Production of Heavy Unstable Particles by Negative Pions*

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(Received November 10, 1953)

In addition to two previously discussed cloud-chamber examples of V-particle production by 1.5-Bev π^- mesons from the Cosmotron, four further examples are discussed here. In two of the new examples a $\Lambda^0(V_1^0)$ and a $\vartheta^0(V_4^0)$ are seen to decay in a geometry indicating that they were produced together in a $\pi^- - p$ collision. A third example is best interpreted as production of a $\Lambda^-(V_1^-)$ together with a $K^+(V_2^+)$ by a π^- colliding with a proton. A fourth example shows a probable Λ^- decaying into a π^- and a neutron with a Q value of about 130 Mev. A cross section of $\sim$1 millibarn for V-particle production is inferred from the number of $\pi^- - p$ collisions observed.

IN a previous letter[1] we have reported two examples of Λ^0 particles[2] produced in hydrogen by negative pions (π^-) of 1.5-Bev kinetic energy. For both examples it was shown that if there were only two resulting particles the second was a K^0 particle of a mass of about 650 Mev. Since, however, the K^0 was not seen to decay it was also possible to balance energies and momenta by assuming two lighter neutral particles (including π^0) instead of one K^0 in addition to the Λ^0.

Observations on heavy unstable particles in cosmic radiation indicate lifetimes as long as 10^{-10} to 10^{-9} second with production cross sections at least 10^{-2} times those for π mesons. These facts can be reconciled theoretically[3] if it is assumed that the particles must be produced doubly (two at a time). Different particles may be produced simultaneously, in addition to pairs of identical ones. It appears that no evidence for double production of such particles, exceeding purely statistical coincidence, has been reported in cosmic radiation although a few examples might perhaps be interpreted in this manner.[4] The two examples of production in hydrogen reported by this group indicate multiple production. This interpretation is uncertain, however, since the K^0 particles are not observed to decay and the computed masses are higher than the value of about 500 Mev most commonly found for K particles.

We now wish to describe three additional cases where double production of heavy unstable particles by 1.5-Bev π^- is indicated with more certainty then in the previous two examples. We shall refer to the previous examples as cases A and B. Case C shows a Λ^0 together with a ϑ^0 probably produced in a heavy nucleus. Case D shows the same combination produced in hydrogen. Case E shows what may well be a Λ^- together with a K^+ with mass of about 500 Mev produced in hydrogen. A few cases of Λ^+ have been observed in cosmic radiation[5,6] but evidence for Λ^- is less certain. In a fourth case, called F, we shall describe an additional example best interpreted as a Λ^-.

Details of the experimental method will be described in a later article. A diffusion cloud chamber filled with 20 atmospheres of hydrogen was exposed to a 1.5-Bev π^- beam produced in a carbon target by the 2.2-Bev circulating proton beam in the Cosmotron. The pions were selected and collimated by the field of the Cosmotron magnet and a channel in the concrete shielding around the machine. The beam thus obtained is quite monoenergetic with a spread probably less than ± 0.1 Bev. The beam was finally deflected by a magnet into a concrete house containing the cloud chamber mounted between the pole faces of a magnet providing an average field of 10 500 gauss. This magnetic field has been calibrated to 1 percent accuracy and its vertical and horizontal components have been mapped throughout the chamber.

The examples to be described were obtained out of a total of 26 000 photographs obtained at a rate of one every 7 to 8 seconds. In addition many examples of V events were found for which no associated V event or nuclear interaction in the gas was observed. Finally, we have observed about 170 pion interactions in hydrogen, most of which lead to single and multiple production of pions. These will be described in a later article.

CASE C: Λ^0 WITH ϑ^0

Figure 1 (case C) shows a photograph of two V events, of which (a) is considered to be a Λ^0, and (b) a ϑ^0. Data which lead to this identification are given in Table I. Row 2 gives the momenta as measured on the 35-mm film by means of a Cooke microscope. The measure-

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

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

[2] We are using here the nomenclature suggested for V events at the International Congress on Cosmic Radiation, Bagnères-de-Bigorre, France. Accordingly $\Lambda^{0,+,-} \to \text{nucleon} + \text{pion} + Q_\Lambda$; $K^{0,+,-}$ is any particle whose mass falls between those of pion and proton; for example, $\vartheta^0(\to \pi^+ + \pi^- + Q\vartheta)$ is a K^0.

[3] A. Pais, Phys. Rev. **86**, 663 (1952). References to previous work are cited in this article. A. Pais, Proceedings of the Lorentz-Kamerlingh Onnes Conference, Physica (to be published); M. Goldhaber, Phys. Rev. **92**, 1279 (1953); M. Gell-Mann, Phys. Rev. **92**, 833 (1953).

[4] Leighton, Wanlass, and Anderson, Phys. Rev. **89**, 148 (1953); Fretter, May, and Nakada, Phys. Rev. **89**, 168 (1953); G. D. Rochester and C. C. Butler, Repts. Progr. in Phys. **16**, 364 (1953), give a comprehensive review of cosmic-ray results.

[5] York, Leighton, and Bjornerud, Phys. Rev. **90**, 167 (1953).

[6] International Congress on Cosmic Radiation, Bagnères-de-Bigorre, France (unpublished).

