$\Lambda^0-\theta^0$ Production in $\pi^- - P$ Collisions at 1 Bev

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Two examples of $\Lambda^0-\theta^0$ production have been found in the collision of 1.0-Bev π^- mesons with protons. Data on these two cases are given. The two cases are qualitatively similar, yet there are quantitative differences in terms of the angles of production of the θ^0 and Λ^0 particles. One case is internally consistent with the production of a Λ^0 and θ^0 directly. The other case, in which the Λ^0 and θ^0 particles seem slightly noncoplanar with the incoming π^- meson, is not internally consistent with the direct production of a Λ^0 and θ^0. It is likely that either the θ^0 or the Λ^0 or both θ^0 and Λ^0 are the products of decay of heavier parents. It is also possible that a light particle (γ or ν) may be produced simultaneously with the θ^0 and Λ^0. If one supposes that the Λ^0 is the product of decay of a heavier parent then the Q of such a parent, were it to decay into a proton and π^- meson, is calculated to be 117 ± 30 Mev. This Q value is close to that of the charged hyperons. A short-lived neutral hyperon of this mass has been predicted by Gell-Mann.

IN the last two years a considerable advance has been made in the understanding of the mechanism for the production of hyperons and θ particles. This illumination has been largely due to the work of the Brookhaven cloud-chamber group with their hydrogen diffusion chamber.[1] They have found 3 cases in which Λ^0 particles have been produced in $\pi^- - P$ collisions at 1.4 Bev. In one of these cases a particle which could be a θ^0 is also observed to decay. The only anomalous feature about these events was that the mass deduced by energy and momentum conservation for the K^0 particle seemed to be higher than the mass of the θ^0 particle as measured by Thompson and his collaborators.[2] After these events were found at Brookhaven, Thompson *et al.*[3] found an event in which a Λ^0 and θ^0 particle were produced in what seemed to be a $\pi^- - P$ collision of about 1.5 Bev. In this case both the θ^0 and Λ^0 were well identified. The present note deals with two new examples of $\theta^0-\Lambda^0$ production in $\pi^- - P$ collisions. It is possible that the Λ^0 is the product of decay of a heavier hyperon in one of the examples. The Σ^0 particle postulated by Gell-Mann and Pais fits the data very well.[4,5] These examples were found in pictures taken at Brookhaven with the same hydrogen diffusion chamber used previously. The author is much indebted to the Brookhaven cloud-chamber group for taking these pictures for him with their apparatus.

The nominal energy of the π^- beam in this experiment is 1.11-Bev total energy. This energy has been checked by finding elastic $\pi^- - P$ scatterings in which the energy of the proton is low and readily measurable. The primary energy is then deduced from the energy of the proton. In this way the spurious effects due to possible turbulence and optical distortion in the system are minimized. In nine cases measured this way the momenta of the beam particles are close to the nominal value.[6]

The two examples are shown in Figs. 1 and 2. The further V particle decays near the edge of the chamber after going about 6 cm from the point at which the π^- meson vanishes. Both of the tracks appear to have greater than minimum ionization even though the tracks would be expected to appear heavier because of their position in the chamber. In particular, the negative member of the pair must have ionization greater than minimum because the track is thicker than a minimum track. The momentum of this track can be roughly estimated and seems to be lower than 100 Mev/c. The track is probably due to a π^- meson. The V closer to the end of the π^- track decays into particles of nearly minimum ionization. The positive member of this pair is fairly flat in the chamber and the measured momentum of this particle is 153 ± 8 Mev/c. This particle must be a π meson or lighter. The negative particle runs into the bottom of the chamber and is short and distorted. These two V's are qualitatively consistent with being a Λ^0 and θ^0 respectively. The two particles are nearly coplanar with the incoming track. The tracks are in an unfortunate part of the chamber in that there is some optical distortion which produces some apparent noncoplanarity with the incident π^-. However, after correcting for the optical effects, there still remains a noncoplanarity of about 10° in azimuth, between the particles. The primary track is short but measurements indicate a momentum between 1.05 and 1.3 Bev/c.

