Production of Heavy Unstable Particles by 1.37-Bev Pions*

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Five additional events interpreted as the production of heavy unstable particles by 1.37-Bev pions have been observed in a hydrogen-filled diffusion cloud chamber. In each case the observations are most naturally interpreted as due to the associated production of a hyperon and K-meson. These and earlier observations can be made consistent with known hyperon and K-meson masses if the reaction $\pi^- + p \rightarrow \Sigma^0 + \theta^0$ is assumed to be a possibility with an immediate γ-decay $\Sigma^0 \rightarrow \Lambda^0 + \gamma$ as suggested by Gell-Mann and Pais. The total cross section for production of heavy unstable particles is estimated to be about 0.9 millibarn. The five new events confirm the previous indications that the Λ^0's tend to be emitted backwards in the center-of-mass system of the initial collision and to decay in a plane at a small angle to that of the production plane. The orientations of Λ^0's from the wall also support these angular correlations.

IN a previous report[1] we have discussed four interactions of 1.37-Bev pions from the Cosmotron with protons, which resulted in the production of heavy unstable particles. Investigations of the production mechanism of heavy unstable particles (also referred to as V-particles in this article) in collisions between elementary particles are of interest for several reasons. First, one wishes to know the V-production cross section. Second, one hopes to determine whether two V-particles are normally produced simultaneously in elementary collisions. If so, one can reconcile the observed relatively large production cross section with the relatively long lifetimes of the particles.[2] Third, one is interested in finding what kinds of V-particles (classified according to charge, decay schemes, lifetimes, etc.) are produced together. Fourth, observed angular correlations may give information on the spins of some heavy unstable particles.

We now wish to describe five additional examples of the production of heavy unstable particles observed under similar conditions. While the previous four cases were obtained in a 16-in. diameter hydrogen-filled diffusion chamber provided with a magnetic field, the present five were found in a long chamber (six feet by eleven inches) without magnetic field. Although this chamber had no magnetic field, the V-events produced in the gas could be analyzed from the measured angles and estimated densities of ionization of the emergent tracks and the known momentum of the incident pions. The few V-events produced in the walls of the long chamber are not reported since the measured data are insufficient for useful analysis. However, fifteen such events obtained from the walls of the magnet chamber could be analyzed and will also be reported for comparison with the results on V-events produced in the hydrogen. Details on the operation and arrangement of the cloud chambers appear elsewhere.[3,4]

I. ANALYSIS OF EVENTS PRODUCED IN THE GAS OF THE LONG CHAMBER

Detailed information has been given previously[1] on a total of six events identified individually as Cases A to F. (Cases A, B, D, and E showed V-production in hydrogen, Cases C and F referred to V-events originating in the chamber walls.) The present five additional events produced in hydrogen in the long cloud chamber will be called Cases G to K. Three of these, Cases G, H, and I, involve the production of neutral unstable particles. Two more, Cases J and K, involve the production of charged unstable particles.

Since the momenta of the observed decay product particles are not known here, their masses are not known either without further assumptions. Since, however, the point of origin is known for each V-event, we know the angles between the charged decay products and the line of flight of the unstable particle. By assuming values for the masses of the decay products and for the Q-value of the decay process we can now calculate what the momenta of the decay products must be in the laboratory system. To be accepted, these assumed masses and computed momenta must be in agreement with the observed estimated densities of ionization. In this procedure we will not make arbitrary assumptions as to the masses of the decay products and Q-values, but we shall assume values consistent with known V-particle decay modes. The possibilities which we admit are described below in the Bagnères nomenclature.[5] Among hyperons (Y), which are heavier than nucleons, there are: $\Lambda^0 \rightarrow p + \pi^- + 37$ Mev (mass 1107 Mev), with lifetime $\tau = 3.6 \times 10^{-10}$ sec; $\Sigma^{\pm} \rightarrow$nucleon+pion+115 Mev (mass 1185 Mev), $\tau \approx 10^{-10}$ sec (?); and $\Xi^- \rightarrow \Lambda^0 + \pi^- + 65$ Mev (mass 1312

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

1 Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **91**, 1287 (1953), and **93**, 861 (1954). The incident π^- energy of 1.5 Bev then used has had to be revised to the presently used value of 1.37 Bev. This does not substantially change any of the previous conclusions.

2 M. Gell-Mann, Phys. Rev. **92**, 833 (1953); A. Pais, Phys. Rev. **86**, 663 (1952) and Physica **19**, 869 (1953); M. Gell-Mann and A. Pais, Proceedings of the International Conference on Nuclear Physics, Glasgow, July, 1954 (unpublished).

3 Fowler, Shutt, Thorndike, and Whittemore, Rev. Sci. Instr. **25**, 996 (1954).

4 Eisberg, Fowler, Lea, Shephard, Shutt, Thorndike, and Whittemore, Phys. Rev. **97**, 797 (1955).

5 R. W. Thompson, Science **120**, 585 (1954).

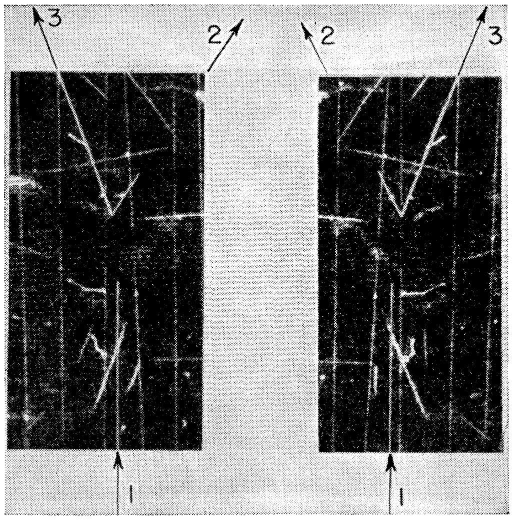

FIG. 1. Case *G*. Photograph of a probable Λ^0 produced in a 1.37-Bev π^--p collision. Track 1 is the incident pion, tracks 2 and 3 are pion and proton, respectively, from Λ^0 decay. Tracks 1, 2, and 3 have been reinforced with white ink for better contrast from other beam and background tracks.

Mev), $\tau \approx 10^{-10}$ sec (?). The symbols $\Sigma^\pm$ and Ξ^- have been used by Gell-Mann and Pais.[2] On theoretical grounds Σ^0 and Ξ^0 might be expected, but have not been identified experimentally. Among *K*-mesons (*K*), which are lighter than nucleons, there are: $\theta^0 \rightarrow \pi^+ + \pi^- + 214$ Mev (mass 494 Mev), $\tau \approx 1.2 \times 10^{-10}$ sec, probably $\theta^+ \rightarrow \pi^+ + \pi^0 + 214$ Mev (mass 494 Mev), τ uncertain;[6] and also tau mesons and kappa mesons (whose presence is nowhere required for the interpretation of our events). On theoretical grounds a θ^- might be expected, but has not been identified experimentally.

We will try to fit the observed *V*-events to one of the decay schemes given in the previous paragraph by using the given decay products and *Q*-values. If one assumed particle is consistent with the observed data, while the others are not, we consider the event to be identified as due to this particle even though the *V*-event could not be identified if its point of production were unknown. In all cases, energy and momentum balance requires that at least one particle in addition to the *V*-event must have been produced. The masses of these additional particles are calculated on the assumption that only one is involved in each case.

TABLE I. Data for event *G*.

