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ABSTRACT

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

(1) $\pi^- + p \rightarrow Y^0 + K^0$ $\quad [Y^0{}_A = \Lambda^0, \; Y^0{}_B = \Sigma^0]$

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

(3) $K^0 \rightarrow (\sim 50\%) \; K_0 + (\sim 50\%) \; \overline{K}^0$

(4) $\overline{K}^0 + p \rightarrow \Sigma^+ + \pi^0$

(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 50 mb.

EVIDENCE FOR THE TRANSITION OF A K^0 INTO A $\bar{K}^0$ MESON*†

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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] 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:

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*This work was done under the auspices of the U. S. Atomic Energy Commission.

†A preliminary report of this evidence was given at the 1958 Annual International Conference on High Energy Physics at Cern, 30 June - 5th July 1958 (pg. 201 of the Proceedings).

[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).

[2]M. Gell-Mann and A. Pais, Phys. Rev. 97, 1387 (1955).

[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]

[4]Lee, Oehme, and Yang, Phys. Rev. 106, 340 (1957).

(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:

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

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[5] Lande, Lederman, and Chinowsky, Phys. Rev. 105, 1925 (1957).

[6] Panofsky, Fitch, Motley, and Chestnut, Phys. Rev. 109, 1353 (1958).

[7] Fowler, Lander, and Powell, Bull. Am. Phys. Soc. 2, 236 (1957).

[8] Amar, Friedman, and Levi Setti, Nuovo cimento 5, 1801 (1957); Baldo-Ceolin, Dilworth, Fry, Greening, Hugita, Limentari, and Sichirollo, Nuovo cimento 6, 130 (1957).

[9] Boldt, Caldwell, and Pal, Phys. Rev. Letters 1, 150 (1958).

followed in each case by:

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

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:

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

followed by

(3) $\Sigma^+ \rightarrow n + \pi^+$.

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, $\overline{K}^0$) 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 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.

The two events were obtained in the course of an experiment on associated production of strange particles.[10] On the basis of an estimated 1200 cm of K^0 path, the cross section for Reaction (3) is of the order of 50 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

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[10] Crawford, Cresti, Good, Gottstein, Lyman, Solmitz, Stevenson, and Ticho. Phys. Rev. 108, 1102 (1957); and Proc. 1958 Am. Intern. Conf. on High Energy Physics at CERN (to be published).

$\pi^- + p \rightarrow \Lambda + K^0$, 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 $K^0 + p \rightarrow \Sigma^+ + \pi^0$;[11] 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 contraint that $\chi^2 = \Sigma [(\alpha_i - \beta_i)/\delta\beta_i]^2$ be a minimum. Here β_i and $\delta\beta_i$ are the ith measurement and its rms error, whereas α_i is the "theoretical" value corresponding to the ith 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 momentum and angle. This momentum would have to be 1310 ± 10 Mev/c, whereas the average beam momentum was independently known to be 1227 ± 3 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 $138.3 \pm 5^\circ$, $2.8 \pm 1.2^\circ$, and 622.6 Mev/c, respectively. These values, when compared with the measured

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[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^+ [or K^+]	6	345 ± 3000	111.8 ± 1.4	-44.9 ± 14	280 ± 30 [454][a]	112.0 ± 1.0 [111.8][a]	-42.5 ± 5 [-44.9][a]
π^+ (or μ^+)	7	251 ± 19	205.6 ± 0.3	-50.2 ± 2.0	207 (259)[b]	205.6 (205.6)[b]	-52.2 (-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 brackets indicate the alternative interpretation $K^0 + p^0 \rightarrow K^+ + n$.

[b] The parentheses indicate the alternative interpretation as the decay $K^+ \rightarrow \mu^+ + \nu$.

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			
$\hat{p}_{inc} \cdot \hat{p}_{\Lambda}$	26.7 ± 1.5	26.6 ± .4	97.8
$\hat{p}_{inc} \cdot \hat{p}_{K0}$	37.4 ± .5	37.3 ± .4	82.2
$\hat{p}_{K0} \cdot \hat{p}_{\Sigma+}$	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 brackets indicate the alternative interpretation $K^0 + p^0 \rightarrow K^+ + n$.

[b] The parentheses indicate the alternative interpretation as the decay $K^+ \rightarrow \mu^+ + \nu$.

azimuth and dip of Track 2, 138.5 ± 3^{o} and 2.0 ± 1.2^{o}, respectively, clearly indicate by their agreement that a $\overline{K}^{0}$ 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^{o} in the center of mass of the $\overline{K}^{0}$ + p system or a K^{+} charge exchange at 85^{o} 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, $\text{Cos}^{-1}(\hat{p}_2 \cdot \hat{p}_6)$, 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 0.54×10^{-10} sec (0.65 of a Σ^{+} mean life), and if it is a K^{+} it lived 0.3×10^{-10} sec (2.5×10^{-3} of a K^{+} mean lifetime). One can then conclude that for this event the odds are about 200 to 1 in favor of the Σ^{+} interpretation on the basis of lifetime alone.

