Evidence for the Transition of a K^0 into a $\bar{K}^0$ Meson*†

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(Received November 4, 1958)

Two pictures have been obtained in a liquid-hydrogen bubble chamber, each of which demonstrates the following sequence:

(1) $\pi^- + p \rightarrow Y^0 + K^0$, $[Y_A{}^0 = \Lambda^0,\ Y_B{}^0 = \Sigma^0]$
(2) $\Lambda \rightarrow p + \pi^-$,
(3) $K^0 \rightarrow (\sim 50\%) K^0 + (\sim 50\%) \bar{K}^0$,
(4) $\bar{K}^0 + p \rightarrow \Sigma^+ + \pi^0$,
(5) $\Sigma^+ \rightarrow n + \pi^+$,

where step (3) is not directly observable, but is a prediction of the theory of Gell-Mann and Pais. On the basis of two events, the cross section for process (4) is 30 mb.

INTRODUCTION

THE particle-classification scheme of Gell-Mann and Nishijima requires the existence of two neutral K mesons of opposite strangeness.[1] It was later pointed out by Gell-Mann and Pais[2] that one could infer on the basis of charge-conjugation invariance that both the K^0 and the $\bar{K}^0$ would have to be superpositions of two states of equal amplitude, one representing a short-lived and the other a long-lived component.[3,4] Through the virtual decay of the short-lived component, a K^0 of positive strangeness would be transformed into a mixture of K^0 and $\bar{K}^0$ states; in the subsequent interaction the $\bar{K}^0$ could then lead to hyperons of negative strangeness, thus showing an apparent nonconservation of strangeness. Several of the predictions of the Gell-Mann and Pais theory have been confirmed by experiments:

(1) Lande *et al.*[5] and Panofsky *et al.*[6] have found long-lived K^0 mesons which decay into three particles as predicted by the theory.

(2) Fowler *et al.* have observed Λ hyperons in a propane bubble chamber exposed to a neutral beam.[7] The events are presumed to result through the interaction of long-lived neutral K mesons made in a hydrogen target by the reaction

$$\pi^- + p \rightarrow Y^0 + K^0.$$

(3) Emulsion workers have reported somewhat similar evidence.[8]

(4) Boldt *et al.* have seen very similar experimental evidence for the strangeness change that we are reporting here.[9] These authors observed the production of K^0 mesons which interacted in subsequent lead plates to produce Λ hyperons of strangeness opposite to that of the original K^0 meson.

We have observed two events in a liquid-hydrogen bubble chamber, shown in Figs. 1 and 2, which give striking additional confirmation for the Gell-Mann–Pais hypothesis. In each case a π^- meson interacts with a proton to give a hyperon and a neutral K meson:

$$\pi^- + p \rightarrow \begin{cases} (\text{neutral } K) + \Lambda^0 \ (\text{in Event } A) \\ (\text{neutral } K) + \Sigma^0 \rightarrow \Lambda + \gamma \ (\text{in Event } B), \end{cases} \quad (1)$$

followed in each case by

$$\Lambda \rightarrow p + \pi^-; \quad (2)$$

The neutral K meson then interacts with a proton at some distance from its point of production to give a hyperon and a π^0 meson:

$$(\text{neutral } K) + p \rightarrow \Sigma^+ + \pi^0, \quad (3)$$

followed by

$$\Sigma^+ \rightarrow n + \pi^+.$$

We here observe the predicted apparent nonconservation of strangeness; a K^0 of strangeness $+1$ is produced in an interaction and subsequently changes into a $(K^0, \bar{K}^0)$ mixture, i.e., a mixture of positive and negative strangeness. The subsequent interaction then results in the production of a negative-strangeness hyperon. From the dynamics of the events we cannot rule out the possibility that the particle produced in the interaction

