Production of Neutral V-Events by Cosmotron Neutrons*†

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Approximately 2000 cloud chamber pictures have been taken in the forward beam of neutrons produced by high-energy protons striking a beryllium target in the cosmotron. Nine V-events interpreted as the decay of a neutral particle produced in a one-inch lead plate in the cloud chamber, were observed. The neutron flux is estimated, from stars observed in the argon gas of the chamber, to be 140 per picture. An upper limit to the cross section for Λ^0-production of 3 millibarns per lead nucleus is deduced for the meson-producing neutrons.

INTRODUCTION

IT was first demonstrated by Fowler *et al.*[1] that neutral V-events could be produced by the forward neutron beam from the Cosmotron. The present experiment was undertaken to shed additional light on the production of unusual particles by this beam. Approximately 2000 pictures were taken of the interactions of the beam neutrons with a one-inch lead plate placed inside a cloud chamber. Half of these pictures were taken at an internal proton energy of 2.2 Bev and half at an energy of 3.0 Bev. Information concerning the flux and energy distribution of the neutrons was obtained from the nuclear interactions in the argon gas used to fill the chamber. Nine V-events were observed which were used to compute the cross section for V^0-production. No event was found which could be unambiguously ascribed to the decay of a charged particle. Three of the events which may be interpreted as the formation of neutral unstable particles in elementary collisions, are discussed in detail.

EXPERIMENTAL APPARATUS

The Yale mobile cloud chamber laboratory previously used for cosmic-ray studies[2] was extensively modified for use with the Brookhaven Cosmotron. The six-ton electromagnet which supplies a field of 8200 oersted, uniform within plus or minus 5 percent over the illuminated region of the chamber, was mounted on a frame and rotated through 90° to enable the chamber to operate in a horizontal position. This framework permits the magnet to be rotated back into position for cosmic-ray studies with little difficulty. The conventional expansion-type cloud chamber used in this experiment consisted of a glass cylinder 16 inches in diameter and 4 inches high, closed by a circular glass disk at the front and with a floating piston at the back. The illuminated region was 25 cm square with a depth of 6.5 cm. A lead plate, 2.5 cm thick in the beam direction, was suspended across the middle of this region. A potential of approximately 600 volts was applied between the top and bottom of the chamber to remove old ions. The chamber was filled with argon gas to a gauge pressure of 5 lb/in.^{2} in the expanded position. Pure ethyl alcohol was used as a vapor source.

The pictures were taken with a 5 cm Voightlander Nokton $f/1.5$ lens at an average demagnification of 11. The photographs taken at an internal proton energy of 2.2 Bev were recorded on Perutz Pergrano 35 mm film, while the 3.0-Bev pictures were taken on Linagraph Ortho. The lens aperture was varied from $f/8$ to $f/16$ for different combinations of film and lighting. Two mirrors mounted in the hollow pole piece of the electromagnet served to give stereoscopic images of the chamber, and each picture consisted of one direct view and two mirror views. The chamber was illuminated by discharging 200 microfarads, charged to 4000 v, through two xenon-filled, Edgerton-type flash tubes mounted on either side of the chamber, and collimating the resulting light with a condensing lens system.

The magnet room was maintained at 20°C±2°C with an air conditioning system. Four equally spaced thermopiles monitored the horizontal temperature gradients around the chamber, and these gradients were kept within ±0.2°C by means of auxiliary fans. In addition, an impressed vertical gradient of 1°−2°C was maintained by placing a heater wire around the top of the chamber.

A unique feature of the experiment was the inclusion, in almost every photograph, of a beam of soft x-rays collimated to give an artificial straight track. The beam was generated by a one-millisecond, 13 000-volt pulse applied to an x-ray tube (Machlett Laboratory, *A*-2 diffraction type, tungsten target). This beam proved very useful in standardizing the performance of the chamber and in eliminating conditions which caused severe gas distortion. The x-ray track was normally straight to within $\pm 2.5\mu$ on the film which corresponds to a momentum of 30 Bev/c for a 15-cm track. The circuits for this device and the application

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† This paper is based upon a dissertation submitted by R. M. W. to Yale University in partial fulfillment of requirements for the Ph.D. degree.
[1] Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **90**, 1126 (1953).
[2] Whetten, Preston, Adams, Walker, and Kraybill, Phys. Rev. **93**, 1356 (1954).

of the beam with other filling gases and under different conditions will be discussed in a separate publication.