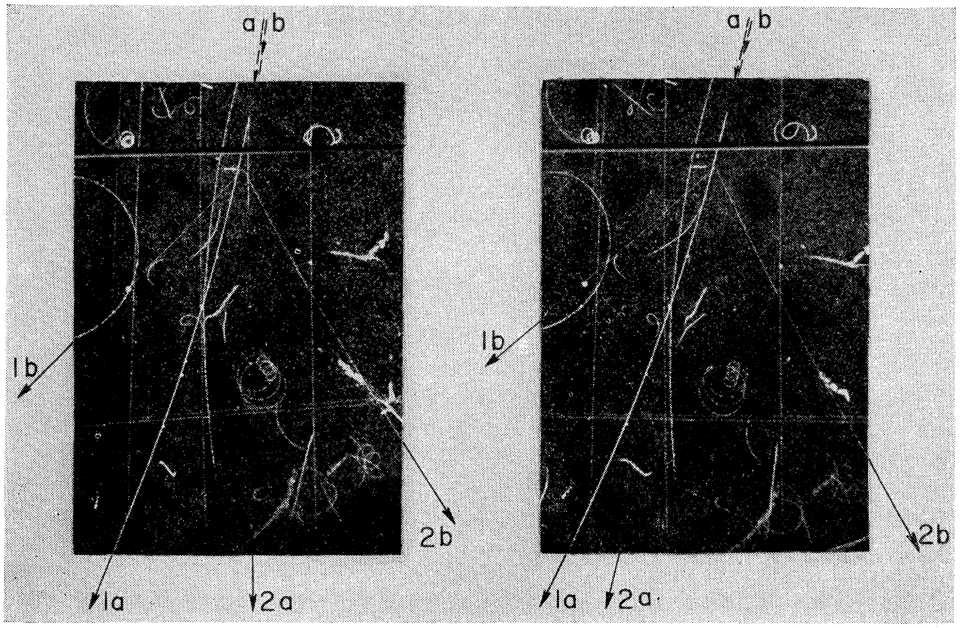

FIG. 1. Case C. Diffusion cloud-chamber photograph of two neutral V particles (a) and (b), whose lines of flight are almost colinear. (a) is believed to be a Λ^0 decaying into a proton (1a) and a negative π meson (2a). Tracks $1a$ and $2a$ practically coincide in the right view. (b) is probably a ϑ^0 decaying into π^+ (1b) and π^- (2b).

ments have been corrected for dip angle and space variations of magnetic field and magnification. The mass limits given in row 4 were deduced from measured momenta and estimated ionization densities. Row 5 shows what particle was assumed for further calculation. The angles between tracks in row 6 were obtained from a 3-dimensional reprojecting system as well as by geometrical reconstruction and calculation. The Q value for (a) is, within the given error, consistent with the usually accepted value of 37 Mev for a Λ^0. The Q value for (b) is rather large compared to the best value of 214 Mev given in the literature[7] for a ϑ^0.

From the measured momenta and angles in space for each track one can infer that the lines of flight of the Λ^0 and ϑ^0 practically coincide. From the total number of Λ^0 and ϑ^0 (originating in the walls) found in the 26 000 pictures one concludes that the probability for random association of the two particles in such a geometry is $\sim 10^{-9}$. We therefore should be justified in assuming that the Λ^0 and ϑ^0 were produced in one act. Since no incident particle is visible in the chamber and since the Λ^0 and ϑ^0 travel at an angle of about 24° upwards from the bottom of the chamber, we assume that they were produced in or below the bottom glass plate, though probably not much further down since the pion beam was fairly well collimated. The origin must, of course, lie on the line of intersection of the decay planes of the Λ^0 and ϑ^0. Both particles travel in directions between 0.5° and 1.5° to this line for a range of reasonable choices for the position of the origin.

The following procedure can now be used to determine the Q values more accurately than before. Since we know the directions of the lines of flight of Λ^0 and ϑ^0 with fair certainty we can deduce the momentum of one decay product in each V event from the momentum of the other. As row 2, Table I, shows, the momenta of 1a and 2b are known much better than those of 1b and 2a. We therefore have deduced the momenta of 1b and 2a. For the momenta of 1a and 2b we have chosen their lowest values within the given experimental errors. This choice will result in somewhat lower Q values than calculated above. The new momenta are given in row 8 and the recalculated Q values in row 9. The indicated remaining errors are now mainly due to the mentioned uncertainty in the directions of flight of Λ^0 and ϑ^0. The Q value for the ϑ^0 is still not in good agreement with the usual value of 214 Mev.

From the momenta in row 8 and the given angles one finds the momenta of Λ^0 and ϑ^0 given in row 10. Assuming that the particles were produced in a collision between a π^- and a nucleon and that no additional particle was involved ($\pi^- + p \rightarrow \Lambda^0 + \vartheta^0$) one calculates from the resultant of the momenta of Λ^0 and ϑ^0 that the total energy of incident pion and nucleon must have been 2050 ± 25 Mev before the collision. On the other hand, with the mases of 1119 ± 10 and 546 ± 20 Mev for Λ^0 and ϑ^0, respectively, one finds for the sum of their energies a value of 2068 ± 30 Mev. This value must be equal to the initial energy just calculated, if no other particles are involved in the collision, and one indeed finds agreement. Therefore the Λ^0 and ϑ^0 could have been produced in a $\pi^- - p$ collision, the π^- previously having been scattered upward by 24°, with the required energy. Such repeated interactions could take place in a heavy nucleus. For this interpretation the almost colinear flight of the Λ^0 and ϑ^0 would mean that in the

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

TABLE I. Measurements and results for case C.