* This work was done under the auspices of the U. S. Atomic Energy Commission.
† A preliminary report of this evidence is given in the *1958 Annual International Conference on High-Energy Physics at CERN*, edited by B. Ferretti (CERN, Geneva, 1958), p. 201.
[1] M. Gell-Mann, Phys. Rev. **92**, 833 (1953); T. Nakano and K. Nishijima, Progr. Theoret. Phys. (Kyoto) **10**, 581 (1953); and K. Nishijima, Progr. Theoret. Phys. (Kyoto) **13**, 285 (1955).
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[3] Violations of charge-conjugation invariance have recently been established, but it has been shown that the principal predictions of the Gell-Mann–Pais theory hold under more general assumptions.[4]
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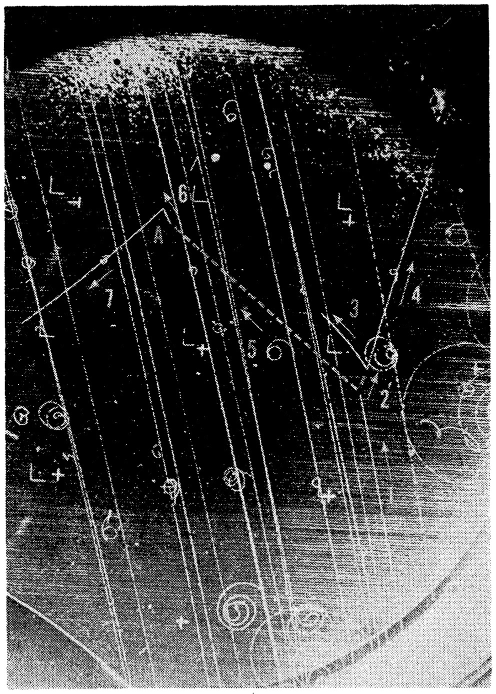

FIG. 1. Event *A*. This is an associated production event $\pi^- + p \rightarrow K^0 + \Lambda$ in which the hyperon Λ (Track 2) decays into a π^- meson (Track 3) and a proton (Track 4). By the time the neutral *K* meson (Track 5) reaches point *A* and produces the interaction $\bar{K}^0 + p \rightarrow \Sigma^+ + \pi^0$, its "strangeness" has changed from $+1$ to -1. The Σ^+ (Track 6) then decays into a π^+ (Track 7) and a neutron.

of the neutral *K* and the proton is a K^+. However, in both events the positive particle produced in the interaction has a very short lifetime, which is strongly in favor of the Σ^+ interpretation.

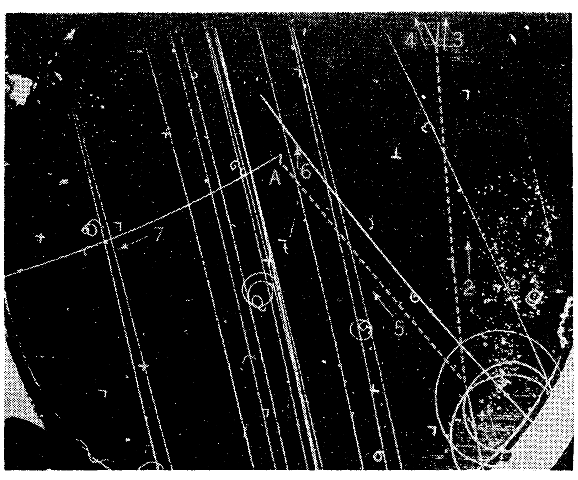

FIG. 2. Event *B*. This is an associated production event $\pi^- + p \rightarrow K^0 + \Sigma^0$ in which the Σ^0 decays immediately into a Λ hyperon (Track 2) plus a gamma ray. The Λ subsequently decays into a π^- meson (Track 3) and a proton (Track 4). By the time the neutral *K* meson (Track 5) reaches point *A* and produces the interaction $\bar{K}^0 + p \rightarrow \Sigma^+ + \pi^0$, its "strangeness" has changed from $+1$ to -1. The Σ^+ (Track 6) then decays into a π^+ meson (Track 7) and a neutron.

The two events were obtained in the course of an experiment on associated production of strange particles.[10] On the basis of an estimated 2100 cm of $\bar{K}^0$ path, the cross section‡ for Reaction (3) is of the order of 30 mb. We present here a detailed account of one of these two events, and a brief summary of the second event.

ANALYSIS OF EVENTS

Event A

The analysis of this event (Fig. 1 and Tables I and II) consists of:

(a) identifying tracks 2, 3, and 4 as a Λ decaying into a π^- and a proton, respectively;

(b) determining that the Λ is produced directly via the reaction $\pi^- + p \rightarrow \Lambda + K^0$, and not indirectly from the compound reaction $\pi^- + p \rightarrow \Sigma^0 + K^0$ and $\Sigma^0 \rightarrow \Lambda + \gamma$, and that the associated K^0 should indeed be expected to follow a line of flight coincident with Track 5;

(c) showing that the recoiling track, Track 6, is consistent dynamically with being the Σ^+ in the reaction[11] $\bar{K}^0 + p \rightarrow \Sigma^+ + \pi^0$; and

(d) finally demonstrating that Track 7 is consistent with being the π^+ in the decay $\Sigma^+ \rightarrow n + \pi^+$.[12] We will now consider separately these stages of analysis.