OPERATION WITH THE COSMOTRON

The cloud chamber trailer was located 120 feet from the Cosmotron's target in the forward direction. The neutron beam is generated by protons striking a beryllium target in the east straight section and these neutrons emerge from the machine after passing through the thin aluminum side of the vacuum tank. Rough collimation is afforded by a 6 in.×6 in.×10 ft channel in the concrete shielding. In order to confine the beam at the trailer to the approximate dimensions of the illuminated region, the neutron beam is further defined by an iron collimator three feet thick with a slot approximately four inches wide by one-half inch high. This collimator is set just outside the shielding and is mounted on three screws to permit freedom in adjusting the final position of the beam. The final collimator alignment was obtained by narrowing the slot and centering the observed jet of neutral-induced charged particles emerging from the lead plate inside the cloud chamber. Gamma rays were almost completely removed from the beam by the addition of a $1\frac{1}{2}$ inch lead filter inside the concrete shielding. Unwanted charged particles were removed by passing the collimated beam through an 8500-oersted sweeping magnet.

This expansion chamber shared the available Cosmotron time with a diffusion cloud chamber operated by the Brookhaven Cloud Chamber group. The expansion chamber had a repetition rate of one per minute and operated from a target in the east straight section of the Cosmotron, while the diffusion chamber has a repetition rate of one per seven seconds and used a target in the south straight section. Hydraulically operated rams injected the appropriate target for each pulse. It was also possible to alter the intensity on the pulses alloted to our apparatus. The chamber was expanded and became sensitive before the arrival of the neutron pulse. The tracks are therefore post-expansion and have the advantage of being very sharp. A series of auxiliary experiments were performed to study the general properties of the beam and to determine the intensity of background particles. It was concluded that more than 90 percent of the neutral-induced events observed in the chamber were caused by neutrons proceeding directly from the internal target. We observed, however, an appreciable general background of charged particles which, although they did not limit this experiment in any way, would probably preclude much increase in neutron flux if it were desired for another experiment.

NEUTRON FLUX

Snow *et al.*[3] have measured the absorption cross sections for various substances in this neutron beam using a scintillation detector which is sensitive only to high-energy neutrons. It was found that the elastic scattering results were consistent with a neutron energy of 1.4±0.2 Bev. Neutrons below 1 Bev might constitute a sizeable fraction of the beam and would not be detected by the counter. However, Chen *et al.*[4] give only slightly lower values for the absorption cross section for 870-Mev protons, and various emulsion studies[5] show either approximately constant or decreasing values for proton-nuclear interaction cross section with decreasing energy from 2.2 Bev to 130 Mev. Therefore, the value of 560 mb for the nuclear interaction cross-section in argon, obtained from the results of Snow *et al.*, has been assumed in computing the flux of neutrons.

There were 98 argon stars observed at 2.2 Bev and 68 stars observed at 3.0 Bev. The corresponding total neutron flux was $(1.9\pm0.2)\times10^5$ for the 2.2-Bev data, an average of 145±15 per picture, and $(1.3\pm0.2)\times10^5$ for the 3.0-Bev data, an average of 135±15 per picture. The errors given are the standard deviations. These values represent lower limits for the neutron flux, since only stars with three or more prongs have been counted. It is expected, even at 1 Bev, that events with 2 or less prongs constitute a sizeable fraction of the measured absorption cross section. However, a knowledge of the neutron flux is desired primarily in order to obtain an upper limit for rate of Λ^0-production. Since this upper limit will be increased with a lowered neutron flux, it is not considered essential to correct the measured number of events for stars less than three prongs.

The fraction of argon stars in which negative mesons were identified is 0.22±0.04. The corresponding total flux of meson-producing neutrons is $(0.42\pm0.08)\times10^5$ at 2.2 Bev and $(0.29\pm0.06)\times10^5$ at 3.0 Bev. This represents a lower limit for the flux of meson-producing neutrons since no account has been taken of the number of positive mesons produced or of the reabsorption of mesons inside the argon nucleus.

NEUTRON ENERGY DISTRIBUTION

It is a difficult problem to measure the energy of the neutron beam, and only very general conclusions are possible at present. The experiments which bear on this problem were all performed at a proton energy of 2.2 Bev with internal targets composed of either beryllium or carbon. Since the prong distributions for the argon stars were not materially different for internal proton energies of 2.2 Bev and 3.0 Bev, it is assumed that the neutron energy distributions are approximately the same.

[3] Snow, Coor, Hill, Hornyak, and Smith, Phys. Rev. **93**, 791(A) (1954).

[4] Chen, Leavitt, and Shapiro, Phys. Rev. **94**, 784(A) (1954).

[5] Smith, Leavitt, Shapiro, Swartz, and Widgoff, Phys. Rev. **92**, 851(A) (1953); Bernardini, Booth, and Lindenbaum, Phys. Rev. **85**, 827 (1952); Lees, Morrison, Muirhead, and Rosser, Phil. Mag. **44**, 304 (1953); Morrison, Muirhead, and Rosser, Phil. Mag. **44**, 1326 (1953); P. E. Hodgson, Phil. Mag. **44**, 1113 (1953); **45**, 190 (1954); Widgoff (private communication).