	(1)	(2)	(3)
1. Estimated ionization density	~Minimum	~Minimum	2 to 4 ×minimum
2. Assumed particle	Pion	Pion	Proton
3. Angle between incident π^- and direction of flight of *V* (degrees)		12.5±4	
4. Angle between direction of flight and decay products (degrees)		35.5±3	13.5±1
5. Assignment of momenta (Mev/*c*) consistent with 2, 3, 4, and $Q=37$ Mev		144	360

[6] Hodson, Ballam, Arnold, Harris, Rau, Reynolds, and Treiman, Phys. Rev. **96**, 1089 (1954). Hill, Salant, and Widgoff, Bull. Am. Phys. Rev. **29**, No. 7, 32 (1954).

Case *G*, Interpreted as a Λ^0 Produced in π^--p Collision

Figure 1 shows a photograph of a track of a negative pion (1) disappearing suddenly in hydrogen. The *V*-event with tracks labeled (2) and (3) lies in a plane which contains the end point of (1) and is consistent with a Λ^0 but not with a θ^0. The information leading to this identification is given in Table I. Although no momenta are measured it seems safe to assume that track (1) is a beam pion with a momentum of 1500±200 Mev/*c*, as has been determined for this beam.[4] There is no evidence for the nature of the missing neutral particle produced by the incident pion. Assuming an incident pion with momentum of 1500 Mev/*c* and only

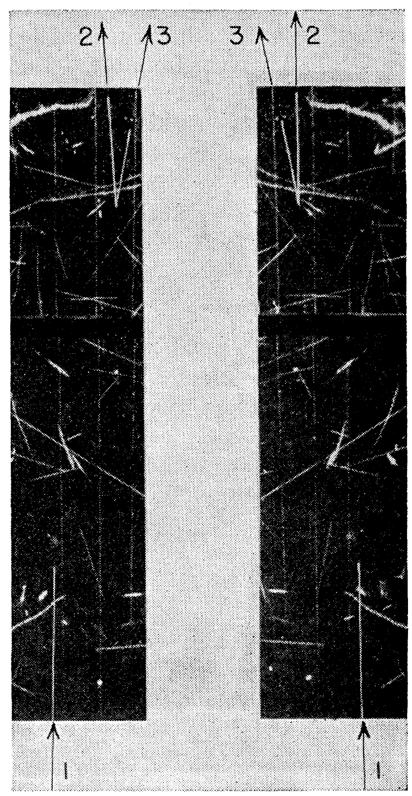

FIG. 2 Case *H*. Photograph of a possible θ^0 produced in a 1.37-Bev π^--p collision. Track 1 is the incident pion, tracks 2 and 3 are pions from θ^0 decay. These tracks have been reinforced with ink for better contrast from other beam and background tracks.

a single neutral particle we find for its mass a value of 670 Mev, consistent with the values found in Cases *A* and *B*. This mass is relatively unaffected by the error in the flight angle of the Λ^0 (12.5±4°), being most sensitive to the assumed momentum of the incident pion. In this beam very few pions have been observed to have momenta as low as 1200 Mev/c. With this as the lower limit, the mass for the unobserved neutral particle is computed to be 570 Mev, still larger than 494 Mev, the presently accepted value for the θ^0.[7] Naturally, for an individual event this interpretation is uncertain since it is possible that two or more neutral particles are involved instead of a single K^0.

Case *H*, Interpreted as a Probable θ^0 Produced in a π^--p Collision

Figure 2 shows a pion (1) disappearing in the hydrogen with the probable appearance of a θ^0. Table II gives the pertinent data for this event. The plane containing (2) and (3) also contains the end point within an uncertainty of only 2 mm, although the decay takes place quite far from the origin. The interpretation of this event is sensitive to the exact value taken for the direction of track (3). With the nominal value of 4°, the *V*-event is not consistent with either a Λ^0 or a θ^0 particle, since for either particle the required ionization densities do not agree with the observed values. To be consistent with a Λ^0 decay, track (3) must make an improbably small angle of 1.3° with the line of flight of the Λ^0. Therefore, the observed *V*-event is probably not a Λ^0 particle. For consistency with a θ^0, track (3) must make an angle of 2° with the line of flight of the θ^0, which is more probable. For this assumption the unseen neutral particle has a mass of 1107 Mev for an incident pion of 1600 Mev/c. Thus it is not necessary here to postulate an improbable value for the momentum of the incident pion, or a *K*-meson with mass in excess of 494 Mev, but one can obtain a satisfactory solution using only a θ^0 and a Λ^0. (Assuming that the observed decay event is a Λ^0 despite the poorer agreement with the measured angles leads to a mass for the missing particle that is quite consistent with that of a θ^0.)

TABLE II. Data for event *H*.

	(1)	(2)	(3)
1. Estimated ionization density	Minimum	2 to 4 ×minimum	Minimum
2. Assumed particles	Pion	Pion	Pion
3. Angle between incident π^- and direction of flight of *V* (degrees)		12.5±1.5	
4. Angle between direction of flight and decay products (degrees)		26±2	4±2
5. Momenta (Mev/c) consistent with 2, 3, 4, and Q=214 Mev		93	1168

[7] Thompson, Buskirk, Etter, Karzmark, and Rediker, Phys. Rev. **90**, 1122 (1953).

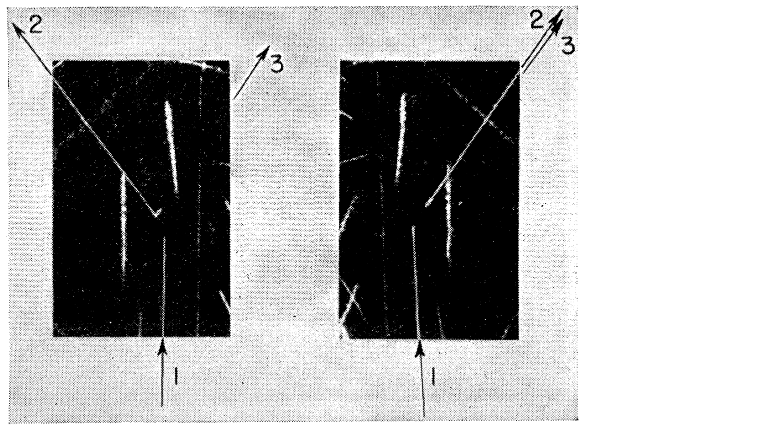

FIG. 3. Case *I*. Photograph of probable θ^0 produced in a 1.37-Bev π^--p collision. Track 1 is the incident pion, tracks 2 and 3 are pions from θ^0 decay. These tracks have been reinforced with ink for better contrast from other beam and background tracks.

Case *I*, Interpreted as a θ^0 Produced in a π^--p Collision

Figure 3 shows another example of a pion disappearing in hydrogen with the subsequent appearance of a θ^0. Table III gives the measured data on angles and ionization densities. This *V*-event is entirely consistent with a θ^0 particle having a Q-value of 214 Mev. The plane containing (2) and (3) also contains the end point of (1). No assignment of momenta is possible to allow this particle to be a Λ^0 since the proton would ionize more than 10 times the minimum rate. If one again assumes a single unseen particle involved in the interaction, its mass is computed to be 1310±140 Mev for an incident pion momentum of 1500±300 Mev/c. This is considerably larger than the value of 1107 Mev for a Λ^0, though an improbably low value of the incident pion momentum would yield this mass for the unseen

TABLE III. Data for event *I*.

