Evidence for Double Production of V^0 Particles*†

R. W. THOMPSON, J. R. BURWELL, R. W. HUGGETT, AND C. J. KARZMARK
Department of Physics, Indiana University, Bloomington, Indiana
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An example of the double production of V^0 particles is described and interpreted as evidence for the process: $\pi^- + p \rightarrow \Lambda^0 + \theta^0$. The Λ^0 and θ^0 are well identified from analysis of their decays in the chamber, from which $Q(\Lambda^0) = 37 \pm 4$ Mev and $Q(\theta^0) = 223 \pm 10$ Mev. The nature of the incident particle is suggested by calculation of its mass from the observed V^0-particle momenta.

If the interpretation of the event is correct, the spin of the θ^0 is determined to be integral and the possibility that one of the decay fragments is a muon is excluded. We therefore have $\theta^0 \rightarrow \pi^+ + \pi^-$.

I. INTRODUCTION

ONE of the most significant results from the Brookhaven Cosmotron has been the clear evidence obtained by Shutt and his collaborators for the production of heavy unstable particles in pairs. Working with a pressurized hydrogen diffusion magnet chamber exposed to the 1.5-Bev π^- beam, these authors have found four examples indicating, directly or indirectly, the simultaneous production of a Y^0 particle and a K^0 particle in an elementary (π^-,p) collision. In case D,[1] the entire process, including the decay of both neutral particles, is seen in the gas of the chamber. In cases A and B,[2] the (π^-,p) collision and the Y^0 decay are seen, and the simultaneous production of a K^0 is inferred by application of the conservation laws. In case C,[1] a Y^0 decay and a K^0 decay are seen in the same photograph, and their simultaneous production in the bottom wall of the chamber is strongly suggested.

The argument that one of the products is a neutral hyperon is based on mass determination of the positive decay fragment which is distinctly heavily ionizing in all four cases. The mass values derived from momentum and ionization estimates are consistent with the proton mass. Furthermore, the $Q(p,\pi)$ values, when they can be directly determined from measured momenta (cases A and C give $Q = 51$ and 54 ± 20 Mev, respectively), are compatible with the cosmic-ray mean value of 37 ± 1 Mev[3] for the normal Λ^0. Thus, although the quoted errors do not entirely exclude the possibility that the heavy neutral product is one of the types reported by Leighton *et al.*,[4] the most likely possibility is that it is, in fact, a normal Λ^0, as observed in cosmic radiation.

The identification of the K^0 meson is perhaps less unambiguous. In cases A and B, in which the K^0 decay is not observed, the best estimate of the K^0 mass is indirectly obtained from the known π^- beam energy and from the angular orientation of the Y^0 fragments, with the assumptions that the Y^0 is a normal Λ^0 and that the K^0 and the Λ^0 are the only particles produced in the process. The resulting masses in the two cases are $(1350 \pm 70)m_e$ and $(1280 \pm 80)m_e$, respectively. Both are somewhat higher than, although perhaps not entirely incompatible with, the θ^0 mass of $(966 \pm 10)m_e$ determined from cosmic-ray observations.[3,5] However, in both events, as these authors are careful to point out,[2] it is possible to balance energies and momenta if it is assumed that two neutral particles (one of which may be a π^0) are produced in addition to the Λ^0.

In case C, low upper limits for the masses of both K^0 decay fragments can be set. The directly determined $Q(\pi,\pi)$ value is 271 ± 30 Mev; again somewhat higher than the cosmic-ray value of 214 ± 5 Mev, although much lower than the results for cases A and B which correspond to $Q(\pi,\pi)$ values of 410 ± 35 Mev and 375 ± 40 Mev, respectively.[6] In case D, none of the tracks permits good direct measurement, so the momenta are indirectly derived from the π^- beam energy and the angles, again under the assumptions that the only products of the reaction are the two V^0 particles which are observed to decay, etc. The result is $Q(p,\pi) = 27 \pm 11$ Mev for the Y^0 and $Q(\pi,\pi) = 258 \pm 41$ Mev for the K^0. Again the $Q(\pi,\pi)$ is a little high, and in this case the $Q(p,\pi)$ is a little low; but in view of the quoted errors, both are compatible with the cosmic-ray results for the Λ^0 and θ^0.