Fowler *et al.*,[6] have made a study of three-prong events occuring in a hydrogen-filled diffusion cloud chamber operated in this same neutron beam. They find that the kinetic energies of the neutrons causing these events vary from 1.2 to 2.2 Bev with a median value of 1.7 Bev. If it is assumed that the mesons observed in argon stars were produced in the first nucleon-nucleon encounter, then the argon events which contain mesons represent incident neutrons which could have produced mesons in the hydrogen chamber experiment. It is true that only a particular class of *n-p* events and no *n-n* events were measured by Fowler *et al.*, and the latter events certainly contribute to the observed meson rate in argon. However, the absence in the hydrogen data of any meson production event less than 1 Bev implies a low cross section for meson production by nucleons below 1 Bev from the beam and it is therefore felt reasonable to assume that the observed meson events in argon represent neutrons with energies above 1 Bev.

The apparatus used by Snow *et al.*[3] to measure the cross section previously mentioned gave an average beam energy of 1.4±0.2 Bev. This apparatus has a steeply rising response with increasing energy and the neutron energy which they find is an indication that the true average neutron energy is lower than the median value deduced by Fowler *et al.*[6] However, the energy of the beam is inferred from the shape of the elastic scattering pattern and this is a less direct measurement than the cloud chamber result.

To obtain some additional evidence concerning the energies of the incident neutrons, the momenta of 21 selected secondary protons, emitted from the Pb plate at an angle of less than 5° from the neutron direction, have been measured. These tracks show a median momentum of 0.95 Bev/c, corresponding to a median proton energy of 0.4 Bev/c. This value is certainly a lower limit to the median neutron energy, since some energy has been carried off by production of π^0 mesons. On the other hand, the experiments of Snow and Fowler and co-workers tend to select mainly the higher-energy neutrons and their values should be upper limits to the average neutron energy.

ANALYSIS OF *V*-EVENTS

A *V*-event is defined as an event in which two tracks of opposite sign intersect at a point to form a *V*-shaped pattern, and for which it is possible to measure at least one momentum and the angle between the tracks. We will use the term V^0-particle to mean either Λ^0 or θ^0 particles which decay by the schemes:

$$\Lambda^0 \rightarrow p^+ + \pi^- + 37 \text{ Mev};$$
$$\theta^0 \rightarrow \pi^+ + \pi^- + 214 \text{ Mev}. \tag{1}$$

In those events in which it was not possible to distinguish between the Λ^0 and θ^0 by the direct identification of the secondaries, a dynamical approach suggested by Podolanski and Armenteros[7] was used. The variables $\epsilon = 2p_t/p$ and $\alpha = (p_1^2 - p_2^2)/p^2$, where p is the total V^0-particle momentum in the laboratory system, p_1 and p_2 equal the total secondary momenta, respectively, and p_t equals the transverse momentum of each of the secondaries, afford convenient representations of the decay schemes. Lines of constant p and p_t were constructed on the plane for the Λ^0 and the θ^0 decays and these were used to classify *V*-events if the momentum of both secondaries could be measured. In those ambiguous events in which only one secondary momentum could be measured, the direction and momentum of the assumed incident V^0-particle were calculated for both the Λ^0 and θ^0 decay schemes.

The curvatures were measured with a traveling microscope whose ways were straight to within ±1 micron. Orientation in space was determined by reprojecting through the original lens and mirror system onto a horizontal screen which could be moved in a vertical direction. The intersection of the direct and mirror images determined a point in space on the track. A number of space coordinates on a track could be determined by moving the viewing screen up and down. The normal precision for locating a point was ±0.05 cm in the horizontal plane and ±0.1 cm in the vertical plane.

EXPERIMENTAL RESULTS

There were nine *V*-events observed in this experiment, and the pertinent information concerning these is summarized in Table I. Events 32400, 32470, and *A*27 were obtained at an internal proton energy of 3.0 Bev and the rest were obtained at 2.2 Bev. There is little doubt that most of the observed *V*-events represent Λ^0 or θ^0 decays; although, of course, any individual event might be a neutron-induced two prong star. Of the nine *V*-events only one was observed upstream from the lead plate. On the assumption that the production per nucleon is the same in glass and lead, approximately 0.4 V^0's should have been observed

TABLE I. Summary of data for nine *V*-events.