	Track	Event a 1a	2a	Event b 1b	2b
1	Sign of charge	+	−	+	−
2	Measured momenta (Mev/c)	272±8	205±40	451±70	391±15
3	Estimated ionization density	>5×min	<1.5×min	<1.5×min	<1.5×min
4	Mass limit (Mev)	>780	<170	<380	<330
5	Assumed particle	proton	pion	pion	pion
6	Angle between tracks (degrees)	31.1±1		70±1	
7	Q values calculated from above data (Mev)	54±20		271±30	
8	Momenta for (2a) and (1b) calculated from direction of line of flight, assuming lowest momenta for (1a) and (2b) (Mev/c)	264	189±20	441±15	376
9	Q values recalculated (Mev)	49±10		266±20	
10	Momentum of unstable particle (Mev/c)	437		673	

center-of-mass system (c.m.s.) of π^- and nucleon the Λ^0 went almost straight backward. The same will be found for the next example to be discussed. From the observed momenta and angles a π^- of the beam colliding with a nucleon could *not* have produced the Λ^0 and ϑ^0 traveling in the observed direction, with simultaneous production of some other particle going downward to balance transverse momenta.

CASE D: Λ^0 AND ϑ^0 PRODUCED IN $\pi^- - p$ COLLISION

Figure 2 (case D) shows a photograph of a π^- track (marked π^-) disappearing abruptly in the hydrogen, and two nearby V events of which (a) is considered to be a Λ^0 and (b) a ϑ^0. Data which lead to this identification are given in Table II. The measured momentum of the incident particle (row 2) agrees well with the momentum of 1630 Mev/c for a 1.5-Bev π^-. The other momenta are not well determined, mostly because the tracks are of short length. The longest track (2b), furthermore, seems to show a slight deflection, perhaps due to scattering or to $\pi - \mu$ decay, which makes its momentum also unreliable. The given mass limits (row 4), however, seem to justify the assumed choices for the individual particles (row 5). In particular, since in a collision in hydrogen only one proton was present and since this proton is probably found in 1a, 2b could hardly be another proton in spite of the rather high upper mass limit.

The decay planes of both particles contain the end point of the incident track. The directions of flight of Λ^0 and ϑ^0 and incident π^- appear coplanar, though this is not accurately determined because of the small angle between π^- and ϑ^0 (b). Therefore no additional neutral particle has to be assumed, although calculation shows that kinematically this would be possible. One is therefore justified in assuming the same reaction as in case C ($\pi^- + p \rightarrow \Lambda^0 + \vartheta^0$). All pertinent angles are given in rows 6 and 7. From these angles and the momentum of the incident π^- one can calculate the momenta of the decay products directly. The results (row 9) agree with the measured values (row 2) within the errors. With the momenta from row 9, Q values have been calculated (row 10). Two experimental errors are given separately with each Q value. The first was determined from the probable variation of Q with the possible variations of all of the angles (rows 6 and 7) used for the computation. The second error was found from the variation of Q with a possible uncertainty of ±100 Mev/c for the momentum of the incident π^-. One sees that within the errors both Q's may agree with the usual values of 37 and 214 Mev, respectively, although the Q for the ϑ^0 is again rather high and agrees with the value found for case C. It should be pointed out that the error for the Q for the Λ^0 depends most strongly on the measurement

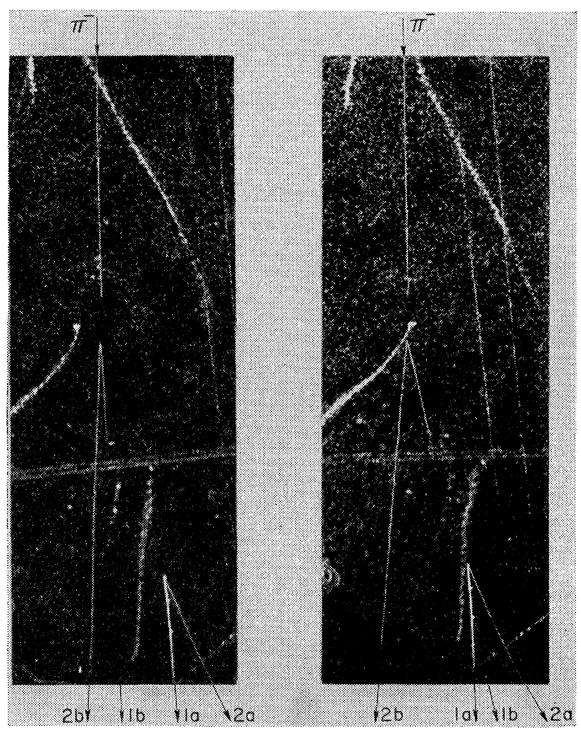

FIG. 2. Case D. Photograph of a 1.5-Bev π^- producing two neutral V particles in a collision with a proton. Tracks 1a and 2a, believed to be proton and π^-, respectively, are the decay products of a Λ^0. A ϑ^0 is probably seen to decay into π^+ (1b) and π^- (2b). Because of the rather "foggy" quality of this picture tracks 1b, 2a, and 2b have been retouched for better reproduction.