II. DESCRIPTION OF EVENT R-530

In the experiment with the large magnetic chamber,[3] triggered by cosmic-ray penetrating showers, we have obtained a photograph showing two V^0 events, which is similar to the Brookhaven examples described above. If that identification is correct, the event confirms the Brookhaven work and in addition provides clarification as to the specific nature of the neutral unstable particles which are produced.[7]

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† A report of this work was given at the Washington meeting of the American Physical Society, 1954 [Phys. Rev. 95, 661(A) (1954)].

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

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

[3] Thompson, Buskirk, Etter, Karzmark, and Rediker, Phys. Rev. **90**, 329 (1953).

[4] Leighton, Wanlass, and Anderson, Phys. Rev. **89**, 148 (1953).

[5] See the report of the Indiana group at the Fourth Rochester Conference on High Energy Physics (University of Rochester Press, Rochester, to be published).

[6] These Q values were computed from the K^0 masses given in reference 2, assuming $m_\pi c^2 = 139.7$ Mev.

[7] Since event R-530 was reported at the Washington meeting, we have learned from Dr. Thorndike that the estimate of the

The photograph (film No. R-530) is shown in Fig. 1. The two decay apexes, (1,2) and (3,4), are well-illuminated although near the top of the chamber. The tracks of the four decay fragments are the only tracks in the photograph, except for track 5 which is spatially unrelated. Tracks 2 and 3 pass out of the illuminated region at the front, and track 1 passes out to the rear. Fortuitously, all four curvatures can be fairly well determined as may be judged from the comparator plots in Fig. 2 and Fig. 3. The curvature and angle data have been reduced by the new least-squares methods developed for this large chamber,[8] and the results for the two V^0 events are given in Table I.

In addition to the data in Table I, the observed ionizations provide information as to the nature of the

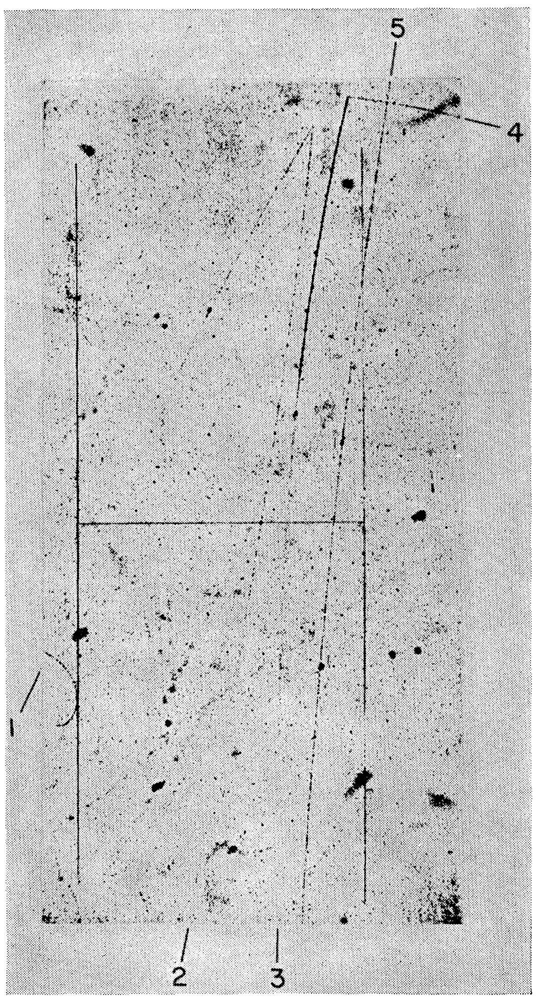

FIG. 1. Right eye view of R-530.