	(1)	(2)	(3)
1. Estimated ionization density	Minimum	1 to 2 ×minimum	1 to 4 ×minimum (foreshortened)
2. Assumed particles	Pion	Pion	Pion
3. Angle between incident π^- and direction of flight of *V* (degrees)		42±3.5	
4. Angle between direction of flight and decay products (degrees)		50±10	40±10
5. Assignment of momenta (Mev/c) consistent with 2, 3, 4, and Q=214 Mev		262	313

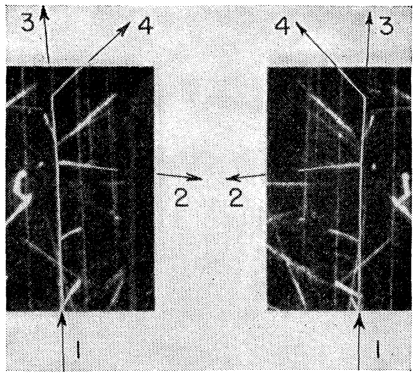

FIG. 4. Case *J*. Photograph of charged hyperon produced in a 1.37-Bev π^--p collision. Track 1 is the incident pion, track 2 is probably a *K*-meson, track 3 is the hyperon, and track 4 is probably a pion from hyperon decay. These tracks have been reinforced with ink for better contrast from other beam and background tracks.

particle. Other possible explanations for the discrepancy are discussed in Sec. IV. On the other hand, if we assume that the mass of the observed particle is 600–650 Mev, then the computed mass of the unseen particle is consistent with a Λ^0 particle for an incident pion with 1500 Mev/*c*.

Case *J*, Interpreted as a $Y^\pm$ and $K^\mp$ Produced in π^--p Collision

Figure 4 shows a pion interaction in hydrogen in which two charged particles are emitted. Several features of this event indicate that the outgoing particles can best be identified as heavy unstable particles. Table IV gives the data on the angles and ionization densities. Since track (3) makes a very small angle with track (1), it is rather difficult to determine whether tracks (1) and (3) lie in the plane containing (2). Since tracks (2) and (4) lie in a common plane, all four tracks must lie in a common plane, assuming that no neutral particle is produced in the collision.

Consider first tracks (1), (2), and (3). Conservation of momentum alone determines the momenta of (2) and (3), if we postulate the momentum of (1). If (2) is assumed to be a $K^\pm$ with mass of 494 Mev, then (3) has a $\Sigma^\pm$ mass of 1185 Mev ($Q=115$ Mev) for an incident pion with momentum of 1450 Mev/*c*. Each of these masses is consistent with the observed density of ionization and the computed momentum. The mass of 1185 Mev for (3) would agree with that inferred for Case *E*. To make the mass of (3) consistent with that of a Ξ^- (mass 1312 Mev), without making the mass of (2) substantially less than 494 Mev, the incident pion must have a momentum of 1800 Mev/*c* which is unlikely.[8]

[8] Case *E*, previously interpreted as production of a Σ^-, could perhaps have been a Ξ^-. Case *F* could not have been a Ξ^-, since the *Q*-value obtained on this assumption would be too high ($\sim$100 Mev).

Consider now the decay of (3) to give a pion (4) plus at least one additional neutral particle. If the mass of the hyperon (3) is 1185 Mev, the neutral particle a neutron (*n*), and the momentum of the pion is 200 Mev/*c*, then the decay of (3) according to $\Sigma^\pm \rightarrow n+\pi^\pm+Q$ yields a value for *Q* of 115 Mev. On the other hand, if the neutral particle is a Λ^0, and the pion has a momentum of 100 Mev/*c*, then the decay would be consistent with $\Xi^- \rightarrow \Lambda^0+\pi^-+65$ Mev, except that a pion of 100 Mev/*c* would ionize 2×minimum instead of minimum.

Further consideration of Case *J* shows that the above interpretation is unique. For example, an elastic pion scattering is not possible on three accounts. First, track (2) is observed at an angle which is very likely greater than 90°, which is impossible if (2) is a proton. Second, if track (1) is a pion with the nominal beam energy, then a decay of the pion subsequent to the collision could not yield a larger decay angle than 1.5°. Since the observed angle is 54°, this possibility is definitely ruled out. Third, if track (2) were a pion, then track (3) would have a mass of 1700±150 Mev for an incident pion with momentum of 1500±300 Mev/*c*. Such a large mass for (3) would give an ionization density of 1.6×minimum instead of minimum and would be much larger than even that of a Ξ^-. As an alternative explanation of the event one might consider the possibility that track (1) is a *K*-meson produced in the target or in the collimating channel. If track (2) definitely emerges at greater than 90°, the interaction cannot be an elastic *K*-*p* scattering with the subsequent decay of the *K*. Furthermore, there is a very small chance that a *K*-meson so produced would scatter in the cloud chamber and also decay within a few centimeters. Finally, the possibility that a long-lived ($\sim 10^{-8}$ sec) K^- from the Cosmotron undergoes

TABLE IV. Data for event *J*.

	(1)	(2)	(3)	(4)
1. Estimated ionization density	Minimum	>2.5 × minimum	Minimum	Minimum
2. Assumed particles	Pion	*K*-meson	Hyperon	Pion
3. Angle between incident π^- and direction of flight (degrees)		96±8	3±2	
4. Angle between (3) and its decay product (degrees)			54±4	
5. Momenta (Mev/*c*), assuming a $\Sigma^\pm$ for (3)	1450	76	1460	200
6. Momenta (Mev/*c*) assuming a $\Xi^\pm$ for (3)	1800	95	1810	100

the reaction $K^- + p \rightarrow \pi^{\mp} + \Sigma^{\pm}$ with subsequent short-lived ($\sim 3\times 10^{-10}$ sec) decay of the $\Sigma^{\pm}$ is ruled out by energy conservation.

Case *K*, Interpreted as a $Y^{\pm}$ and $K^{\mp}$ Produced in π^--p Collision

Figure 5 shows an event similar to that in Fig. 4, where a π^--p interaction results in two charged particles. The angles show that probably all four tracks lie in a single plane. For reasons similar to those given in Case *J*, this interaction cannot represent the elastic scattering of a pion nor is it likely to be the scattering of a *K*-meson produced in the target of the Cosmotron. Table V gives the data on angles and ionization densities.

The analysis is carried out assuming that tracks (2) and (3) are heavy unstable particles. Track (2) cannot

TABLE V. Data for event *K*.

	(1)	(2)	(3)	(4)
1. Estimated ionization density	Minimum	Minimum	2 to 4 ×minimum	1 to 2 ×minimum
2. Assumed particles	Pion	*K*-meson	Hyperon	Pion
3. Angle between incident π^- and direction of flight (degrees)		32.5±3.5	23±2.5	
4. Angle between (3) and its decay product (degrees)				51±7
5. Momenta (Mev/*c*), assuming $\Sigma^{\pm}$ for (3)	1350	652	878	235
6. Momenta (Mev/*c*), assuming $\Xi^{\pm}$ for (3)	1950	940	1265	160

be as heavy as a hyperon because the minimum density of ionization would require so great a momentum for (2) that conservation of energy and momentum would be impossible for a beam pion for track (1). If we assume that track (2) is a *K*-meson with mass of 494 Mev, and track (3) is a hyperon ($\Sigma^{\pm}$) with mass of 1185 Mev, conservation of energy requires that the incident pion have a momentum of 1350 Mev/*c*. With this identification the measured densities of ionization and computed momenta are consistent. The subsequent decay of (3) into a neutron and pion requires that (4) have a momentum of 235 Mev/*c*, which is possible for the observed ionization density of 1 to 2 times minimum. It is impossible to make track (3) a $\Xi^{\pm}$ with associated production of a $K^{\mp}$ without assuming the incident pion has the unreasonably large momentum of 1950 Mev/*c*.