Event	Identification	Q (Mev)		p (Mev/c)		Angle with beam	
		Λ^0	θ^0	Λ^0	θ^0	Λ^0	θ^0
18828	Ambiguous	37[a]	210[a]	500	500	25°	25°
18996*A*	Ambiguous	37[a]	210[a]	840	2000	16°	20°
18996*B*	θ^0 (*S*)[b]	···	245±100	···	750	··	5°
20166	Λ^0 (*S*)	45±20	···	680	···	35°	··
20334	Λ^0 (*D*)	50±20	···	826	···	35°	··
22*T*	θ^0	···	210[a]	···	685	··	32°
32400	Λ^0	42±20	···	827	···	22°	··
32470	Λ^0 *D*	36±15	···	950	···	34°	··
*A*27	Λ^0 *S*	36±15	···	500	···	22°	··

[a] Denotes cases where the Q value has been assumed in order to calculate the momentum of the postulated V^0-particle.
[b] *S* represents cases where both secondaries are identified. *D* represents identification by dynamical analysis.

[6] Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **95**, 1026 (1954).

[7] J. Podolanski and R. Armenteros, Phil. Mag. **45**, 13 (1954).

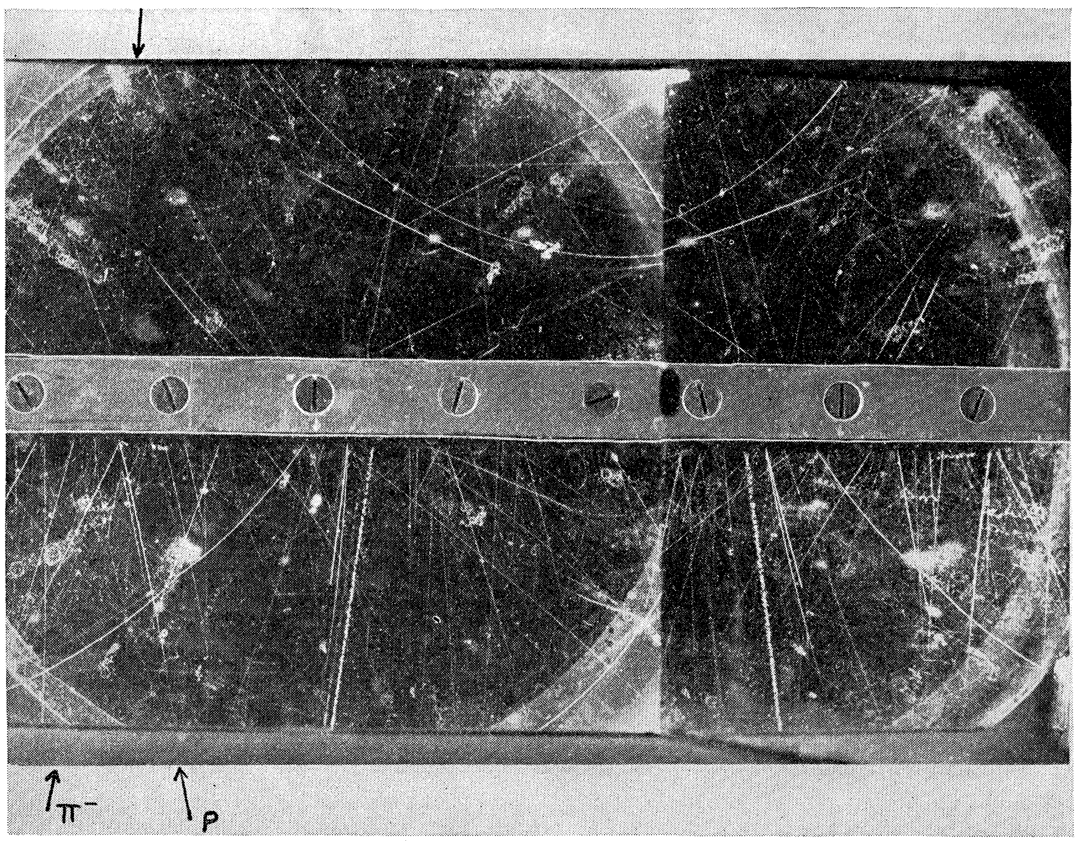

FIG. 1. Decay of a Λ^0-particle produced in the lead plate by a negative particle of momentum 2.2 ± 0.4 Bev/c.

upstream based on the number observed downstream. Within 10 percent there were the same number of argon stars in front of the lead plate as behind it, and the prong distributions were very similar. This indicates clearly that the particles causing the V-events are produced in the lead plate and that they are not identical with the neutral particles which cause argon stars. In every case where it was possible to measure the momentum of both secondaries, agreement was found well within the experimental error, for the interpretation of the event as either a Λ^0 or θ^0 decay.

In addition to the nine V-events there were two additional events which had the same general appearance but for which no momentum measurements could be made.