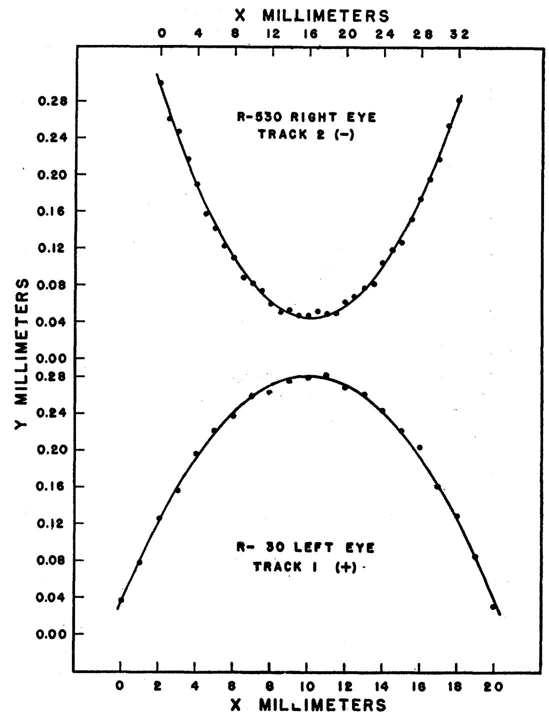

FIG. 2. Comparator plot of positive and negative fragments from decay (1,2) in R-530.

fragments. The estimated ionization of track 3 is from 6 to 10 times the minimum value, to be compared with factors of 7 and 2.8 to be expected for a proton and a K meson ($970m_e$) of this momentum, respectively. Thus the ionization of track 3 is consistent with the proton mass, but is a little too heavy to favor the K-meson mass. The ionization of track 4 appears to be a little more than, but certainly less than 3 times, the minimum value. A pion of this momentum would be heavily ionizing by a factor 2. Thus the estimated ionizations of tracks 3 and 4 together with the $Q(p,\pi)$ value given in Table I fairly well identify the decay (3,4) to be that of a Λ^0 where the Q of 37 ± 4 Mev is limited in this case to a sufficiently narrow interval that anomalous values of 10 or 75 Mev[4] are probably excluded.

The ionizations of tracks 1 and 2 are apparently at or near the minimum value and thus are less informative. The identification of decay (1,2) is therefore based

TABLE I. Basic data on the two V^0 events.

Track	Event (1,2) 1	Event (1,2) 2	Event (3,4) 3	Event (3,4) 4
Charge	+	−	+	−
Momentum (Bev/c)	0.35 ± 0.01	0.94 ± 0.04	0.30 ± 0.02	0.106 ± 0.008
Angle between tracks	$40.4\pm0.2°$		$88.1\pm0.2°$	
V^0 momentum (Bev/c)	1.23 ± 0.05		0.32 ± 0.02	
α	-0.512		$+0.758$	
p_T (Bev/c)	0.172		0.099	
Q value (Mev)	$Q(\pi,\pi)=223\pm10$		$Q(p,\pi)=37\pm4$	
V^0 identity	θ^0		Λ^0	

π^--beam kinetic energy at Brookhaven has been revised from 1.5 Bev down to 1.37 Bev. The effect of this revision is to reduce the $Q(\pi,\pi)$ values of the K^0 in Cases A, B, and D to 375, 330, and 233 Mev, respectively.

[8] Thompson, Buskirk, Cohn, and Karzmark, Proceedings of the Bagnères Conference, Report No. A-3, 1953 (unpublished).