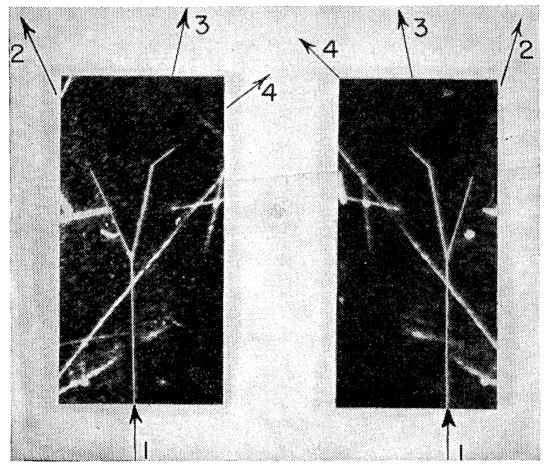

FIG. 5. Case *K*. Photograph of charged hyperon produced in 1.37-Bev π^--p collision. Track 1 is the incident pion, track 2 is a possible *K*-meson, track 3 is the hyperon, and track 4 is probably a pion from hyperon decay. These tracks have been reinforced with ink for better contrast from other beam and background tracks.

Also the Ξ would ionize only 1.5 times the minimum rate. If (2) were a pion (3) could be a Ξ for an incident π^- momentum of 1.2 Bev/*c*.

II. UNSTABLE PARTICLES PRODUCED IN WALLS OF MAGNET CHAMBER

As mentioned above, the few isolated *V*-events produced in the walls of the long chamber and decaying in the gas could not be analyzed usefully, since no momenta could be measured, and their geometrical arrangement with respect to the incident pion was unknown. With the magnet cloud chamber, about twenty-seven possible neutral *V*-events were found for seventeen of which momenta and angles could be measured sufficiently well that *Q*-values could be calculated. Of these, twelve were identified as Λ^0, three as θ^0 (including Case *C*), and two were consistent with either Λ^0 or θ^0. All *Q*-values except one were consistent within the errors with the usual values of 37 and 214 Mev for Λ^0 and θ^0, respectively.

Five possible cases of charged heavy unstable particles originating in the walls were found. One of these could be a K^+ but could just as well be a θ^0, one case may represent a Σ^+ decay, but is very uncertain, and three cases are definite decays of negatively charged particles. One of the latter has been identified as a Σ^- (Case *F*).

III. LIFETIMES, CROSS SECTION, AND ANGULAR RELATIONSHIPS

As in the earlier report,[1] chance still plays a large part in the results on lifetime, cross section, and angular relations. However, some available data will be given for the events occurring in the gas as well as for the events produced in the walls of the cloud chamber.

TABLE VI. Observed lifetimes in 10^{-10} sec.

Event	Λ^0	K^0	$Y^{\mp}$	$K^{\pm}$
A	0.4	>4[a]		
B	0.3	>3[a]		
D	9	0.1		
E			2	>0.7
G	2.6	>3.4[a]		
H	>8[a]	8.1		
I	>5[a]	0.7		
J			1.0	>2.9
K			2.1	>2.4

[a] Lower limits for lifetimes, provided decay into neutral particles did not occur.

Table VI gives the data on the lifetimes for the Cases A to K. As with the earlier results, the values are still consistent with the results obtained from cosmic ray studies[9] which indicate for the Λ^0 a lifetime of $(3.6_{-0.7}^{+1.1})\times10^{-10}$ sec and for the θ^0 $(1.2_{-0.3}^{+0.8})\times10^{-10}$ sec.

The cross section now computed for production of heavy unstable particles is close to the 1 mb originally estimated.[1] In both chambers 470 interactions were observed (not including 9 resulting in heavy unstable particle production). Making use of Fermi's calculation of statistical weights for different charge states,[10] one can estimate that ~15 percent of the observed interactions leading to meson production should give all neutral prongs and therefore remain undetected in the present experiment. Then about 550 pion interactions may have really occurred in both chambers. A count of the π-μ decays in the long chamber served to give the flux of pions through that chamber. When combined with the interactions observed in that chamber, the cross section for pion interaction was found to be 34.6 ± 2.7 mb.[4,11] One can estimate that, for the given geometry, about 90 percent of the V-events are found, assuming a mean lifetime of 3×10^{-10} sec for the hyperons and 1.5×10^{-10} sec for the K-particles. Within reasonable limits this estimate does not depend strongly on the angular distributions of the lines of flight of the unstable particles. The 9 cases of unstable-particle production in hydrogen may, therefore, correspond to 11 ± 4 cases. These data lead to a cross section for heavy unstable particle production of ~0.7 millibarn for collisions of 1.4-Bev π^- mesons with protons. (This does not yet take into account the decay of V^0-particles into neutral particles only or possible production of long-lived K-particles, the effect of which will be discussed in Sec. IV.)

Tables VII and VIII give the data on angular correlations for all cases considered above. The quantity α is the angle between the production and decay planes, where the production plane is determined by the lines of flight of the incident pion and the heavy unstable particle and the decay plane is determined by the lines of flight of the heavy unstable particle and its decay products. Obviously the concept of decay plane fails for the decay into three products. The quantity β is the angle between the incident pion and the line of flight of the unstable particle in the c.m.s. (center-of-mass system) of the incident pion and the struck proton. The quantity γ is the angle between the incident pion and the positive track in the V-event in the rest system of the V-particle. For random distribution α should cover the range 0–90° uniformly. For isotropic angular distributions β and γ should occur preferably around 90° (largest solid angle available).

The angle between the production and decay planes (α) still exhibits the rather close correlation shown earlier.[1] For the Λ^0 particles, α is less than 45° for all events produced in the gas. For the events produced in the chamber walls this effect is less pronounced, possibly because it is diluted by the uncertainty in origin of the events. For the θ^0 events, α does not show such an effect, but the data are few. For the charged unstable events, the heavy particle ($Y^{\pm}$) decays in a plane which is also closely correlated with the production plane. An investigation of several cosmic ray examples[12] has shown a similar effect for the hyperons. Probably this effect indicates that hyperons have spin greater than $\frac{1}{2}$.

TABLE VII. Angular correlations for events produced in gas.[a]

Event	α	β	γ
A Λ^0	5 ± 5	141	107
B Λ^0	30 ± 20	125	19
D Λ^0	27 ± 10	174	151
D θ^0	70 ± 5	6	
E Y^-	7 ± 5	30	77[b]
G Λ^0	38 ± 5	160	115
H θ^0	22 ± 10	28	
I θ^0	58 ± 3	98	
J $K^{\pm}$		169	
J $Y^{\mp}$	20 ± 20	11	46[b]
K $K^{\pm}$		70	
K $Y^{\mp}$	10 ± 10	110	28[b]

[a] α with its error was measured, where errors were determined directly; all other angles were computed for the assumed decay schemes.
[b] For these cases, γ is the angle between the incident pion and the neutron from the hyperon in the rest system of the hyperon.