Three of the V-events may be interpreted as having been formed in elementary collisions and these are discussed in detail below.

Event 20166

This V-event, shown in Fig. 1, is identified as a Λ^0 decay. Curvature and ionization estimates indicate that the positive particle is a proton and the negative particle is a meson. The Q value based on the assumption of Λ^0 decay is 45 ± 20 Mev. A negative, minimum-ionizing track enters the lead plate on the upstream side and disappears. Measurements show that within the limits of error, this negative particle and the Λ^0 could have intersected at a single point inside the lead plate. No other charged particles are observed which could be associated with either the Λ^0 or the incident negative particle. The measured momentum of the upstream track is 2.2 ± 0.4 Bev/c. If it is assumed that the incident upstream track is a π meson then the upper limit of its momentum must be approximately 2.0 Bev/c, corresponding to the maximum meson energy available from the Cosmotron. If it is further assumed that this meson interacts with a proton inside a lead nucleus as if the proton were free, then the mass M_X, of the unknown particle in the postulated reaction,

$$\pi^- + p \rightarrow \Lambda^0 + X \qquad (2)$$

ranges from $950m_e$ to $1150m_e$ if the Q value of the Λ^0 is adjusted to 37 Mev. This event is therefore consistent with the reaction

$$\pi^- + p^+ \rightarrow \Lambda^0 + \theta^0, \qquad (3)$$

which has previously been reported.[8–10]

[8] Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **91**, 1287 (1953).

[9] Fowler, Shutt, Thorndike and Whittemore, Phys. Rev. **93**, 861 (1954).

[10] Thompson, Burwell, Huggett, and Karzmark, Phys. Rev. **95**, 1676 (1954).

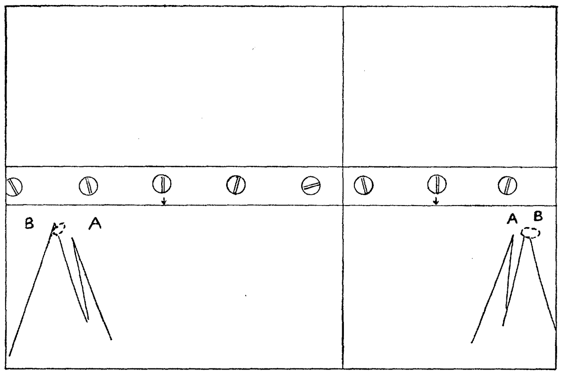

FIG. 2. The two V-events shown here appear to come from the same point within the lead plate. The event A may be either a Λ^0 or θ^0 particle. The event B is tentatively identified as a θ^0 particle.

The event is not consistent with the assumption that the incident particle is a negative K-meson of mass $\sim 1000 m_e$ which interacts to form a Λ^0 by the reactions,

$$K^- + p \to \Lambda^0 + \theta^0,$$
or
$$K^- + p \to \Lambda^0 + n. \quad (4)$$

Events 18896*A* and 18896*B* (Fig. 2)

Event A is a definite V-event in which only the momentum of the negative track can be measured. This event is completely consistent with either a Λ^0 or a θ^0 decay.

The apex of V-event B is obscured, and it is not certain that this can be classified as a genuine V-event. The directions of the positive and negative tracks have been measured carefully and they appear to intersect in a region where the apex is covered by other tracks. Nothing is seen emerging from the other side of the obscured region, although both tracks would be in a well illuminated region if they continued in their measured directions. The particles are both identified as mesons and the Q value calculated on the assumption of a two-body decay is 245 ± 75 Mev. This event is tentatively identified as the decay of a θ^0 particle.

If event B is interpreted as a θ^0 and event A as either a Λ^0 or a θ^0, the neutral particles could have come from a single point in the lead plate, within the limits of error. Events A and B, therefore, are tentatively identified as a single event in the lead in which two V^0-particles are produced.

Although the event occurs inside a lead nucleus, it is interesting to speculate about the elementary interactions that would produce such a pair of V^0-particles. It can be shown that no reaction of the type

$$N + N \to X_1 + X_2 + \theta^0 + \theta^0, \quad (5)$$

where N represents either a proton or neutron and where X_1 and X_2 are nucleons or hyperons, can explain this event. Moreover, reaction (3) is also inconsistent with the data. However, if it is assumed that the V^0's are produced in the following reactions:

$$N^0 + N \to \Lambda^0 + \theta^0 + N, \quad (6)$$

it is found that the incoming beam nucleon has an energy of 1.8 Bev. This is a reasonable energy, since the forward neutrons which are produced in elastic collisions in the Cosmotron target should have energies as high as 2.2 Bev.