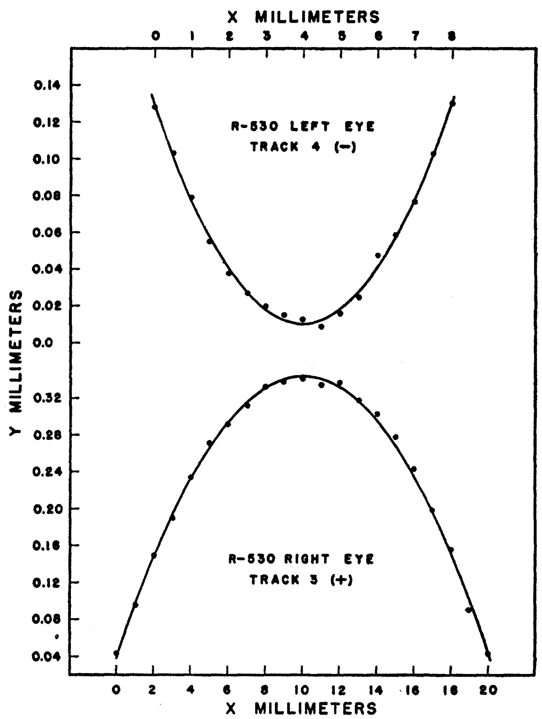

FIG. 3. Comparator plot of positive and negative fragments from decay (3,4) in R-530.

on the dynamics of the decay. The fact that the $Q(\pi,\pi)$ value of 223 ± 10 Mev, from Table I, is very near the mean value of 214 ± 5 Mev for the θ^0 is a necessary but not a sufficient condition that decay (1,2) be a θ^0. The possibility of identification with various other decay schemes may be tested by computation of Q values for the various appropriate fragment masses.

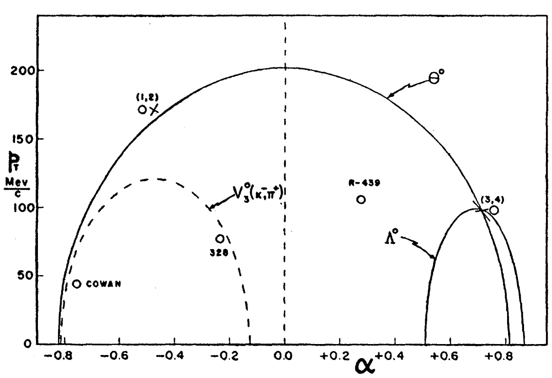

FIG. 4. Q-curve plot (for $\beta=1$) showing the relationship of decays (1,2) and (3,4) to various decay schemes. The solid curves are drawn for $\Lambda^0\rightarrow p+\pi^-+37$ Mev and $\theta^0\rightarrow\pi^++\pi^-+214$ Mev. The dashed curve is drawn for $V_3{}^0\rightarrow K^-+\pi^++60$ Mev (see reference 4). The coordinates of the circles are the observed values of p_T and α. In addition, for decays (1,2) and (3,4), crosses are plotted showing the computed displacement of the circles for $\beta\rightarrow1$. Events No. 328 and R-439 are the anomalous events reported by the Indiana group (see references 3 and 5). The point at the lower left-hand corner of the plot is the event found by E. W. Cowan [Phys. Rev. **94**, 161 (1954)].

A more revealing procedure is to make the comparison in terms of the Q-curve plot[3] as shown in Fig. 4. It is seen that decay (1,2) falls very near the θ^0 curve,[9] in a position which corresponds to a relatively probable angle of emission in the center-of-mass system. However, the position is such that identification of decay (1,2) with other decay schemes or isolated anomalous points is not suggested by the data.