The second event is very similar to the first one. There are two V particles decaying that are associated with the disappearance of a π^-. One of the V particles decays into two lightly ionizing particles, and the longer-lived one into two tracks with greater than minimum ionization. These two V particles also have properties consistent with those of the θ^0 and Λ^0 respectively. Unfortunately the θ^0-like particle travels only

[1] Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **91**, 1287 (1953); and **93**, 861 (1954).
[2] Thompson, Buskirk, Etter, Karzmark, and Rediker, Phys. Rev. **90**, 1122 (1953).
[3] Thompson, Burwell, Huggett, and Karzmark, Phys. Rev. **95**, 1576 (1954).
[4] M. Gell-Mann, Phys. Rev. **92**, 833 (1953).
[5] M. Gell-Mann and A. Pais, Proceedings of the Glasgow conference.

[6] The values of the incoming momentum in Bev/c obtained in this fashion are as follows: 1.05 ± 0.04, 1.07 ± 0.06, 1.11 ± 0.08, 1.11 ± 0.02, 1.08 ± 0.05, 1.04 ± 0.05, 1.13 ± 0.10, 1.11 ± 0.06, 0.985 ±0.05.

TABLE I. Experimental data on $\Lambda^0-\theta^0$ production, with the momenta and Q's deduced from momentum conservation.

Case	Momentum deduced from cons. of momentum P_θ Bev/c	P_Λ Bev/c	Direction of θ^0 and Λ^0 with respect to the direction of the π^- θ_Λ	θ_θ	Opening angles of the decay products with respect to the direction of the Λ^0 and θ^0 $\varphi_{P\Lambda}$	$\varphi_{\pi\Lambda}$	$\varphi_{+\theta}$	$\varphi_{-\theta}$	Q's deduced from momentum and opening angle Q_Λ in Mev	Q_θ in Mev
I	0.396±0.015	0.745∓0.010	11° ±1.5°	21°±2°	$6°_{-1°}^{+2°}$	64°±2°	$77°_{-3°}^{+5°}$	20°±3°	37_{-5}^{+10}	200±15
II	0.488±0.015	0.767∓0.010	22.5°±1°	37°±3°	6.5°±1°	66°±1°	27°±2°	49°±2°	43±5	195±20

2.5 mm before decaying, which makes accurate angle or coplanarity measurements difficult. The primary track in this case is somewhat longer than in the first case and the measured momenta is 1.10±0.04 Bev/c. Unfortunately, none of the momenta of the secondary particles are measurable.

The analysis of these two events is done as follows. The incoming π^- is assumed to have momentum 1.1 Bev/c. The reaction is assumed to have only two products. Then, from conservation of momentum, the momenta of the two products can be deduced. If one knows the momentum of the parent particle and the angles of its decay products relative to its line of flight, the Q of decay may be deduced if the identities of the decay products are assumed. Unfortunately the angle of the π^- meson from the first θ-like particle is not well determined because of distortion; however, in this case the momentum and angle of the π^+ meson are well determined so that the Q may be deduced.