For the events produced in the gas, the line of flight of the V-event in the c.m.s. with respect to the incident pion (angle β) shows that the Λ^0 prefers to travel backward in the c.m.s.[13] If we make the assumption that two heavy particles and no pions are produced in

[9] D. I. Page, Phil. Mag. **45**, 863 (1954); G. D. Rochester and C. C. Butler, Repts. Progr. in Phys. **16**, 364 (1953). Also see Proceedings of the Duke University Cosmic Ray Conference, 1953, p. II-22 (unpublished).

[10] E. Fermi, Annais da Academia Brasileira de Ciencias **26**, 61 (1954).

[11] This value agrees well with the total cross section, 34 ± 3 mb, of Cool, Madansky, and Piccioni, Phys. Rev. **93**, 249 (1954).

[12] Ballam, Hodson, Martin, Rau, Reynolds, and Treiman, Phys. Rev. **97**, 245 (1955).

[13] One can estimate that, because of the difference in momenta in the laboratory system, the chance of observation of a Λ^0 travelling forward in the c.m.s. is about 30 percent smaller than that of a Λ^0 travelling backward. This bias is far from sufficient to explain the observed distribution.

each interaction, then these cases show the Λ^0 always going backwards except for Case *I* where $\beta=180-98=82°$. The events produced in the cloud chamber wall show the same effect, only three Λ^0 particles being emitted at less than 90° while nine were emitted backwards. In fact, five were emitted at angles greater than 150°, where the solid angle forms only 13 percent of the hemisphere. Reynolds and Treiman[14] have observed a similar effect with cosmic rays. For the charged hyperon cases, on the other hand, two are emitted at small angles and one at 110°.

Several authors[15] have discussed a possible dependence on spin of the *V*-particles for the distribution of γ (here defined as the angle between the incident pion and the positive decay product of a *V*-event in its rest system), which of course would also affect the distribution of the α just discussed. The angle γ is also tabulated in Tables VII and VIII. For four cases where the Λ^0 is produced in the gas the values of γ are 19, 107, 115, and 151 degrees, which shows no obvious preference. For the events coming from the walls, there appears to be a preference for γ near 180° where

TABLE VIII. Angular relations for 15 events produced in walls of magnet chamber, including Case *C*.

Angle interval, degrees	Number of cases in angle interval α Λ^0	α θ^0	β Λ^0	β θ^0	γ Λ^0	γ θ^0
0–22½	6	0	0	2	0	0
22½–45	1	1	0	0	0	0
45–67½	2	2	1	1	2	1
67½–90	3	0	2	0	1	1
90–120			1	0	3	1
120–150			3	0	2	0
150–180			5	0	4	0

the relative solid angle is small. The distribution of γ may not be isotropic, but there is no evident reason for such a lack of symmetry. We prefer to believe that the effect seen for the *V*-events from the wall is due to an experimental bias. In the three cases where charged hyperons were produced in the gas (Cases *E*, *J*, *K*), the nucleon from the decay of the $Y^{\pm}$ went forward in the rest-system of the $Y^{\pm}$ with $\gamma=28$, 46, and 77 degrees. Much better statistics are needed for the detailed distributions. At this point, however, from the distribution in α alone, there is fair evidence that the spins for some hyperons may be at least as high as $\frac{3}{2}$. At the same time, it is perhaps improbable that the hyperon spin is much larger than this value since then the distribution of γ should be so peaked forward and backward that the experimentally observed angles in the range $60°<\gamma<120°$ (Table VII) become very improbable. The expected distribution in γ, however, depends not only on the hyperon spin but also on the other angular momenta involved in the production mechanism, such as the spin of the *K*-particle and the states of angular momenta in which the two particles were emitted. Therefore the observed distribution of γ might be consistent with a large spin for the hyperon under some conditions.

TABLE IX. Masses for all heavy unstable particles produced in the gas.

Case	Hyperon	*K*-Meson
A	1107(Λ^0)	650±70[a]
B	1107(Λ^0)	620±70
D	1107(Λ^0)	517±20
E	1185(Σ^-)	510±50
G	1107(Λ^0)	670±70
H	1023±150	494(θ^0)
I	1310±90	494(θ^0)
J	1217±120	494($K^{\pm}$)
K	1185($\Sigma^{\pm}$)	560±80

[a] Masses with indicated errors were derived from assumed particles, labelled Λ^0, $\Sigma^{\pm}$, θ^0, $K^{\pm}$, for nominal incident π^- momentum of 1500 Mev/*c*. Errors take into account ±200 Mev/*c* uncertainty for π^- momentum and other, mostly less important, uncertainties.

IV. MASSES AND IDENTITY OF *V*-PARTICLES PRODUCED IN HYDROGEN

Table IX shows a compilation of all the masses found for the 9 events occurring in the gas. It is apparent that all of these events are consistent with associated production of a hyperon together with a *K*-meson.[16]

From the geometry of the cloud chambers, assuming that hyperons and *K*-mesons are usually produced together (associated production) and decay with the lifetimes cited in Sec. III, one infers that in about 10 to 20 percent of all *V*-production events both produced particles should be observed to decay. This fraction of expected double decays becomes smaller if some produced particles have long lifetimes, or if decay into neutral particles only should take place often. In a total of eleven *V*-production events observed in π^--p collisions (nine reported here and two mentioned in footnote 16), two have shown both particles decaying. This is certainly consistent with the fraction expected from associated production.

Further arguments to be reported in detail at a later

[14] G. T. Reynolds and S. B. Treiman, Phys. Rev. **94**, 207 and 797 (1954).

Note added in proof.—A production mechanism suggested by M. Goldhaber (Phys. Rev. **92**, 1279 (1953)) consists of simultaneous production of two θ^0's, possibly virtual, which can form compound states with pions or nucleons, resulting in the different observed heavy unstable particles. As pointed out by Goldhaber, strongly nonisotropic angular distributions for the emitted particles may result.

[15] L. Wolfenstein, Phys. Rev. **94**, 786 (1954); Treiman, Reynolds, and Hodson, Phys. Rev. **97**, 244 (1955).

[16] Several additional events have been found meanwhile, under somewhat different conditions, which are also consistent with this production mechanism. In particular, one probable Λ^0+K^0 event in a 0.9-Bev π^--p collision, found by W. D. Walker (University of Wisconsin) in photographs obtained with the same equipment as the photographs under discussion, shows both Λ^0 and K^0 decaying. Here the Λ^0 again shows angular correlations similar to those exhibited by the hyperons tabulated in Table VIII. Here γ is less than 90°. Furthermore, one event in a 1.8-Bev π^--p collision, and one event in a 2.7-Bev p-p collision show the same general behavior. (For the latter event see Block, Harth, Fowler, Shutt, Thorndike, and Whittemore, Bull. Am. Phys. Soc. **29**, No. 7, 33 (1954).)

date involve indications of V-production thresholds observed in proton and neutron beams. For instance, in a 1.5-Bev proton beam only one possible case of a heavy unstable particle was observed to originate in the chamber wall. This proton energy is near the threshold for associated production of hyperons with K-mesons. ("Fermi energy" in compound nuclei favors production.) In a neutron beam of average energy of 1.7 Bev, some particles were produced in the wall. In a 2.7-Bev proton beam, heavy unstable particles were again produced in gas as well as wall.[16,17]

Out of 26 photographs showing V-events originating from the chamber wall only one, reported as Case C, showed both a Λ^0 and a θ^0 decaying. Associated production was indicated for this case. Three to five such cases should have been observed if mostly associated production occurred, and if the geometries for V-events from the wall and from the hydrogen were identical. The latter is not strictly true, and discovery of associated V-events from the walls is probably less likely. Furthermore, cosmic ray results on V-events,[18] mostly obtained in plates of heavy metals, have indicated very little associated production. Examples of associated production in cosmic radiation have been discussed in detail by several authors.[12,19]

The possibility of associated production can be used to explain[2] the relatively long lifetimes observed for heavy unstable particles ($\sim 10^{-10}$ sec instead of 10^{-22} sec for an "excited" nucleon or pion) together with their relatively large production cross section ($\sim$1 millibarn, or $\sim$3 percent of the total interaction cross section for 1.4-Bev π^--p collisions).