TABLE II. Data for case *D*.

		Incident track	Event a 1a	Event a 2a	Event b 1b	Event b 2b
1	Sign of charge	−	+	−	+	−
2	Measured momenta (Mev/c)	1620±160	210^{+210}_{-70}	140^{+300}_{-60}	210^{+210}_{-70}	840±300
3	Estimated ionization density	<1.5×min	>5×min	<1.5×min	<1.5×min	<1.5×min
4	Mass limit (Mev)		>400	<370	<350	<870
5	Assumed particle	pion	proton	pion	pion	pion
6	Angle between incident π^- and direction of flight (degrees)		11.1±1		2.3±0.5	
7	Angle between direction of flight and decay products (degrees)		8.8±1	11.3±1.5	29.3±2	11.0±2
8	Momentum of (a) and (b) calculated from incident momentum and angles (Mev/c)	1630	282		1357	
9	Momenta of decay products from momenta of (a) and (b) and angles (Mev/c)		160	125	400	1027
10	Q values calculated from rows 7 and 9		27±11±3		258±35±21	

of the small angle (2.3°) between incident π^- and ϑ^0 (b). Modifying this angle to make Q_{Λ^0} equal to 37 Mev would reduce Q_{ϑ^0}, which depends on this angle less strongly, to a value of 244 Mev.

From the momenta (row 8) of the Λ^0 and ϑ^0 and their masses of 1097±12 and 538±40 Mev, respectively, one calculates that the kinetic energy of the incident π^- must have been 1.52±0.04 Bev which is quite consistent with the 1.5-Bev beam energy.

CASE *E*: POSSIBLE Λ^- AND K^+ PRODUCED IN $\pi^- - p$ COLLISION

Figure 3 (case *E*) shows a photograph of what on first sight appears to be a π^- scattered forward by a proton with a subsequent decay of the π^-. Closer inspection shows that the momentum of the decay product

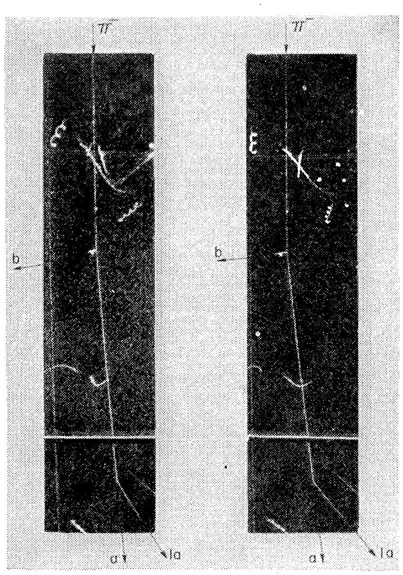

FIG. 3. Case E. Photograph of a $\pi^- - p$ collision event possibly resulting in a Λ^- (a) with a π^- (1a) as a decay product and a K^+ whose decay is not seen.

(1a) and its angle with respect to the track of the decaying particle (a) are much too large for a $\pi-\mu$ or $\mu-\beta$ decay. Therefore (a) must have been a heavy unstable particle.

As far as can be ascertained from the "scattering" event, particle (a) might have been produced at the Cosmotron target or at the cloud chamber wall, and scattered by a proton in the cloud chamber. Certainly the rate of production of heavy mesons would have to be large (~10 percent of that for pions) and their decay lifetime long (~10^{-8} sec) for the beam to contain an appreciable contamination of heavy mesons. No beam particles have shown a decay resembling that of (a). If (a) were produced in the target, it would be quite remarkable that it lives until it reaches the cloud chamber, is scattered, and then decays within the chamber. Such an origin is possible but seems unlikely. If (a) were a particle produced in the wall and scattered in the chamber, it would be remarkable that the incident track has both direction and momentum characteristic of beam tracks. For these reasons we assume that the incident particle is a beam π^- producing a charged unstable particle in a collision with a proton.

Data are given in Table III. Since the tracks are short and the momenta are high, the latter are not well determined. We therefore assume that the incident particle had the beam energy of 1.5 Bev, and compute the momenta of (a) and (b) by assuming that no additional neutral particle was produced. This assumption is very probably justified because (a), (b), and incident track are coplanar. One finds the momentum values given in row 8. If the mass of (a) is given, that of (b) is determined so that their total energies equal that of the incident π^-. In Table IV a number of such consistent values are given. The errors on the mass values of (b) include the uncertainties given for the angle measurements as well as an improbably large uncertainty of ±300 Mev for the energy of the incident π^-. To obtain a mass of 930 Mev (proton) for (b) does not seem to be possible unless (a) is a pion, without making

TABLE III. Data for case E.

		Incident track	Track a	Track 1a	Track b
1	Sign of charge	−	−	−	+
2	Measured momenta (Mev/c)	1800 ± 600	1400 ± 400	>120[a]	−
3	Estimated ionization density	$<1.5\times$min	$<1.5\times$min	$<1.5\times$min	3 to $6\times$min
4	Mass limit (Mev)		<1500		
5	Assumed particle	pion		pion	
6	Angle between incident track and collision products (degrees)		8 ± 1		79 ± 3
7	Angle between (a) and its decay product (degrees)			36 ± 1	
8	Momenta from incident momentum and angles (Mev/c)	1630	1604		227

[a] Track 1a is slightly distorted. Therefore only a lower limit can be given.

quite unreasonable assumptions for the uncertainties of the measured angles and of the incident momentum.[8] In the cosmic radiation Λ^+ particles have been found[6] with Q values of about 130 Mev, leading to a mass of 1200 Mev. Row 5 of Table IV shows that such a mass for (a) would lead to a mass for (b) which is quite consistent with that usually found for K particles. Case E can therefore be interpreted as the charged counterpart of case C and case D in which Λ^0 and K^0 were produced. For this interpretation the present photograph is an example of the reaction $\pi^-+p\rightarrow\Lambda^-+K^+$.