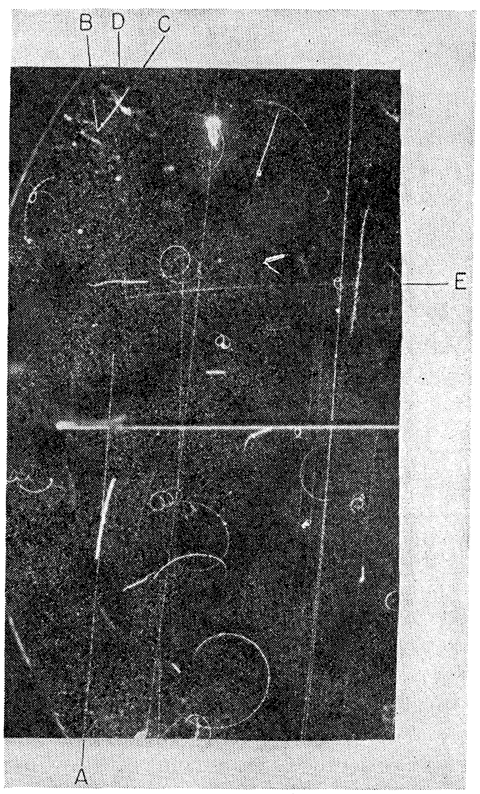


FIG. 1. $\Lambda^0-\theta^0$ production in a π^--P collision. Track A is the incoming π^- meson which disappears in flight. Direct measurements on this track give a momentum between 1.05 and 1.3 Bev/c. The adjacent π^- meson which crosses the chamber has a momentum of 1.14±0.10 Bev/c. Tracks B and C are the decay products of a Λ^0. Track C is short but momentum measurements give a momentum of less than 100 Mev/c and a negative sign. Tracks D and E are the π^- and π^+ mesons from the decay of the θ^0. Measurements on the π^+ meson give 153±8 Mev/c for the momentum.

The data concerning the angles of emission and the Q values deduced from the opening angles are given in Table I. In both cases it will be seen that the Q values of the V's agree fairly well with the values of 37±1 Mev[2,7] for the Λ^0 and 214 Mev for the θ^0.[2] Consequently it seems reasonable to conclude that the particles are the same as those found in cosmic radiation. There are, however, qualitative differences between the two events. In event I both the Λ^0 and θ^0 come out at a smaller angle than in the corresponding particles in event II. This would seem to indicate an energy much nearer threshold. As nearly as one can tell, however, the energies of the primaries are the same in both cases. In fact, if one assumes the accepted Q values for the Λ^0's and θ^0's, the momenta of these particles may be deduced, and then, by adding the longitudinal component of momenta of these particles, one finds an incoming momentum of 1.150±0.050 Bev/c for Case I and 1.090±0.050 Bev/c for Case II. In order to make these two cases consistent, the momentum of the incoming π^- in Case I would have to be lowered below 950 Mev/c.[8] On the basis of (1) the measurements on the primary and adjacent tracks in Case I, (2) the checks given by the momenta of the secondaries, and (3) the primary spectrum measurements, it seems very unlikely that the momentum of the incoming track was below 1 Bev/c.

Checks on the internal consistency of the two cases can be made in the following ways. First, the momentum of the Λ^0 particle is deduced from the opening angles of its products with respect to the line of flight by assuming the accepted Q value. Then, by using the conservation of momentum, the momentum of the

[7] Van Lint, Trilling, Leighton, and Anderson, Phys. Rev. **95**, 295 (1954).

[8] One should probably expect that the momenta of the beam particles from the cosmotron will change slightly from pulse to pulse of the cosmotron. With this in mind the longest beam tracks in the picture in which event I occurred were measured. The results of the momentum measurements are, in Bev/c: 1.14±0.10, 1.07±0.05, 1.04±0.04, 1.07±0.02, 1.14±0.06. The errors are assigned on the basis of the consistency of the two views. Corrections for optical or chamber distortions are made on the basis of nearby no-field tracks.

TABLE II. Momenta of the Λ's and θ's as deduced from opening angles and the Q's of the θ's as deduced from momentum and energy of the Λ^0's. In this table the uncertainties in the momenta of the θ^0 and Λ^0 are deduced from the uncertainties in the opening angle measurements. The uncertainties in the P_Λ produce the uncertainties in the calculated values of P_θ and E_θ in the manner shown, i.e., a + change in P_Λ produces a − change in P_θ.