(a) Tracks 2, 3, and 4 were constrained to fit first a Λ and then a K^0 decay subject to the constraint that $\chi^2 = \sum [(\alpha_i - \beta_i)/\delta\beta_i]^2$ be a minimum. Here β_i and $\delta\beta_i$ are the *i*th measurement and its rms error, whereas α_i is the "theoretical" value corresponding to the *i*th measurement that yields energy and momentum conservation. The χ^2 value for the Λ interpretation was 0.6, whereas χ^2 for the *K* interpretation was 1.1. On the basis of this test, the *V* event could be either a K^0 or a Λ decay.

However, by measuring the energy of the delta ray on Track 4, we can clearly establish that this track is a proton. That this *V* event is not a K^0 decay can be further demonstrated by calculating the momentum of the incident pion required to produce a K^0 at this

[10] Crawford, Cresti, Good, Gottstein, Lyman, Solmitz, Stevenson, and Ticho, Phys. Rev. **108**, 1102 (1957), and *1958 Annual International Conference on High-Energy Physics at CERN*, edited by B. Ferretti (CERN, Geneva, 1958).

‡ *Note added in proof.*—The neutral *K* path length corresponds to 821 events in which a Λ is observed to decay in the chamber. The average neutral *K* momentum is 530 Mev/c. The sum of the total path lengths for K^0 and $\bar{K}^0$ depends only on the chamber geometry and the $K_1{}^0$ lifetime (the $K_2{}^0$ lifetime is effectively infinite), and is found to be 5350 cm. However, the fraction f of path length assigned to $\bar{K}^0$ depends on the assumed mass difference $\Delta m = m(K_1{}^0) - m(K_2{}^0)$. For our geometry, we calculate that if Δm is 0, $\hbar/\tau_1$, or ∞, then the corresponding f is 0.13, 0.40, or 0.50. Our 30-mb cross section corresponds to the choice[9] $\Delta m = \hbar/\tau_1$, yielding a $\bar{K}^0$ path of $0.4 \times 5350 = 2100$ cm.

[11] From a dynamic analysis, we cannot rule out the possibility that Track 6 is the K^+ in the alternative reaction $K^0 + p \rightarrow K^+ + n$. However, as we will show, this latter alternative is very unlikely because of the short lifetime of Track 6.

[12] We cannot rule out by dynamics the possibility that Track 7 is the μ^+ in the decay $K^+ \rightarrow \mu^+ + \nu$.

TABLE I. Table of measured and adjusted quantities for Event A.

Particle	Track No.	Measured quantities: Momentum, p (Mev/c)	Measured quantities: Azimuth, ϕ (deg)	Measured quantities: Dip, λ (deg)	Final adjusted quantities: Momentum, p (Mev/c)	Final adjusted quantities: Azimuth, ϕ (deg)	Final adjusted quantities: Dip, λ (deg)
π^-	4	54.6±0.8	113.7±0.6	62.0± 6.1	54.6	113.7	−62
p	5	955 ±218	73.5±0.3	1.6± 1.6	821.3	73.5	1.6
Λ	3		74.7±1.4	− 1.9±14	841.2±11.6	74.7±0.3	− 1.7±1.0
K^0	2		138.5±0.3	2.0± 1.2	622.6±20	138.3±0.3	2.0±0.8
Σ^+	6	345 ±3000	111.8±1.4	−44.9±14	280 ±30	112.0±1.0	−42.5±5
[or K^+]					[454][a]	[111.8][a]	[−44.9][a]
π^+	7	251 ±19	205.6±0.3	−50.2± 2.0	207	205.6	−52.2
(or μ^+)					(259)[b]	(205.6)[b]	(−50.2)[b]
Incident π^-	1	945 ±220	101.2±0.3	0.3± 1.2	1248±16	101.2±0.3	− 0.2±0.5

[a] The square brackets indicate the alternative interpretation $K^0+p^0 \rightarrow K^+ + n$.
[b] The parentheses indicate the alternative interpretation as the decay $K^+ \rightarrow \mu^+ + \nu$.

momentum and angle. This momentum would have to be 1310±10 Mev/c, whereas the average beam momentum was independently known to be 1227±10 Mev/c. On the other hand, if we assume the particle to be a Λ, we obtain 1248±16 Mev/c for the incident-pion momentum, which is clearly consistent with 1227 Mev/c.