A calculation has been performed to investigate whether a neutrino (ν) or π^0 could have been produced in addition, which might then change the above conclusions. One finds that only the combinations $[\Lambda^-, K^+, \pi^0]$ or $[\Lambda^-, K^+, \nu]$ are possible (though unlikely because of the observed coplanarity) while the combinations $[\Lambda^+, K^-, \pi^0]$, $[\Lambda^+, K^-, \nu]$, $[p, K^-, \pi^0]$, or $[p, K^-, \nu]$ are kinematically not possible.

From the mass of (b) of 520 Mev and its momentum of 227 Mev/c one finds that (b) should show an ionization density of $\sim4\times$min which agrees with the estimated ionization density given in row 3.

Assuming a decay of $\Lambda^-\rightarrow n+\pi^-$, the calculated momentum for 1a of 1604 Mev/c and measured momentum for (b) of $\geqslant120$ Mev/c lead to a Q value $\geqslant50$ Mev. Track 1a may be somewhat distorted so that these figures probably represent lower limits only. If much of the apparent curvature of 1a is due to distortion, the Q value may be as high as 130 Mev, corresponding to a momentum of 440 Mev/c for 1a, as has been assumed in the previous discussion.

[8] For the present discussion it is of particular importance to exclude the possibility that the mass of (b), M_b, could be that of a proton (930 Mev) for the assumption that (a) is a K^- of mass 500 Mev. One finds that $\partial M_b/\partial p_0=8.1$ Mev/(100 Mev/c), where p_0 is the momentum of the incident π^- (so far assumed to be the beam momentum of 1630 Mev/c). Furthermore $\partial M_b/\partial\alpha_a=-11.3$ Mev/degree and $\partial M_b/\partial\alpha_b=-3.7$ Mev/degree, where α_a and α_b are the angles recorded in Table III, row 6, for (a) and (b), respectively. It is very hard to conceive how π^- of momenta >1700 Bev/c could be contained in the beam. With this upper limit and the uncertainties for α_a and α_b given in Table IV one sees that $M_b\leqq890$ Mev if all uncertainties are assumed to act together in a direction to increase M_b. Only by decreasing α_a by 3° and α_b by 9°, for example, could one obtain a value for M_b of 930 Mev. The values for M_a and M_b noted in rows 2 and 3 of Table IV are then not possible without destroying a nucleon.

CASE F: EXAMPLE OF A Λ^-

The photograph shown in Fig. 4 (case F) shows another V event which may be interpreted as a Λ^-. The picture shows a negative particle (a) of momentum 1190 ± 170 Mev/c and of estimated ionization density $\leqslant1.5\times$min, apparently produced in the wall of the chamber. The angle between (a) and the beam direction is 8°. Particle (a) decays into a negative particle (1a) of momentum 83 ± 3 Mev/c and estimated ionization density 2 to $3\times$minimum.[9] The mass of the decay product thus lies between 110 and 150 Mev, identifying it as a π^-. The angle between (a) and 1a is 76°. If one additional neutral decay product is assumed one calculates Q values and mass values for (a) as given in Table V. One sees that only the assumption of a neutron (row 1) leads to Q and mass values compatible with those found in cosmic radiation. Particle (a) can also not be identified as a $\tau^-\rightarrow2\pi^0+\pi^-+70$ Mev because 1a alone would have an energy of 230 Mev in the rest system of the τ^-. The assumption in row 4 ($K^-\rightarrow\mu^-+2\nu$) is unlikely because the decay product is most probably

TABLE IV. Consistent masses for particle (a) and particle (b) of case E.

	Particle (a)	Mass of (a) (Mev)	Particle (b)	Mass of (b) (Mev)
1	π^-	140	proton	934 ± 6
2	K^-	500	?	860 ± 20
3	?	760	?	760 ± 30
4	$\Lambda^-(Q=37$ Mev)	1107	K^+	570 ± 50
5	$\Lambda^-(Q=130$ Mev)	1200	K^+	520 ± 50

TABLE V. Q values and masses for case F, assuming different masses for the neutral decay product.

	Charged decay product	Neutral decay product	Mass of neutral decay prod. (Mev)	Q for (a) (Mev)	Mass of (a) (Mev)
1	π^-	n	930	130^{+25}_{-15}	1200
2	π^-	π^0	140	430 ± 70	710
3	π^-	K^0	500	230 ± 35	870
4	μ^-	2ν	0	$>520\pm80$	>620

[9] For the assumption of a Λ^0 traveling backwards the momentum of (a) is much too high.