The tenuous identification of events A and B and the fact that Eq. (5) is a three-body reaction, makes it impossible to conclude with certainty that the event is an interaction of this type. However, it is remarkable that Eq. (6) provides such a consistent interpretation of the data.

DETECTION EFFICIENCY AND PRODUCTION CROSS SECTION

It is difficult to assess the efficiency of V^0-particle detection in this experiment where so few events were found. A calculation was performed to determine an upper limit for the fraction of Λ^0-particles produced in the lead plate which decayed after leaving the illuminated region and hence escaped detection. It was assumed that the Λ^0-particles were produced by the reaction

$$N^0 + N \to \Lambda^0 + N, \quad (7)$$

and that their angular distribution in the center-of-mass system was isotropic. The relativistic time dilation makes it more probable that high-energy Λ^0-particles will escape detection and since (7) gives the maximum energy to the Λ^0, this calculation should give a true lower limit for the detection efficiency. Also Fowler *et al.*,[9] and Reynolds and Treiman[11] give evidence that the angular distribution of Λ^0-particles is peaked in the backward direction, and if this is true the detection efficiency should be higher than calculated from an assumed isotropic distribution. The calculation gives a lower limit for detection ranging from 0.75 to 0.50 for incident nucleon energies from 500 Mev to 2 Bev. These values do not include any allowance for the possibility that Λ^0's may decay into two neutral particles, nor for the additional loss of events which decay within the lead plates.

The most difficult factor to assess quantitatively is the scanning efficiency—the number of events which are observed relative to the true total number of events actually present in the pictures. The pictures taken at an internal proton energy of 2.2 Bev were very full and the scanning was done by several people. However, each of these pictures was scanned at least twice by different observers and this makes it likely that most of the events were found. It is believed that the scanning efficiency for these pictures is at least 50 percent and probably more than 75 percent. The 3.0-Bev pictures were generally of high quality and not too full. All of

[11] G. T. Reynolds and S. B. Treiman, Phys. Rev. 94, 207 (1954).

these latter pictures were scanned by two experienced observers and it is believed that the scanning efficiency was higher than 75 percent for these pictures.

The over-all detection efficiency of Λ^0's which decay into two charged particles is therefore believed to be at least 0.4.

Including the correction for detection efficiency, the cross section $\sigma(\Lambda^0,\text{Pb})$ for Λ^0 production by this neutron beam incident upon lead is less than 1 mb. If only neutrons are included which are able to produce mesons and which probably have energies in excess of 1 Bev, then the cross section is still less than 3 mb.

DISCUSSION OF EXPERIMENTAL RESULTS

The salient fact which emerges from this experiment is the low rate of production of Λ^0's by this neutron beam incident upon lead. In order to convert the cross section per lead nucleus to the cross section per nucleon, the possible loss of the Λ^0's in traversing the lead nucleus must be taken into account. This has been done approximately in a calculation performed by Jastrow.[12] In this calculation, it was assumed that only the first collisions are energetic enough to produce V-particles and that the V-particles are emitted in the forward direction.

The results of the calculation showed that even if Λ^0's intersect with a cross section of 40 mb in such a way that they are destroyed as free Λ^0's, the nucleon-nucleon production cross section $\sigma(\Lambda^0,N)$, based on meson-producing neutrons, is less than 0.2 mb. There is no evidence that Λ^0's should be lost with a cross section of this magnitude, and if no loss is assumed, then $\sigma(\Lambda^0,N)<0.06$ mb. This result shows that the cross sections for V-particle production by the reactions,

$$N^0+N\rightarrow\Lambda^0+N, \tag{9}$$

$$N^0+N\rightarrow\Lambda^0+\Lambda^0, \tag{10}$$

which have thresholds at 500 Mev and 900 Mev, respectively (neglecting internal motion of the nucleus) are considerably less than the reported cross section of $\sim$1 mb for 1.5-Bev π^- mesons incident upon hydrogen.[9]

The low value of $\sigma(\Lambda^0,N)$ may be due to a strong energy dependence of reaction (10), combined with a low average neutron energy, as suggested by our momentum measurements of secondary protons. However, it may also be due to reactions (9) and (10) being forbidden. In this respect it is interesting to inquire if the few Λ^0's which were observed could have been produced in other ways. Certainly, the Λ^0's which were found must have been generated by other mechanisms. Reaction (6) could account for all the observed V-events but since little is known about the number of neutrons which have energies greater than the threshold near 1.6 Bev for this reaction, no conclusions can be drawn about this process. The observed events could have been produced in secondary interactions inside lead nuclei in which π^- mesons, produced in primary encounters, generated the Λ^0-particles by reaction (3). Since the excitation function for Λ^0-particle production by π mesons is unknown as is the meson energy spectrum produced by this neutron beam incident upon argon, it is difficult to make a quantitative estimate of the number of such particles produced in this way. However, if the fraction of pions above 1.5 Bev is taken from the results of Fowler *et al.*[6] in this same neutron beam, and if the cross section for V-particle production by the meson is taken as $\sim$1 mb, then $\sim$10 events should have been produced in this way. Also, Jastrow's more refined calculations give an estimated cross section for the indirect process in lead of about 1 mb. It may be significant that one event was observed which is interpreted as the production of a Λ^0-particle in lead by a π^- meson which was probably produced in the glass of the cloud chamber. The data are therefore consistent with the assumption that reactions (9) and (10) occur infrequently or not at all.