Inspection of Table IX shows four events (A, B, G, I) where the masses of Y and K cannot easily be reconciled simultaneously with those of Λ^0 (1107 Mev) and θ^0 (494 Mev). For agreement one would have to assume improbably small momenta for the incident π^- for all of these cases. Furthermore, in none of the four cases in question was it possible to ascertain that only two particles were produced since only one neutral particle was seen to decay, and therefore, only one line of flight was established. Event H is similar in the latter respect but is consistent with Λ^0 and θ^0 masses. For the remaining four events (D, E, J, K) both lines of flight could be established, and thus coplanarity could be used as an argument for production of two particles only, and here indeed reconcilable masses were found. There are several possible explanations for the discrepancies from known Λ^0 or θ^0 masses in events A, B, G, I. First, it is not yet certain that there are no K-mesons with masses other than 494 Mev (970 electron masses) although most observed events are consistent with this mass. Second, neutral pions (or perhaps photons) in addition to the K-mesons and hyperons may have been produced. It is unlikely that two pions were produced instead of a K-meson because then in at least some cases the mass inferred for the neutral particle should have been smaller than that of a θ^0. Also the inferred K-masses in question are all too large by similar amounts ($\sim$150 Mev). Third, a possibility worth considering is that the Λ^0's in the events in question were not produced directly but themselves were decay products of a hypothetical Σ^0 decaying into $\Lambda^0+\gamma$ with very short lifetime ($\sim 10^{-22}$ sec).[2] No metastable Σ^0 decaying into $p+\pi^-+115$ Mev has ever been observed. Since $\Sigma^\pm$ and Λ^0 have quite different Q-values, they cannot easily be called members of the same charge triplet (or quartet). For considerations of charge independence[2] in production of heavy unstable particles, the assumption of a Σ^0 with mass nearly equal to that of the $\Sigma^\pm$ is thus desirable. By just assuming that a particle of mass of 1185 Mev (Σ^0) was produced instead of one of 1107 Mev (Λ^0) one can almost reconcile Cases A, B, G, and I with simultaneous production of Σ^0 and θ^0. In addition, however, the postulated almost immediate decay of $\Sigma^0\rightarrow\Lambda^0+\gamma$ can considerably alter the course of the Λ^0 which is finally observed to decay from that of the original Σ^0, since the γ ray can carry a momentum of $\sim$75 Mev/c. Thus the observed angle of the direction of flight of the Λ^0 is not necessarily the same as that of the original Σ^0. Application of this possibility can be used further to obtain consistency with simultaneous Σ^0, θ^0 production in the four cases under discussion. Then we would have the following final production schemes for the nine events. Cases A, B, G, and I: $\pi^-+p\rightarrow\Sigma^0+\theta^0$, $\Sigma^0\rightarrow\Lambda^0+\gamma$, Cases D, H: $\rightarrow\Lambda^0+\theta^0$ (direct production of Λ^0 thus would not seem to be ruled out), and Cases E, J, and K: $\rightarrow\Sigma^\pm+K^\mp$. The production symmetry for $\Sigma^\pm$ with Σ^0 thus experimentally indicated is an advantage which makes this explanation for the observed apparent discrepancies not improbable.

V. STATISTICAL FACTORS IN PRODUCTION AND DECAY

Having tentatively accepted the possible production of Σ^0, we wish to state some possible further theoretical consequences, specifically making use of Gell-Mann's[2] scheme. There it is assumed that for all production phenomena (strong interaction because of large cross section) isotopic spin T and z-component of isotopic spin T_z are conserved while for the decay phenomena (weak interaction because of long lifetimes) T and T_z change by ΔT and $\Delta T_z=\pm\frac{1}{2}$. Σ is assigned $T=1$, and $T_z=+1$, 0, -1 for Σ^+, Σ^0, and Σ^-, respectively, Λ^0 has $T=0$, $T_z=0$, and θ-mesons $T=\frac{1}{2}$, $T_z=+\frac{1}{2}$, $-\frac{1}{2}$ for θ^+, θ^0, respectively, and $T=\frac{1}{2}$, $T_z=+\frac{1}{2}$, $-\frac{1}{2}$ for $\bar{\theta}^0$, θ^-, respectively, where $\bar{\theta}^0$, θ^- are anti-particles to θ^0, θ^+. (Any K-mesons which are not θ's are omitted from this

[17] This dependence on energy qualitatively confirms the result reported by S. L. Ridgway and G. Collins, Bull. Am. Phys. Soc. **29**, No. 7, 32 (1954).

[18] Leighton, Wanlass, and Anderson, Phys. Rev. **89**, 148 (1953); Fretter, May, and Nakada, Phys. Rev. **89**, 168 (1953); Bridge, Peyrou, Rossi, and Safford, Phys. Rev. **90**, 921 (1953); **91**, 362 (1953).

[19] Thompson, Burwell, Huggett, and Karzmark, Phys. Rev. **95**, 1576 (1954).

discussion, for example tau and kappa-mesons.) For π^--p collisions (total $T_z=-\frac{1}{2}$ to be conserved, if for nucleons $T=\frac{1}{2}$, $T_z=+\frac{1}{2}$, $-\frac{1}{2}$ for proton and neutron, for pions $T=1$, $T_z=+1$, 0, -1 for π^+, π^0, π^-, respectively) the reactions $\rightarrow\Lambda^0+\theta^0$, $\Sigma^0+\theta^0$, $\Sigma^-+\theta^+$ are then possible while the reaction $\rightarrow\Sigma^++\theta^-$ is not possible. Similarly for π^--n collisions ($T_z=-\frac{3}{2}$) the reaction $\rightarrow\Sigma^-+\theta^0$ is possible while $\rightarrow\Lambda^0+\theta^-$, $\Sigma^0+\theta^-$ are not. Thus production of Σ^+ or θ^- in π^--nucleon collisions would not be possible. (In Pais' scheme $\pi^-+n\rightarrow\Sigma^0+\theta^-$ is possible,[2] but $\pi^-+p\rightarrow\Sigma^++\theta^-$ is still not possible.) Within the bad statistics, no identified Σ^+ was observed in the magnet chamber. Only a possible Σ^- produced in the gas (Case E) and a Σ^- originating in the wall (Case F) were found in addition to two other negative decays not further identified. (Of course, Σ^+ or θ^- could be produced in the walls by collisions of secondary π^+-mesons or nucleons.)