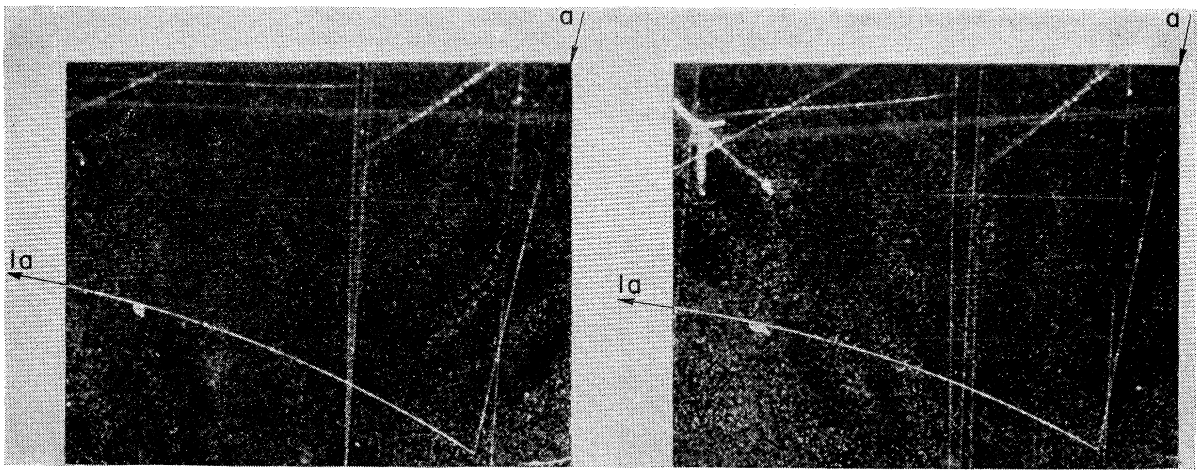

FIG. 4. Case F. Photograph of a negative unstable particle (a) best interpreted as a Λ^-. The decay product (1a) is identified as a π^- from momentum and ionization density.

identified as a π^-. We therefore are left with the conclusion that the present photograph shows the decay of a $\Lambda^- \rightarrow n + \pi^- + Q$, where $Q = 130_{-15}^{+25}$ Mev. The errors on the latter are due to the uncertainty of the measured momentum of (a).

It has been pointed out[10] that if the hypothesis of charge independence applies to $\Lambda^{+,-,0}$, then the Λ^- must have isotopic spin z component $(-3/2)$ with isotopic spin 3/2, in which case a doubly-charged Λ^{++} should also exist. No Λ^{++} decays have been reported to date, but the number of observed Λ^- and Λ^+ is so small that no significant discrepancy exists. A track which might be interpreted as a Λ^{++} has been reported by Ascoli.[11]

LIFETIMES, CROSS SECTION, AND ANGULAR RELATIONSHIPS

The role played by chance in apparent lifetimes, cross sections, and angular relationships deduced from a small number of cases is very large. Nevertheless the few available observations will be compiled in the following paragraphs.

Table VI shows the lifetimes. All values are consistent with mean lifetimes of 10^{-10} to 3×10^{-10} sec cited in the literature.[4–6]

TABLE VI. Observed lifetimes of all particles in units of 10^{-10} sec.

Particle	A	B	C	D	E	F
Λ^0	0.4	0.3	6	9		
Λ^-					2	3
ϑ^0			2	0.1		
K^0	>4[a]	>3[a]				
K^+					>0.7	

[a] Not taking into account that decay may result in two neutral particles and thus be invisible.

[10] D. C. Peaslee, Phys. Rev. 86, 127 (1952).
[11] G. Ascoli, Phys. Rev. 90, 1079 (1953).

For a mean lifetime of 3×10^{-10} sec for the Λ^0 and 1.5×10^{-10} for the ϑ^0, the given cloud-chamber geometry, a π^--beam energy of 1.5 Bev, and isotropic angular distributions (in the c.m.s.) of Λ and K particles one can estimate that 60 percent of the Λ and 50 percent of of the K should be seen to decay inside the chamber. One can conclude that for 80 percent of all occurring cases one should see at least one of the two particles decay and for 20 percent of all cases one should see both decaying. (For shorter lifetimes or angular distributions peaked forwards or backwards the probabilities are even larger.) Therefore the 4 cases of unstable particle production in hydrogen (A, B, D, E) observed here may correspond to 5 ± 3 cases that actually happened.[12] This number can be compared with the other 170 $\pi^- - p$ interactions observed, including events with two and four outgoing prongs. Making use of Fermi's statistical theory of meson production[13] and of the isotopic spin formalism, Fermi[14] has calculated the probabilities for the different combinations. One finds that combinations resulting in no outgoing prongs are expected to occur in only 12 percent of all interactions. Therefore our 170 observed cases may correspond to 190 actual interactions. The total interaction cross section has been found to be 34 ± 3 millibarns.[15] Therefore the cross section for heavy unstable particle production by 1.5-Bev π^- in hydrogen is ~ 1 millibarn.

Table VII gives the angles between the decay planes of the particles and their production planes (the plane formed by the incident track and the line of flight of the unstable particle.) The absence of large angles for the Λ particles is surprising and might be taken as an indication for a large spin for these particles. In fact the

[12] Decays of Λ^0 and ϑ^0 into neutral particles cannot be observed in this experiment and are not taken into account here.
[13] E. Fermi, Progr. Theoret. Phys. (Japan) 5, 570 (1950).
[14] E. Fermi (private communication).
[15] Cool, Madansky, and Piccioni, Phys. Rev. 93, 637 (1954).

separation between the decay and production planes seems smaller than would be expected unless the spin is taken to be unreasonably large.

