident neutron. The energy E of the incident neutron calculated from p_z must be equal to E_m. p_z and E_m are indeed quite consistent with each other. Of the available c.m. energy of 810 Mev, the mesons have received about 90 percent. The deuteron passes almost straight backward in the c.m. system while both mesons pass forward.

Of 24 such 3-prong events so far analyzed we have identified the following π-meson production events: 10 definitely $(\pi^++\pi^-)$, 5 either $(\pi^++\pi^-)$ or $(\pi^0+\pi^-)$, 1 definitely $(\pi^0+\pi^-)$ (from momentum balance), 2 definitely single π^-, 4 possibly single π^-, and 2 which could not be determined. Thus at least $\frac{2}{3}$ of these events appear to be due to multiple meson production. The c.m. energy in all of these events was large enough to produce at least 4 mesons. To date we have not observed a single 5-prong event attributable to production of 3 charged mesons by a process such as $n+p=p+p+\pi^++\pi^-+\pi^-$. The possibility of a low meson production multiplicity in nucleon-nucleon collisions, mostly at considerably higher energies, has been indicated by a number of cosmic-ray observers.[2]

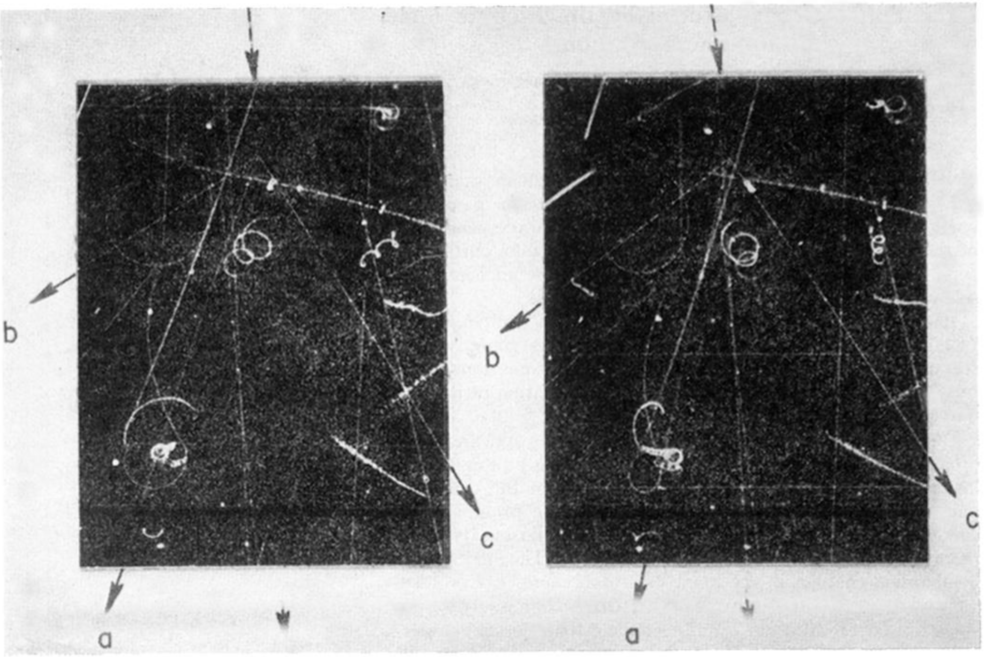
---

* Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **90**, 1126 (1953).

[2] See, for example, M. L. Vidale and M. Schein, Phys. Rev. **84**, 593 (1951); G. W. Rollosson, Phys. Rev. **87**, 71 (1952); W. Bosley and H. Muirhead, Phil. Mag. **43**, 783 (1952); A. B. Weaver, Phys. Rev. **90**, 86 (1953); McCusker, Porter, and Wilson, Phys. Rev. **91**, 384 (1953).

FIG. 1. Stereoscopic photograph of event *A*. Neutron enters in direction of broken arrow. Track *a* is identified as a π^-, track *b* as a π^+, track *c* as a proton. Horizontal black line is sweeping field electrode. Tracks pass underneath electrode.



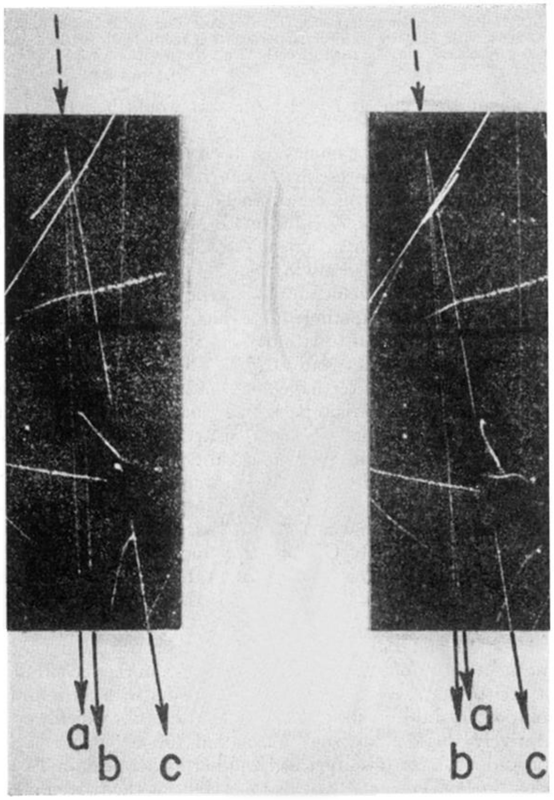


FIG. 2. Stereoscopic photograph of event *B*. Neutron enters in direction of broken arrow. Track *a* is a π^-, track *b* a π^+, track *c* a deuteron.