(b) By using the known momentum of the incident pion and of the Λ hyperon, one can predict the direction and magnitude of the K^0 momentum. The predicted azimuth, dip, and momentum are 138±5°, 2.8±1.2°, and 622.6 Mev/c, respectively. These values, when compared with the measured azimuth and dip of Track 2, 138.5±3° and 2.0±1.2°, respectively, clearly indicate by their agreement that a $\bar{K}^0$ or K^0 has interacted at Point A of Fig. 1.

(c) Track 6 is so short and steeply dipping that curvature measurements yield no information concerning its momentum. Consequently, only the direction of Track 6 can be used effectively in the analysis. Track 6 is consistent with that from either a Σ^+ produced at an angle of 137° in the center of mass of the $\bar{K}^0+p$ system or a K^+ charge exchange at 85° in the center of mass of the K^0+p system. Table II gives the laboratory angles as well as the angles in the center-of-mass or rest systems both for the reaction products and the decay products. Both alternatives fit the measured laboratory production angle, $\cos^{-1}(\hat{p}_2\cdot\hat{p}_6)$, equally well.

(d) From Tables I and II, one can see that the decay Track 7 can be fit as well by the $K^+ \rightarrow \mu^+ + \nu$ interpretation as by the $\Sigma^+ \rightarrow \pi^+ + n$ interpretation. The choice between these two alternatives is decided on the basis of the flight time of Track 6. If it is a Σ^+, it lived 1.2×10^{-10} sec (1.6 Σ^+ mean lives), and if it is a K^+ it lived 0.3×10^{-10} sec (2.5×10^{-3} K^+ mean lives). The odds are thus strongly in favor of the Σ^+ interpretation, if the K^+ and Σ^+ interpretations are taken as having otherwise-equal *a priori* probabilities.

Event B

The analysis of this event follows essentially the same lines as that of Event A with the following exceptions:

(a) The interaction at Point A in Fig. 2 is definitely established to be produced by a K and not a Λ by the fact that only the K could be produced at such a large angle.

(b) Event B also differs from Event A in that the Λ of Event B is the decay product of a directly produced Σ^0. This means that one cannot use the Λ hyperon's momentum and direction to predict the line of flight and momentum of the K^0. However, the K^0 momentum and direction plus the Λ hyperon's momentum and direction are consistent with the compound reaction $\pi^- + p \rightarrow K^0 + \Sigma^0$ and $\Sigma^0 \rightarrow \Lambda + \gamma$.

Here again as determined from dynamics alone, Track 6 could just as well be the K^+ from the charge-exchange reaction $K^0 + p \rightarrow K^+ + n$ as it could be the

TABLE II. Reaction and decay angles in degrees for Event A.

$\cos\theta_{\mu\nu}(\equiv\hat{p}_\mu\cdot\hat{p}_\nu)$	$\theta_{\mu\nu}$, lab system: Measured	$\theta_{\mu\nu}$, lab system: Adjusted	$\theta_{\mu\nu}$, center-of-mass system: Adjusted
Reaction angles			
$\hat{p}_{\mathrm{inc}}\cdot\hat{p}_\Lambda$	26.7±1.5	26.6±0.4	97.8
$\hat{p}_{\mathrm{inc}}\cdot\hat{p}_{K^0}$	37.4±0.5	37.3±0.4	82.2
$\hat{p}_{K^0}\cdot\hat{p}_{\Sigma^+}$	52.1±8.0	50.3±5.0	142
$[\hat{p}_K\cdot\hat{p}_{K^+}]$[a]		[52.1±5.0][a]	[83][a]
Decay angles			
$\hat{p}_{\Sigma^+}\cdot\hat{p}_{\pi^+}$	59.5±8.0	59.3	74.0
$(\hat{p}_{K^+}\cdot\hat{p}_{\pi^+})$[b]		(59.5)[b]	(109)[b]
$\hat{p}_\Lambda\cdot\hat{p}_{\pi^-}$	67.0±5.0	67.0	150
$\hat{p}_\Lambda\cdot\hat{p}_p$	3.5±2.5	3.5	30

[a] The square brackets indicate the alternative interpretation $K^0+p^0 \rightarrow K^+ + n$.
[b] The parentheses indicate the alternative interpretation as the decay $K^+ \rightarrow \mu^+ + \nu$.