	Momenta and energy deduced from opening angles				Momentum and energy and Q of θ^0 deduced from momenta and energy of Λ^0		
	P_θ in Bev/c	E_θ in Bev	P_θ in Bev/c	E_θ in Bev	P_{θ^0} in Bev/c	E_θ in Bev/c	Q_θ in Mev
I	0.745±0.04	1.343±0.020	0.440±0.02	0.660±0.013	0.395∓0.035	0.707∓0.02	309±3
II	0.710±0.04	1.324±0.020	0.537±0.02	0.728±0.015	0.523∓0.025	0.726∓0.02	226±6
A[a]	0.610±0.04	1.273±0.02			0.988∓0.031	1.177∓0.02	362±10
B[a]	0.745±0.04	1.343±0.020			0.923∓0.03	1.107∓0.02	318±10

[a] Fowler *et al.*, reference 1. Note that in Case B a π^0 cannot have been produced in conjunction with a θ^0. In Case A a hypothetical π^0 meson would have to be closely correlated in angle and velocity with the θ^0. It seems unlikely that π^0's are produced in either case.

second particle is deduced. Finally, by using the conservation of energy, the energy, mass, and Q of the θ^0 are deduced. In Case II the Q of the θ^0, deduced in this way, is close to Thompson's value.[2] In Case I, however, the Q value deduced for the θ^0 is 309 Mev. This state of affairs is rather reminiscent of the cases found by the Brookhaven group in the 1.4-Bev π^- meson beam.[1] The results of these calculations together with those on the Brookhaven cases A and B of Fowler *et al.*[1] are given in Table II. Cases A and B are interesting in that the deduced mass of a possible K^0 in these cases is rather insensitive to the assumed beam energy and momentum of the Λ^0 particle.[9]

One might suppose that such a particle, which according to Table II seems to have a mass of 1200 to 1300 electron masses, would rapidly decay into a θ^0 particle and another neutral particle. If such a particle had a mass of more than 1240 electron masses, then it would be energetically impossible to produce them in conjunction with a Λ^0 particle in a $\pi^- - P$ collision at 1.1 Bev. If the mass of such a K^0 particle were in the neighborhood of 1200 electron masses and emitted a γ ray or neutrino then the average momentum of such a light particle in the laboratory would be about 140 Mev/c. This particle should be detectable by momentum balance alone, but it doesn't seem to be. It is also possible that both Λ^0 and θ^0 are decay products or that γ's or ν's are produced simultaneously with the θ^0 and Λ^0.

It seems slightly more reasonable to assume that it is the Λ^0 rather than the θ^0 that is the decay product. A particle which decays into a Λ^0 particle has been

TABLE III. Calculation of the Q value of the Λ^0 from the momenta and energy of the θ^0. In this table the uncertainties are calculated from the uncertainties in the measurement of P_{θ^0} from the opening angles. Because of the errors in the measurement of the angle of production of the θ^0 and uncertainties in the beam energy, the Q value in Case II is consistent with the accepted value for the Λ^0 particle.

Case	P_Λ in Bev/c	E_Λ in Bev	Q in Mev
I	0.707±0.017	1.39 ±0.013	117±3
II	0.745±0.010	1.322±0.015	14_{-5}^{+10}

[9] After the present manuscript was started, the author received a preprint from the Brookhaven group giving their most recent results. The author wishes to thank Dr. Fowler, Dr. Shutt, Dr. Thorndike, and Dr. Whittemore for the preprint. They have also reconsidered these first cases A and B and found them to be consistent with the production of a Σ^0 and θ^0. By using a calculation similar to the one given above, that is, assuming that momentum is balanced by a θ^0, one then finds an energy missing from the reaction of the order of 70 Mev. This missing energy is assumed to be associated with the decay of the Σ^0, and in this way the Q of the Σ^0 may be bracketed between 70 and 140 Mev.