Table VIII shows the angles between incident π^- and direction of emission of Λ^0 in the c.m.s. Again the result is surprising because of the absence of angles near 90° for which the solid angle is largest. The solid angle between 170° and 180° amounts to only 1.5 percent of the hemisphere, yet both *C* and *D* fall into this region. This may indicate that large angular momentum states are involved in the production of these particles, which might be consistent with the possibility of a large spin of the Λ^0. Since $\lambda_0 \approx 2\times 10^{-14}$ cm in the c.m.s. for a π^- of 1.5-Bev laboratory energy, angular momentum states up to $L=6$ may be possible.

TABLE VII. Angles between decay plane and production plane.

Particle	*A*	*B*	*C*	*D*	*E*
Λ^0	5°±5°	30°±20°	18°±7°	27°±10°	
Λ^-					7°±5°
ϑ^0			60°±6°	70°±5°	

TABLE VIII. Angle between incident π^- and direction of emission of $\Lambda^{0,-}$ in c.m.s.

Particle	*A*	*B*	*C*	*D*	*E*
Λ^0	141°	125°	177°	174°	
Λ^-					30°

SUMMARY

These examples of the production of heavy unstable particles in $\pi^- - p$ collisions have been shown to be consistent with a double production process,

$$\pi^- + p \rightarrow \Lambda + K,$$

occurring with a cross section of about 1 millibarn for 1.5-Bev π^-. Further work is required to determine whether production is *always* double in these and nucleon-nucleon collisions.

In four cases the Λ is a Λ^0, and in two of these the K^0 is observed to decay and can be considered to be a ϑ^0, although the *Q* values of about 260 Mev are not quite consistent with the cosmic-ray value of 214 Mev. One case is interpreted as a Λ^-, and an additional charged decay originating outside the chamber is thought to be a Λ^- with *Q* value of 130 Mev.

The data suggest an angular correlation between Λ-decay planes and production planes, which may mean that Λ particles have large spin, and a preferred backward (or forward) emission in the c.m.s., which may mean that Λ particles are produced in states of high angular momentum. Many more data are needed to determine such angular relationships.

We wish to express our thanks to the many members of the Cosmotron Department whose efforts have created the opportunity for this work and whose cooperation is enabling us to pursue it. Our thanks are also due to the other members of the cloud-chamber group without whose support this work could not be continued.

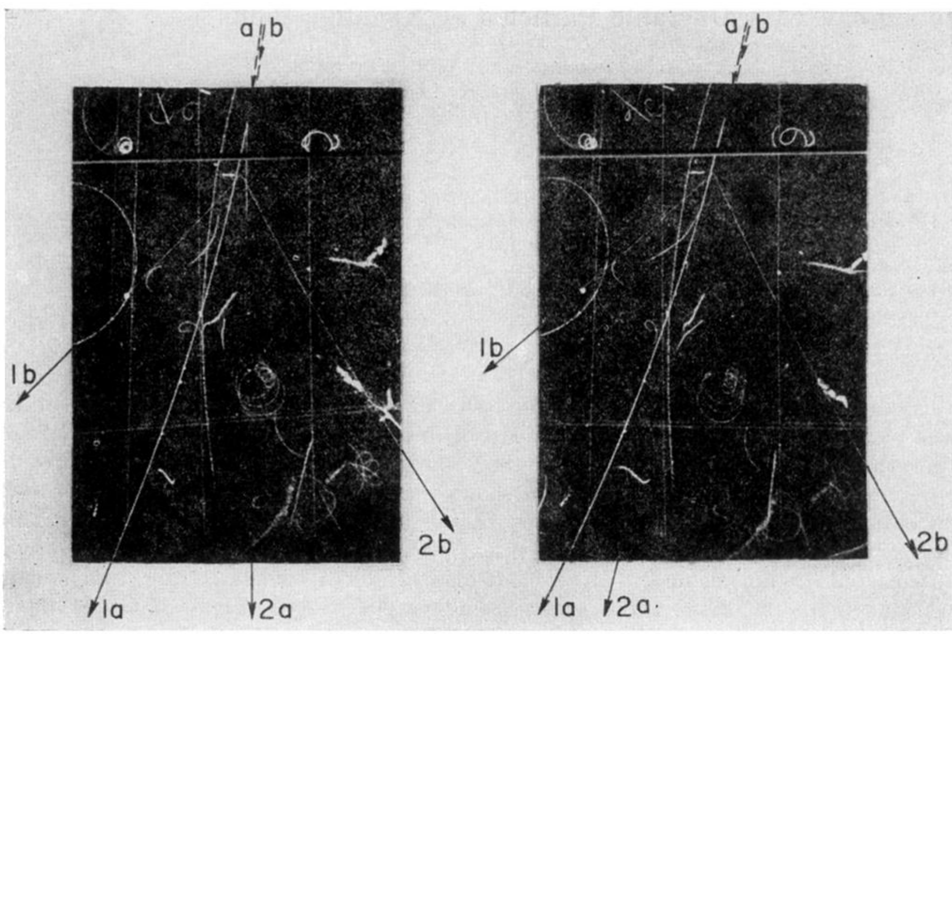

FIG. 1. Case C. Diffusion cloud-chamber photograph of two neutral V particles (a) and (b), whose lines of flight are almost colinear. (a) is believed to be a Λ^0 decaying into a proton (1a) and a negative π meson (2a). Tracks $1a$ and $2a$ practically coincide in the right view. (b) is probably a ϑ^0 decaying into π^+ (1b) and π^- (2b).