Σ^+ from the reaction $\bar{K}^0+p \rightarrow \Sigma^+ + \pi^0$. Tracks 6 and 7 are consistent with either $K^+ \rightarrow \mu^+ + \nu$ or $\Sigma^+ \rightarrow \pi^+ + n$. However, the short lifetime of Track 6 strongly favors the Σ^+ interpretation—if track 6 is a K^+ it lived 1.9 $\times 10^{-3}$ mean lives, if a Σ^+, 0.6 mean lives. Finally we remark that in event A the neutral K lived 2.6 K_1^0 mean lives, and in event B, 3.0 K_1^0 mean lives.

ACKNOWLEDGMENTS

We wish to thank Professor Luis W. Alvarez for his interest and guidance throughout this experiment. The assistance of the crew members of the bubble chamber and the Bevatron is gratefully acknowledged. We also wish to thank Mr. George Kalbfleisch for his assistance with the analysis of the data.

PHYSICAL REVIEW VOLUME 113, NUMBER 6 MARCH 15, 1959

Decay of $_\Lambda H^3$ and the Spin Dependence of the Λ-Nucleon Interaction*

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(Received October 24, 1958)

A calculation is made of the fraction of the π-mesonic decays of the hypertriton $_\Lambda H^3$ which yield the two final products He^3 and π^-. This fraction is a function of the spin of $_\Lambda H^3$ and of the ratio p/s of the amplitudes for decay of the free Λ via the s- and p-wave channels. The results are compatible with the present experimental data. They indicate that probably $p/s \leqslant 1$, and that the spin of $_\Lambda H^3$ is $\frac{1}{2}$, which implies that the singlet Λ-nucleon interaction is more attractive than the triplet. These results are in agreement with those of a previous calculation by Dalitz for $_\Lambda H^4$.

ANALYSIS of the binding energies of the light hypernuclei shows that, in the absence of strong three-body forces, the Λ-nucleon interaction must be spin dependent. On this basis Dalitz and Downs[1] have been able to calculate the strengths of both the singlet and the triplet interactions for either interaction more attractive than the other, but neither the hypernuclear binding energies nor the radius and shape of the nuclear cores are known accurately enough to determine which of these interactions is in fact the more attractive. A more sensitive indication is provided by the probability for two-body mesonic decay of the light hypernuclei, since this depends strongly on the spin of the parent hypernucleus. Dalitz and Downs have made a qualitative estimate of this probability, and Dalitz[2] a detailed calculation, for the decay of $_\Lambda H^4$; Dalitz has also made a rough calculation for $_\Lambda H^3$. The present work gives a more exact calculation for the $_\Lambda H^3$ case.

Although data on the hypertriton are at present rather scarce, the greater simplicity of the three-body problem increases its importance. For $A>3$, it has been necessary to describe the hypernucleus as a Λ bound to a core nucleus which is not greatly distorted by the presence of the Λ. For $A=3$, on the other hand, calculations can be made with a wave function that takes into account correlations between each pair of particles. Because of this, we expect results obtained for $_\Lambda H^3$ to be eventually the most reliable.

The Λ decay interaction is $H=s+p\mathbf{q}\cdot\boldsymbol{\sigma}/q_\Lambda$, where $\mathbf{q}$ is the pion momentum and $\mathbf{q}_\Lambda$ its value for free Λ decay, and $\boldsymbol{\sigma}$ is the Λ spin vector. Since the spin of the product nucleus He^3 (we consider only π^- decay) is $\frac{1}{2}$, two-body decay can proceed only through the p-wave channel if $_\Lambda H^3$ has spin $\frac{3}{2}$, but through both the s and p channels if the $_\Lambda H^3$ spin is $\frac{1}{2}$. The proportion of π^- decays which yield two final products ($_\Lambda H^3 \rightarrow He^3+\pi^-$) is given by the ratio of the two-body transition probability to the sum of the transition probabilities of all modes which give a π^-:

$$f=q\left|\int \bar{\psi}_{He^3}\bar{\psi}_{\pi^-}H\psi_{_\Lambda H^3}dV\right|^2 \Big/ \sum_n q_n \left|\int \bar{\psi}_n\bar{\psi}_{\pi^-}H\psi_{_\Lambda H^3}dV\right|^2.$$