III. ANALYSIS AS DOUBLE PRODUCTION

The relative orientation of the two neutral decays suggests that the Λ^0 and θ^0 were produced in the same interaction. A copunctuality test may be applied here since all four decay fragment momenta are directly measured. The result is that the lines of flight of the θ^0 (as deduced from the vector sum $\mathbf{P}_\theta=\mathbf{p}_1+\mathbf{p}_2$) and the Λ^0 (as deduced from $\mathbf{P}_\Lambda=\mathbf{p}_3+\mathbf{p}_4$) pass within 0.2 mm of each other[10] and thus very probably intersect. The intersection falls at the inside surface of the top wall (brass) of the chamber, with an uncertainty of a few millimeters. Thus the interaction may have occurred just within the brass wall or in the gas (argon) itself. In either case, the absence in the chamber of ionizing tracks from the same origin suggests that the interaction may have been a relatively simple one, involving a single peripheral nucleon. This interpretation is supported by the quantitative analysis below.

TABLE II. Energy balance for pion incidence.

Initial energy (Bev)	Final energy (Bev)
$E_\pi=1.53$[a]	$E_\Lambda=1.16$
$m_pc^2=0.94$	$E_\theta=1.32$
$E_\pi+m_pc^2=2.47\pm0.05$	$E_\Lambda+E_\theta=2.48\pm0.05$

[a] This figure is the total energy of a pion of momentum $\mathbf{P}=\mathbf{P}_\Lambda+\mathbf{P}_\theta$.

Under assumption that the target particle was a single nucleon and that the Λ^0 and θ^0 were the only particles produced, the conservation laws can be applied to test various assumptions as to the nature of the incident particle. The vector diagram of the process is shown in Fig. 5. It may be verified that, of the known particles exhibiting strong nuclear interactions, the best fit is obtained if the incident particle was a pion.[11] In Table II, the initial and final energies of the system under this assumption are seen to agree within the experimental errors. However, the percentage agreement is somewhat misleading since the main contributions to the total energy are the nucleon rest mass and the θ^0 momentum, and these contribute to

[9] This is anticipated since the Q value is close to the mean of 214 Mev, for which the θ^0 curve in Fig. 4 is drawn.

[10] The figure of 0.2 mm is fortuitously small since the errors from the momenta and the reconstruction process are several times as large.

[11] The incident pion may easily have been produced in a nuclear interaction in the absorber (8 in. of copper) immediately above the chamber without other products of that interaction being visible in the chamber.

both the initial and final energies in essentially the same way. Also, for the same reason, the errors in the initial and final energies given in Table II are not independent.

An alternate method which is considerably more sensitive is to compute the mass of the incident particle, although it is clear that the value so obtained will be rough since the incident particle is quite relativistic. From the equation

$$mc^2=\{[(P_\Lambda{}^2c^2+M_\Lambda{}^2c^4)^{\frac{1}{2}}+(P_\theta{}^2c^2+M_\theta{}^2c^4)^{\frac{1}{2}}-m_pc^2]^2 -|\mathbf{P}_\Lambda+\mathbf{P}_\theta|^2c^2\}^{\frac{1}{2}},$$

and from the data in Table I and Fig. 5, we find $mc^2=0.27\pm0.13$ Bev,[12] which is easily compatible with the pion rest energy.

Thus, with the reservations stated above, the most likely interpretation of the event is the double-production process:

$$\pi^-+p\rightarrow\Lambda^0+\theta^0. \quad (1)$$

In the center-of-mass system, the Λ^0 was emitted in the backward direction at an angle of 168° with the direction of the incident pion. In the laboratory system, the decay planes of the Λ^0 and θ^0 make angles of 26.5° and 10.6°, respectively, with the production plane.

IV. THE SPIN AND DECAY SCHEME OF THE θ^0 MESON

Although it has generally been assumed that the θ^0 decays into two pions (instead of a π and a μ) and therefore has integral spin, neither fact has ever been proved. The Indiana work based on dynamic analysis indicates that the θ^0 decay is a two-body process in which both fragments are L mesons (π or μ).[13] Actually, the dynamic data favor the pion mass for both fragments but this conclusion is not entirely firm. However, there is good evidence that one of the fragments is a pion. For example, the Paris group[14] reports 3 nuclear interactions induced by θ^0 secondaries. Also there is one Indiana event in which the positive fragment undergoes π-μ decay. We have therefore $\theta^0\rightarrow\pi^\pm+(\pi^\mp$ or $\mu^\mp)$.