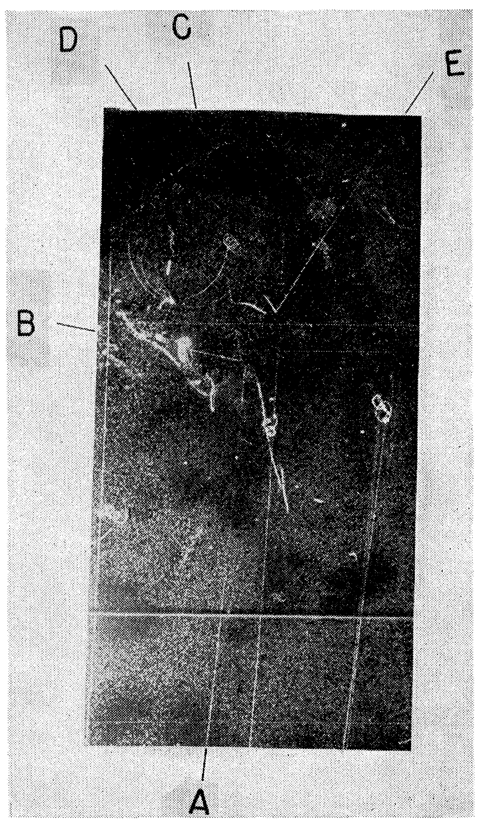


FIG. 2. The second example of $\Lambda^0-\theta^0$ production in a $\pi^- - P$ collision. Track A is that of the primary pion. Its measured momentum is 1.10±0.04 Bev/c. It vanishes in flight and 2.5 mm from its point of disappearance the decay of a neutral meson into two lightly ionizing tracks, B and C, can be seen. A few centimeters further, a neutral hyperon may be seen to decay. The long track E, seems to have about two times minimum ionization as does track D. Track E was probably produced by a proton and D by the π^- meson from the Λ^0 decay.

proposed by Gell-Mann and Pais.[4,5] This is the neutral counterpart of the Σ^+ and Σ^-. To check this possibility, the measured momentum and energy of the θ^0 in the two cases are used to calculate mass and Q of the heavy hyperon (see Table III). The Q deduced in Case II seems consistent with that of the Λ^0; the Q deduced for Case I is 117 Mev,[10] which is the same as the Q observed for the charged Σ's. This number is, of course, subject to experimental uncertainty. The value of the Q is relatively insensitive to errors in the momentum of the θ^0. The change in Q for a 50-Mev change in the incoming energy is 30 Mev. The probable uncertainty in Q is the order of ± 30 Mev. The estimated unbalance of momentum for the products in Case I is (50_{-30}^{+30}) Mev/c and the energy that has vanished from the reaction is 47 ± 25 Mev. This result is consistent with the third particle being a single γ ray or neutrino.

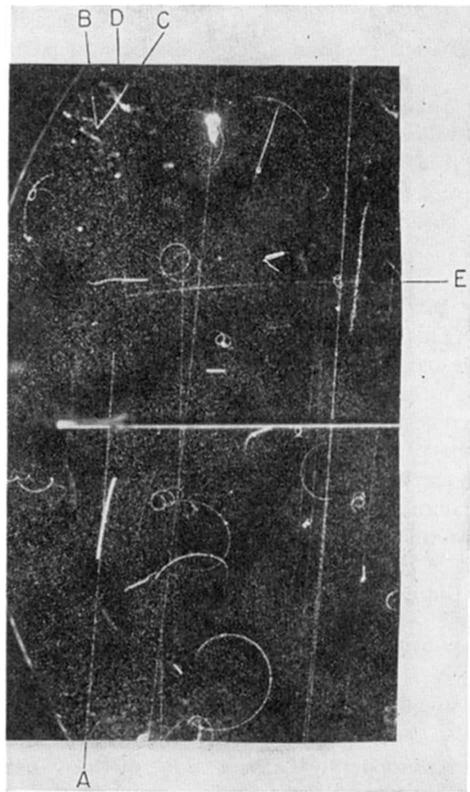
The orientation of the planes of decay of the θ^0 and Λ^0 particles in Case I are rather similar to those observed by the Brookhaven group. The θ^0 decays perpendicular to the plane of production and the Λ^0 in the plane of production ($\Delta\varphi = 20°$). The fact that the noncoplanarity is difficult to detect perhaps indicates that the decay of the parent of the Λ^0 is also nearly in the plane of production. In Case II, in which the Λ^0 is produced directly, the orientations are somewhat different; the θ^0 decays nearly in the plane of production and the Λ^0 plane of decay is at an angle of 40° with respect to the plane of production.