A π^--p reaction can proceed through isotopic spin states $T=\frac{1}{2}$ or $\frac{3}{2}$, with $T_z=-\frac{1}{2}$. The reaction $\pi^-+p\rightarrow\Lambda^0+\theta^0$ is possible only through $T=\frac{1}{2}$ since $T=0$ for Λ^0. For $T=\frac{1}{2}$ the reaction $\rightarrow\Sigma^0+\theta^0$ has statistical weight $\frac{1}{3}$ and $\rightarrow\Sigma^-+\theta^+$ has $\frac{2}{3}$. For $T=\frac{3}{2}$ the relative weights are reversed to $\frac{2}{3}$ and $\frac{1}{3}$, respectively. Whether the reaction proceeds preferably through the initial isotopic spin state of $\frac{1}{2}$ or $\frac{3}{2}$ is not known. We will, however, here also assume their relative statistical weights of $\frac{2}{3}$ and $\frac{1}{3}$. It follows that the relative probabilities of (Σ^0,θ^0) and (Σ^-,θ^+) production are 4/9 and 5/9, respectively. As just stated, we may have observed four (Σ^0,θ^0) and three (Σ^-,θ^+) events, which is not in disagreement with these probabilities. If we believe that two (Λ^0,θ^0) events were observed then the probabilities for (Λ^0,θ^0) and (Σ^0,θ^0) production are of same order of magnitude.

A Λ^0 can decay into (p,π^-) or (n,π^0) with change of isotopic spin from $T=0$ for the Λ^0 to $T=\frac{1}{2}$ for the decay products so that $\Delta T=\frac{1}{2}$, $\Delta T_z=-\frac{1}{2}$. Although isotopic spin is not conserved for the decay mechanism, the interaction between the decay products is usually considered to be charge-independent. If one imagines that the decay products are still in very close proximity after the interaction leading to decay of the heavy unstable particle has ceased, one might still apply the isotopic spin formalism to the final T, T_z state.[20] For $T=\frac{1}{2}$, (p,π^-) has the statistical weight $\frac{2}{3}$, and (n,π^0) has $\frac{1}{3}$. Since we can observe only (p,π^-), four of which were observed to be produced in hydrogen, the true number of Λ^0 produced in the gas and decaying in the chamber (into both combinations) may therefore have been six. The same assumptions can be applied to the θ^0 decay. The two pions from a decaying θ^0 can be in a state $T=0$ or 1, $T_z=0$. The two possibilities for decay (π^+,π^-) or (π^0,π^0) exist. For $T=0$ we have the weights $\frac{2}{3}$ for (π^+,π^-) and $\frac{1}{3}$ for (π^0,π^0). For $T=1$ (π^0,π^0) is not possible.[21] Thus the $3(\pi^+,\pi^-)$ decays observed to be produced in hydrogen imply a total of not more than four θ^0's. Combining these weights for the unseen decays with the previous considerations on lifetimes and geometry, one estimates that a total of nine events resulting in θ^0 and Σ^0 or Λ^0 may have been produced.

All Σ^- and θ^+ can be observed when they decay. It is possible, however, that the θ^+ are long-lived in which case they would have only a small chance to decay inside the chamber. In this case, only the Σ^- are seen to decay in the chamber with a probability of 60 percent as inferred from lifetime and geometry. Then the 3 events observed correspond to five (Σ^-,θ^+) events actually produced. (There is no experimental evidence that the K^+'s involved are really to be identified as θ^+'s.)

The total number of V-production events in the gas for this run may, therefore, have been $9+5=14$, leading to a cross section for production of $\sim$0.9 mb for 1.4-Bev π^--p collisions. This value may represent a somewhat better estimate (disregarding the poor statistics) for the production cross section than the value of $\sim$0.7 mb given in the previous section.

VI. SUMMARY

The five examples given here of the production of hyperons and K-mesons in π^--p collisions, together with those previously reported,[1] indicate that a hyperon and K-meson are normally produced together. None of the nine examples is inconsistent with the reaction $\pi^-+p\rightarrow Y+K$, and in each case the simplest and most natural interpretation of the observed data involves a reaction of that type, which is described by the term "associated production." These observations by themselves do not, however, determine whether associated production occurs because of special selection rules or because of the high spin of the hyperons and K-mesons, since the latter could lead to associated production at these energies.[2] There has been little evidence for associated production in cosmic ray experiments, and the reason for this difference is not clear.

If we use the schemes of Pais and Gell-Mann for the classification of hyperons as a guide to the interpretation of our results, we have the following choices for hyperons: Λ^0, Σ^+, Σ^0, Σ^-, Ξ^-, and Ξ^0. It is then possible to fit the observations with a single species of K-meson, of which the θ^0 is the well-established member: θ^+, θ^0, and θ^-. In most cases, however, our interpretation is to be considered as an hypothesis which fits the observations rather than a demonstrated fact. The events

[20] This procedure is not rigorously justified because the weak decay interaction is not invariant with respect to rotation in isotopic spin space and therefore can be stronger for some charge states than others.

[21] Of course, spin and parity considerations are completely neglected here. Schemes such as those suggested by M. Gell-Mann and A. Pais [Phys. Rev. **97**, 1387 (1955)] may lead to a way of estimating more properly probabilities for decay into different combinations.

are interpreted as follows:

$$\pi^- + p \rightarrow \Lambda^0 + \theta^0 \quad \text{Cases } D \text{ and } H,$$
$$\rightarrow \Sigma^0 + \theta^0 \quad \text{Cases } A, B, G, \text{ and } I,$$
$$\rightarrow \Sigma^- + \theta^+ \quad \text{Cases } E, J, \text{ and } K.$$

The positions of observed decay events and the fraction of cases in which both Y and K decays are observed are consistent with previous information on the mean lifetimes of Λ^0 and θ^0.

To determine the total cross section for V-production, it is necessary to estimate the number of V-production cases where the decays were not seen either because they were outside the sensitive region or involved only neutral secondaries. This estimate is very uncertain, but leads to a cross section of $\sim$0.9 millibarn.

Data on angular correlations might be expected to provide some information on the spins of the particles involved. Three effects have been observed: (1) The angle between line of flight of the hyperon and incident π^- in the c.m.s. of the π^--p system (β) shows that the Λ^0 and Σ^0 prefer to travel backward in the c.m.s. The same backwards preference was noted[4] for nucleons from π^--p interactions which lead to emission of pions. (2) For Λ^0 and $Y^{\pm}$, the angle between production and decay planes (α) is less than 45° in all cases. (3) The angle between incident pion and nucleon from the hyperon decay in the hyperon rest system (γ) has been calculated, but the data are inconclusive because of insufficient statistics. However, the rather striking correlation shown by α may indicate that the spin of the hyperon is at least $\frac{3}{2}$.

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Recurrence Phenomenon in the 24-Hour Variation of Cosmic-Ray Intensity*

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Changes of cosmic-ray intensity in 24-hour intervals were studied at four neutron monitor stations and for one ionization chamber in the geomagnetic latitude range 0°–52° N. There is evidence that the fluctuations in the 24-hour variation of cosmic-ray intensity have a recurrence tendency of 27–28 days. There does not appear to be, however, any unique relationship between this recurrence and the well-known recurrence in the amplitude of the mean daily intensity. The association of this phenomenon with 27 day recurring disturbances in the geomagnetic field is also investigated.