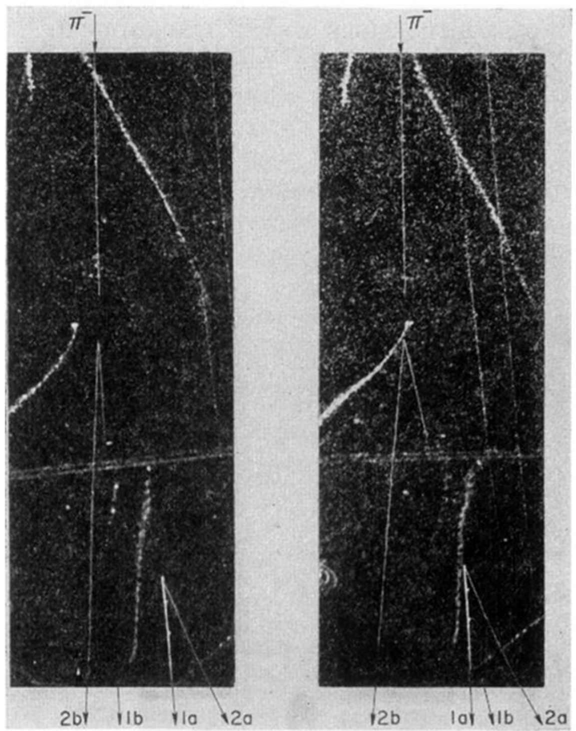

FIG. 2. Case D. Photograph of a 1.5-Bev π^- producing two neutral V particles in a collision with a proton. Tracks 1a and 2a, believed to be proton and π^-, respectively, are the decay products of a Λ^0. A ϑ^0 is probably seen to decay into π^+ (1b) and π^- (2b). Because of the rather "foggy" quality of this picture tracks 1b, 2a, and 2b have been retouched for better reproduction.

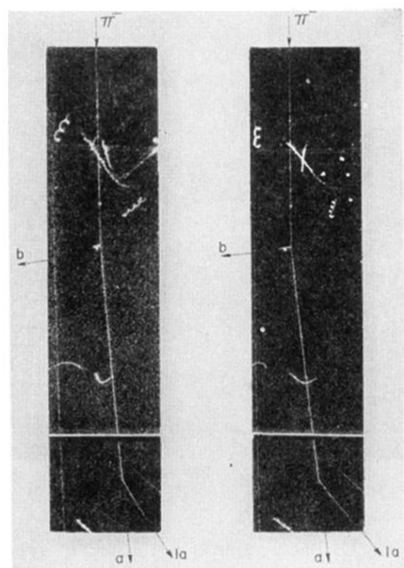

FIG. 3. Case E. Photograph of a $\pi^- - p$ collision event possibly resulting in a Λ^- (a) with a π^- (1a) as a decay product and a K^+ whose decay is not seen.

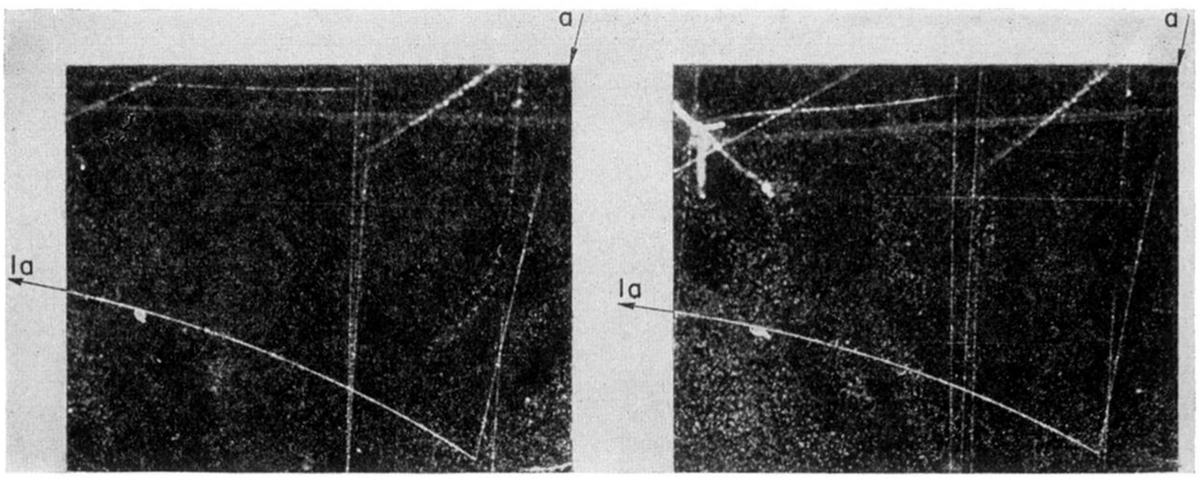

FIG. 4. Case F. Photograph of a negative unstable particle (a) best interpreted as a Λ^-. The decay product (1a) is identified as a π^- from momentum and ionization density.