However, if Eq. (1) is correct, the spin of the θ^0 must be integral and therefore both decay fragments must be pions, $\theta^0\rightarrow\pi^++\pi^-$.

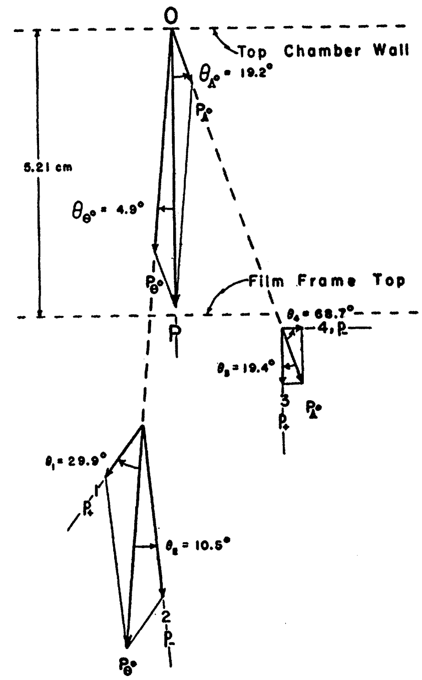

FIG. 5. Vector diagram of R-530.

[12] The motion of the target nucleon in the nucleus (brass or argon) introduces additional uncertainty in the value of mc^2 so derived, although the most likely situation is that the nucleon is moving at right angles to the incident pion in which case the effect is inappreciable.

[13] Thompson, Buskirk, Cohn, and Karzmark, Proceedings of the Bagnères Conference, Report No. B-2, 1953 (unpublished).

[14] Gregory *et al.*, Proceedings of the Bagnères Conference, p. 35, 1953 (unpublished).

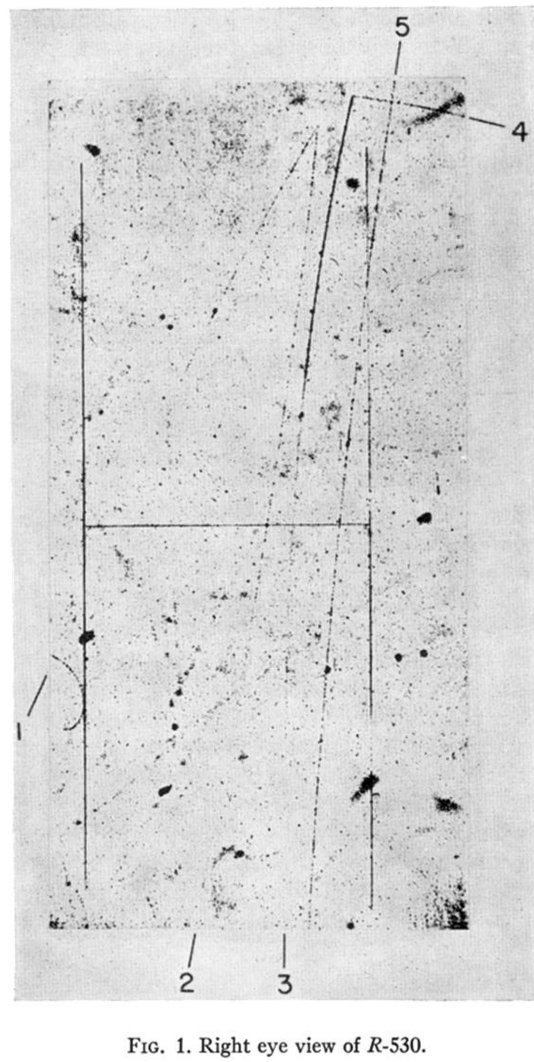

FIG. 1. Right eye view of *R*-530.