I. INTRODUCTION

It is now well established that the amplitude and phase of the daily variation of cosmic-ray intensity are not constant. For example, the amplitude and phase of the 24 hourly variation of the nucleonic component undergo large day-to-day changes.[1] The purpose of the present investigation is to determine whether the amplitude of this variation possesses any recurrence characteristics. Also, since the 27-day daily mean intensity variation has been associated with solar processes and since there is evidence[2] that the amplitude of the daily variation follows roughly the pattern of the solar activity cycle, it is further proposed to investigate whether a 27-day recurrence of the daily variational intensity exists and to explore its association with solar induced geophysical phenomena.

* Assisted by the Office of Scientific Research, Air Research and Development Command, U. S. Air Force.
† Fulbright and U. S. Government scholar from India.
[1] Firor, Fonger, and Simpson, Phys. Rev. **94**, 1031 (1954).
[2] V. Sarabhai and R. P. Kane, Phys. Rev. **90**, 204 (1953).

II. NATURE OF THE PROBLEM

The principle difficulty in approaching this question is the measurement of the daily amplitude for a single day. Usually, an harmonic analysis is obtained for 24 hourly values (or 12 bi-hourly values) so as to determine the amplitude and phase of the best fitting sine curve. Such a procedure may, however, be incorrect and unreliable due to both the large statistical errors involved in counting rate and the presence of prominent day-to-day variations, e.g., a large 27-day recurrence in the mean daily cosmic ray intensity. Consider, for example, the arbitrary plot in Fig. 1 of cosmic-ray intensity over a period of 5 consecutive days. A, B, C, and D represent respectively the four 6 hourly intervals, 0000 to 0600, 0600 to 1200, 1200 to 1800, and 1800 to 2400 hours local time. An harmonic analysis for the 24 hourly values of day 1 and 2 would yield an hour of maximum late at night, and, for days 4 and 5, early in the morning. The amplitudes would be greatly affected by the average slopes of the day-to-day variation. Clearly, the essential features of the daily variation

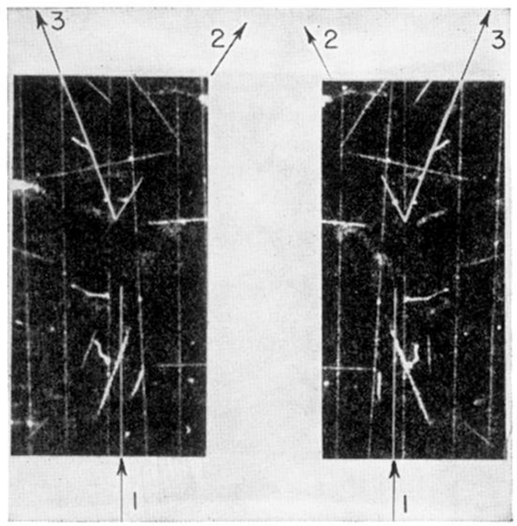

FIG. 1. Case *G*. Photograph of a probable Λ^0 produced in a 1.37-Bev π^--p collision. Track 1 is the incident pion, tracks 2 and 3 are pion and proton, respectively, from Λ^0 decay. Tracks 1, 2, and 3 have been reinforced with white ink for better contrast from other beam and background tracks.

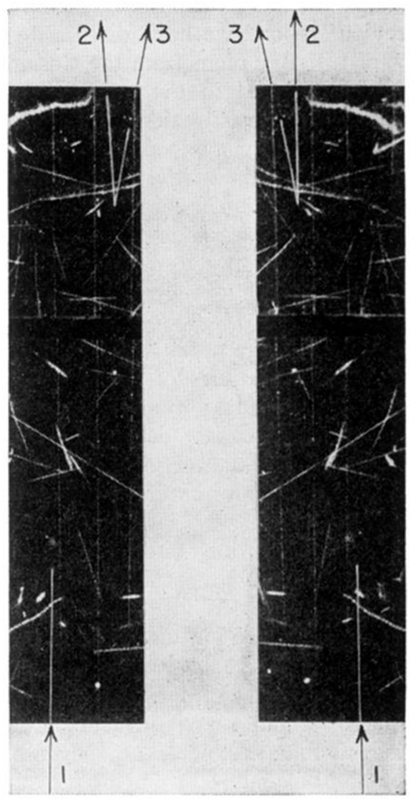

FIG. 2 Case *H*. Photograph of a possible θ^0 produced in a 1.37-Bev π^--p collision. Track 1 is the incident pion, tracks 2 and 3 are pions from θ^0 decay. These tracks have been reinforced with ink for better contrast from other beam and background tracks.

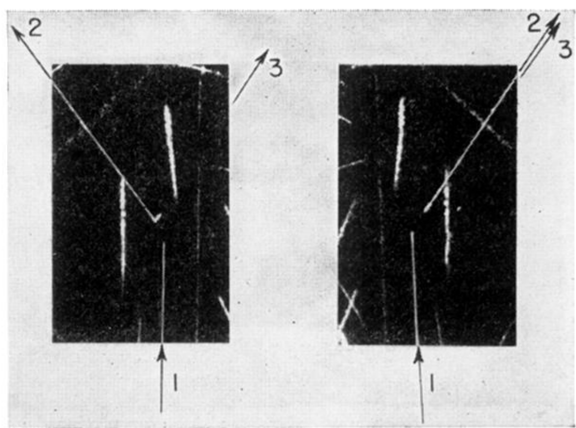

FIG. 3. Case *I*. Photograph of probable θ^0 produced in a 1.37-Bev π^--p collision. Track 1 is the incident pion, tracks 2 and 3 are pions from θ^0 decay. These tracks have been reinforced with ink for better contrast from other beam and background tracks.

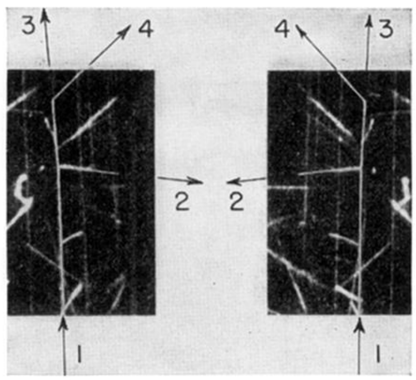

FIG. 4. Case *J*. Photograph of charged hyperon produced in a 1.37-Bev π^--p collision. Track 1 is the incident pion, track 2 is probably a *K*-meson, track 3 is the hyperon, and track 4 is probably a pion from hyperon decay. These tracks have been reinforced with ink for better contrast from other beam and background tracks.

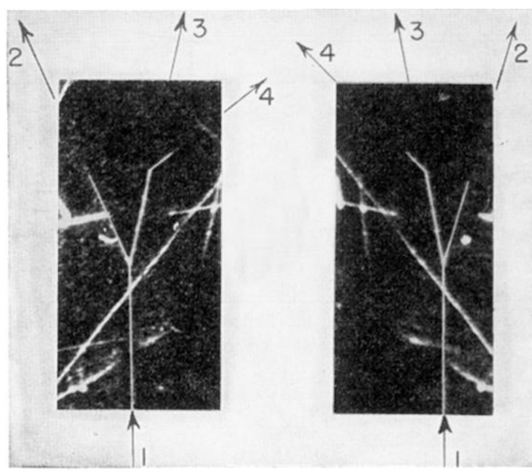

FIG. 5. Case K. Photograph of charged hyperon produced in 1.37-Bev π^{-}-p collision. Track 1 is the incident pion, track 2 is a possible K-meson, track 3 is the hyperon, and track 4 is probably a pion from hyperon decay. These tracks have been reinforced with ink for better contrast from other beam and background tracks.