The square of the matrix element in the numerator splits into two factors: (1) the square of the overlap integral between the space parts of the initial- and final-state wave functions, which represents the probability of the product nucleons sticking together in the He^3 configuration, and (2) a factor depending upon the $_\Lambda H^3$ spin which represents the proportion of suitably oriented initial spin states. The denominator is a more difficult matter, and Dalitz[2] has found it expedient to use two approximations: (1) Since the observed pion momenta all lie in a rather narrow range ($q=113$ Mev/c for the two-body and ~85–100 Mev/c for the many-body decays[3]), we should be able to replace the q_n's by an average value q_{Av}. (2) Since the overlap with the $_\Lambda H^3$ space wave function can be expected to be small for final states of high internal energy among the

* Supported by the joint program of the U. S. Atomic Energy Commission and the Office of Naval Research.
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[2] R. H. Dalitz, Phys. Rev. **112**, 605 (1958).
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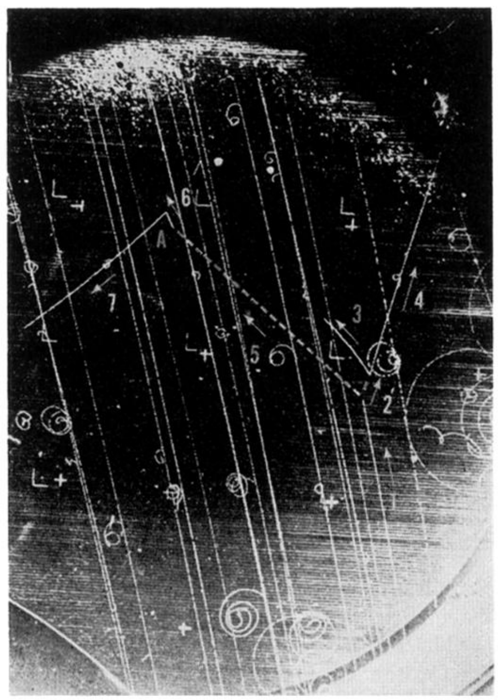

FIG. 1. Event A. This is an associated production event $\pi^-+p\rightarrow K^0+\Lambda$ in which the hyperon Λ (Track 2) decays into a π^- meson (Track 3) and a proton (Track 4). By the time the neutral K meson (Track 5) reaches point A and produces the interaction $\bar{K}^0+p\rightarrow\Sigma^++\pi^0$, its "strangeness" has changed from $+1$ to -1. The Σ^+ (Track 6) then decays into a π^+ (Track 7) and a neutron.

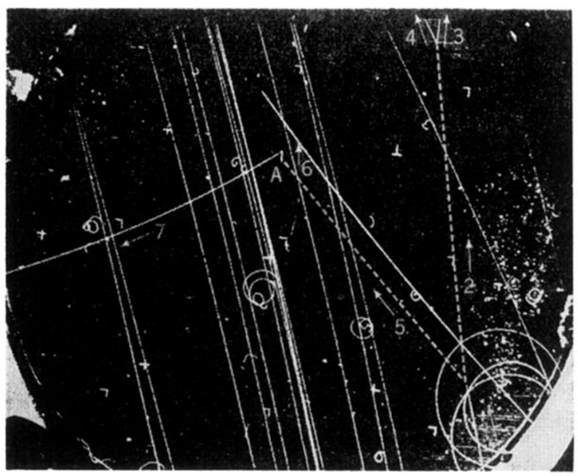

FIG. 2. Event *B*. This is an associated production event $\pi^- + p \to K^0 + \Sigma^0$ in which the Σ^0 decays immediately into a Λ hyperon (Track 2) plus a gamma ray. The Λ subsequently decays into a π^- meson (Track 3) and a proton (Track 4). By the time the neutral K meson (Track 5) reaches point A and produces the interaction $\bar{K}^0 + p \to \Sigma^+ + \pi^0$, its "strangeness" has changed from $+1$ to -1. The Σ^+ (Track 6) then decays into a π^+ meson (Track 7) and a neutron.