The angles of production in the $\pi^- - P$ center-of-mass system are at 82° for the Λ^0 and 114° for the Σ^0. These angles are close to 90° which is rather different from the observations at 1.4 Bev in which the Λ^0's seem to go backward in the center-of-mass system. Observations of the momentum of isolated Λ^0's produced at 1 Bev seem at least to indicate that the backward direction is not preferred at this energy. It is interesting to note that the angular distribution of the Λ^0's at both energies closely parallels the distribution of the nucleons emerging from collisions in which π meson production takes place.[11]

The author wishes to express his gratitude to R. P. Shutt for his generosity in making this experiment possible. He is, of course, indebted to Dr. Fowler, Dr. Thorndike, Dr. Shutt, and Dr. Whittemore in instructing him in the use of their apparatus and taking the cloud chamber pictures. He wishes to thank Dr. G. B. Collins for making his stay at Brookhaven possible. The author has had the benefit of many interesting and informative conversations with his colleagues, Professor Fry, Professor Sachs, and Professor Takeda. The author also acknowledges some critical comments by Professor R. W. Thompson. This work was initiated while the author was at the University of Rochester and was supported by U. S. Atomic Energy Commission contract there. The work was greatly aided by a grant in aid from the Wisconsin Alumni Research Foundation. The author wishes to thank C. Kaufman, L. Watson, and J. S. Williams for their aid in scanning the pictures.

[10] In this case the Q of the Σ^0 means the Q it would have were it to decay into a π^- meson and proton. Actually it seems that $\Sigma^0 \rightarrow \Lambda^0 + \gamma$ or $\nu + 80$ Mev.

[11] Unpublished data of W. D. Walker. These examples were found among fifty $\pi^- - P$ collisions at 1.0 Bev. It is interesting to speculate further on possible parallels of meson production and hyperon production. If one uses the isotopic spin assignments of Gell-Mann (reference 4) then $\Lambda^0 + \theta^0$ can be produced only in an $I = \frac{1}{2}$ state and $\Sigma^0 + \theta^0$ in either $I = \frac{3}{2}$ or $\frac{1}{2}$. At 1 Bev the $\pi^- - P$ cross section is much larger in the $I = \frac{1}{2}$ than in the $I = \frac{3}{2}$ state and at 1.4 Bev the $\frac{1}{2}$ and $\frac{3}{2}$ state cross sections are about equal. If a real parallel between hyperon and meson production exists, one would expect relatively less Σ^0 than direct Λ^0 production at 1.0 Bev than at 1.4 Bev.



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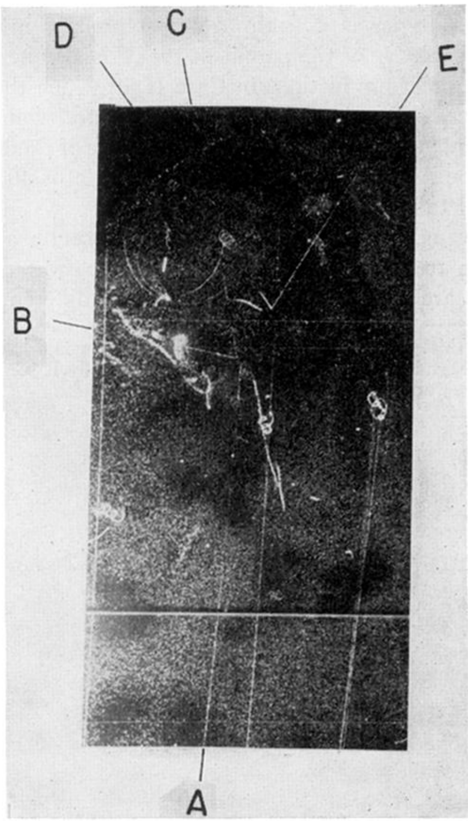

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