[12] Robert Jastrow, Phys. Rev. **97**, 181 (1955).

CONCLUSIONS

(1) One event was found which can be satisfactorily explained by the previously reported reaction:

$$\pi^-+p\rightarrow\Lambda^0+\theta^0. \tag{11}$$

(2) An event which may be interpreted as

$$N^0+N^0\rightarrow N^0+\Lambda^0+\theta^0 \tag{12}$$

has been identified. Due to the lack of knowledge about the number of neutrons with kinetic energies greater than the threshold of 1.6 Bev, no conclusion about the cross section for this process is possible.

(3) The cross section in lead for production of Λ^0-particles by those neutrons which produce mesons, and which probably have energies greater than 1 Bev, is less than 3 mb.

(4) The sum of the cross sections for V-particle production by the reactions

$$N^0+N\rightarrow\Lambda^0+N,$$
$$N^0+N\rightarrow\Lambda^0+\Lambda^0,$$

based on those neutrons which produce mesons, and which probably have energies greater than 1 Bev, is lower than the reported cross section of $\sim$1 mb for 1.5-Bev π^- mesons incident on hydrogen. The data are consistent with the assumption that these reactions occur infrequently or not at all.

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Tantalum Spallation and Fission Induced by 340-Mev Protons*

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Nuclides formed as spallation and fission products during bombardment of tantalum metal with 340-Mev protons in the 184-inch Berkeley cyclotron were separated chemically, identified, and their formation cross sections were calculated. A very broad fission peak which extends from mass 20 to mass 132 is observed. The maximum fission yield occurs in the region of the nuclide Kr^{83} and analysis of a set of contour curves fitted to the data indicates that either Hf^{166} or Lu^{166} is "the most probable fissioning nucleus." The total cross section for fission is estimated to be 4.1 mb. Comparison of the fission data of tantalum with those of uranium and bismuth under the same bombardment conditions indicates that asymmetric fission is much more probable in tantalum than in either of the other elements. In the spallation region it is observed that neutron emission is the predominant spallation reaction. Integration under the spallation yield curve indicates that of those tantalum target nuclei which received at least enough excitation energy to reach the region of "the most probable fissioning nucleus" less than 1 percent undergo fission; the remainder undergo spallation reactions.

Activities which have been observed here for the first time include a 136-minute rhodium activity which has tentatively been assigned as an isomer of Rh^{107}; 29.4-hour Er^{160}; 5.0-hour Ho^{160}; and 74-minute Yb^{167}.

I. INTRODUCTION

THE earliest fission product studies and the reaction on which the most complete data are available concern the thermal neutron fission of uranium. Principal features of this fission process are:

1. Predominantly asymmetric splitting of the compound nucleus as shown by the appearance of two peaks in the fission yield *versus* mass curve.
2. Essentially complete absence of fission products on the neutron deficient side of stability.
3. Extremely steep slopes on both "wings" of the fission yield *versus* mass curve, with no fission products having a mass less than 72 or greater than 162 being observed in abundances greater than 10^{-5} percent of the fission events.

As the incident neutron energy is increased, the shape of the fission yield *versus* mass curve begins to change markedly, particularly in the region of symmetrical fission.[1] Engelkemeir, Freedman, Seiler, Steinberg, and Winsberg,[2] and Steinberg and Freedman[3] observed that when Pu^{239} was irradiated with neutrons of approximately 600 kev the yield of Pd^{109} was 50 percent higher than the yield with thermal neutrons. Turkevich and Niday,[4] as the result of bombarding thorium with pile neutrons of 2.6-Mev average energy, also observed an increase in the symmetrical fission region and suggested that the fission process at these energies is a combination of two types, one asymmetric and the other symmetric.

When the neutron energy is increased still further, the probability of symmetrical fission becomes even more pronounced. Spence[5] has shown that when U^{235} is irradiated with 14-Mev neutrons, symmetrical fission becomes one hundred times more probable than with thermal neutrons. This rise in the symmetrical fission yield is accompanied by a decrease in the yields of those nuclides which lie at the peaks of the thermal neutron yield curve; i.e., the yield of Mo^{99} was about 15 percent lower at 14 Mev than with thermal neutrons.

This increase in the symmetrical fission probability at higher excitation energies has also been observed in charged-particle bombardments. Newton,[6] irradiating thorium with 37.5-Mev alpha particles, showed that the symmetrical fission yield is almost equal to that for asymmetrical fission and that a deep minimum of the type which is observed in the yield curve for the thermal neutron fission of U^{235} has practically disappeared. Here the compound nucleus is the same for both particles so that direct comparison of the two yield

* This work was performed under the auspices of the U. S. Atomic Energy Commission.
[1] For a review of high-energy fission see R. W. Spence and G. P. Ford, Ann. Rev. Nuc. Sci. **2**, 399 (1953).
[2] Engelkemeir, Freedman, Seiler, Steinberg, and Winsberg, *Radiochemical Studies: The Fission Products* (McGraw-Hill Book Company, Inc., New York, 1951), Paper 204, National Nuclear Energy Series, Plutonium Project Record, Vol. 9, pp. 1331–1333.
[3] E. P. Steinberg and M. S. Freedman, reference 2, Paper 219, pp. 1378–1390.
[4] A. Turkevich and J. B. Niday, Phys. Rev. **84**, 52 (1951).
[5] R. W. Spence, Atomic Energy Commission Declassified Report AECD-2625, June 1949 (unpublished).
[6] A. S. Newton, Phys. Rev. **75**, 17 (1949).

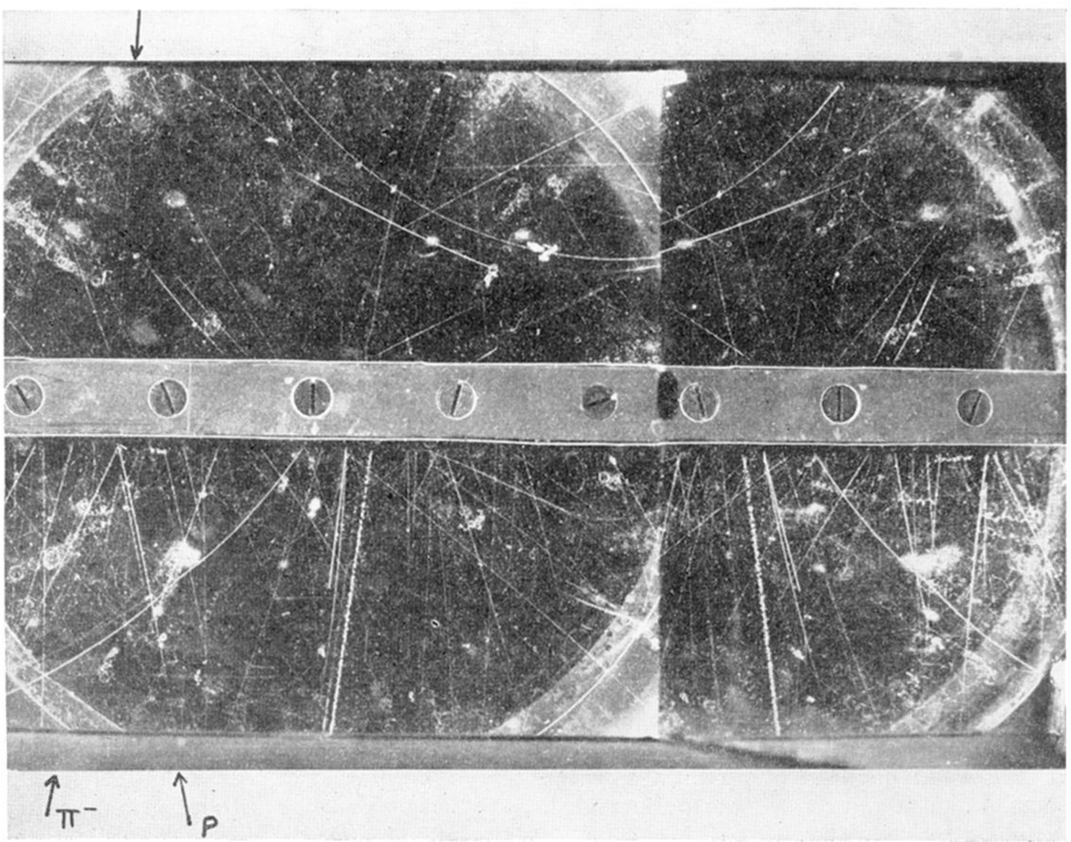

FIG. 1. Decay of a Λ^0-particle produced in the lead plate by a negative particle of momentum 2.2 ± 0.4 Bev/c.