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 equally well be the K^{+} from the charge-exchange reaction $K^{0} + p \rightarrow K^{+} + n$ as it could be the Σ^+ from the reaction $\overline{K}^0 + p \rightarrow \Sigma^+ + \pi^0$. Again Track 7 is consistent with either $K^+ \rightarrow \mu^+ + \nu$ or $\Sigma^+ \rightarrow \pi^+ + n$. The short lifetime of Track 7, namely 0.25×10^{-10} sec, indicates that the latter reaction is the more probable. The probability that this is a K^+ decaying in 0.25×10^{-10} sec is 2.06×10^{-3} whereas the probability of a Σ^+ decaying in 0.25×10^{-10} sec is 0.28. On the basis of lifetime alone, this gives us odds of 136 to 1 that we again have observed the reaction $\overline{K}^0 + p \rightarrow \Sigma^+ + \pi^0$. The neutral K, incidentally, lived 8.2×10^{-10} sec, namely 2.96 K^0_1 mean lives.

ACKNOWLEDGMENTS

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FIGURE LEGENDS

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 $\overline{K}^0 + p \rightarrow \Sigma^+ + \pi^0$, 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 $\pi^- + p \rightarrow K^0 + \Sigma^0$ 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 $\overline{K}^0 + p \rightarrow \Sigma^+ + \pi^0$, its "strangeness" has changed from + 1 to -1. The Σ^+ (Track 6) then decays into a π^+ meson (Track 7) and a neutron.

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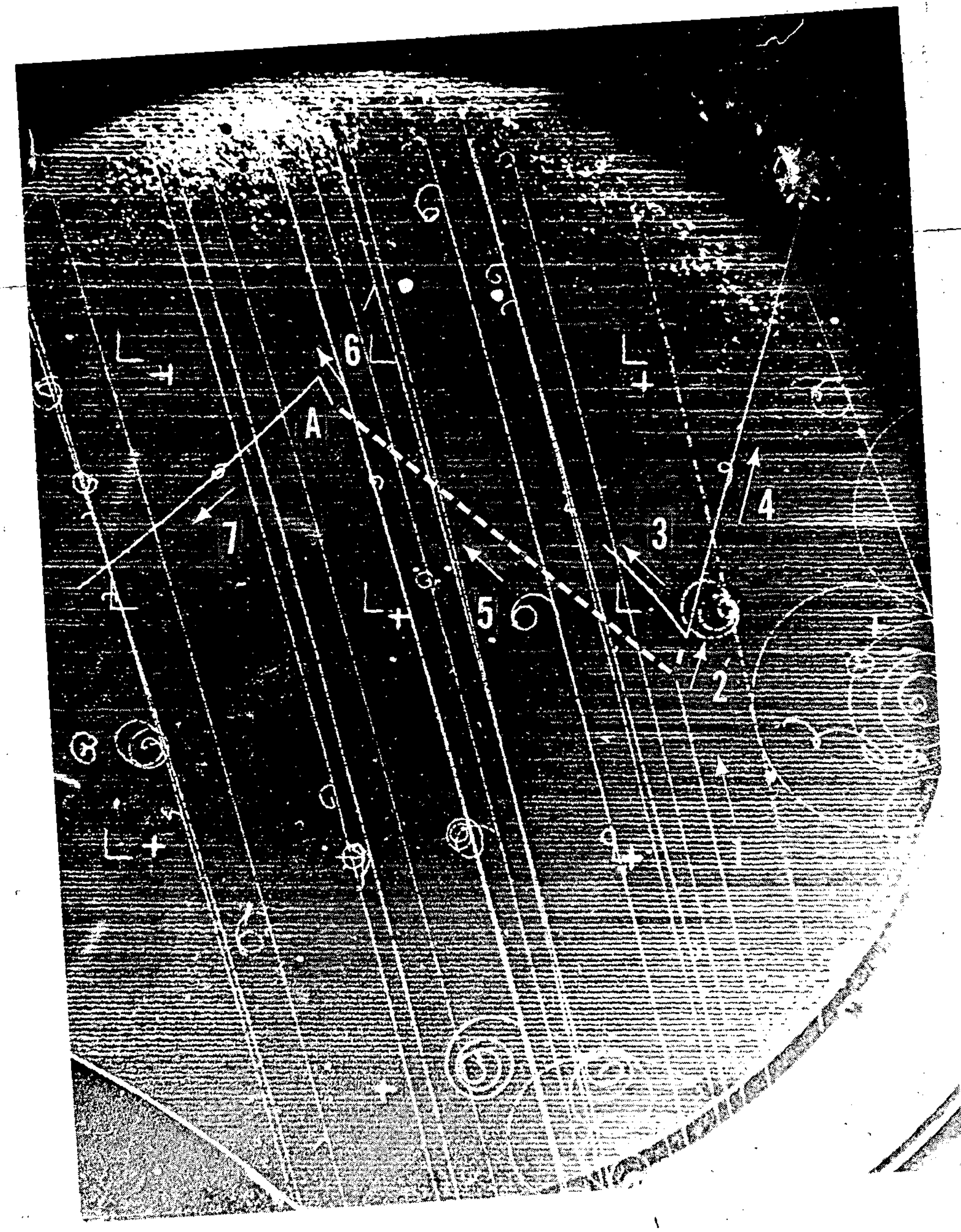

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Fig. 1.

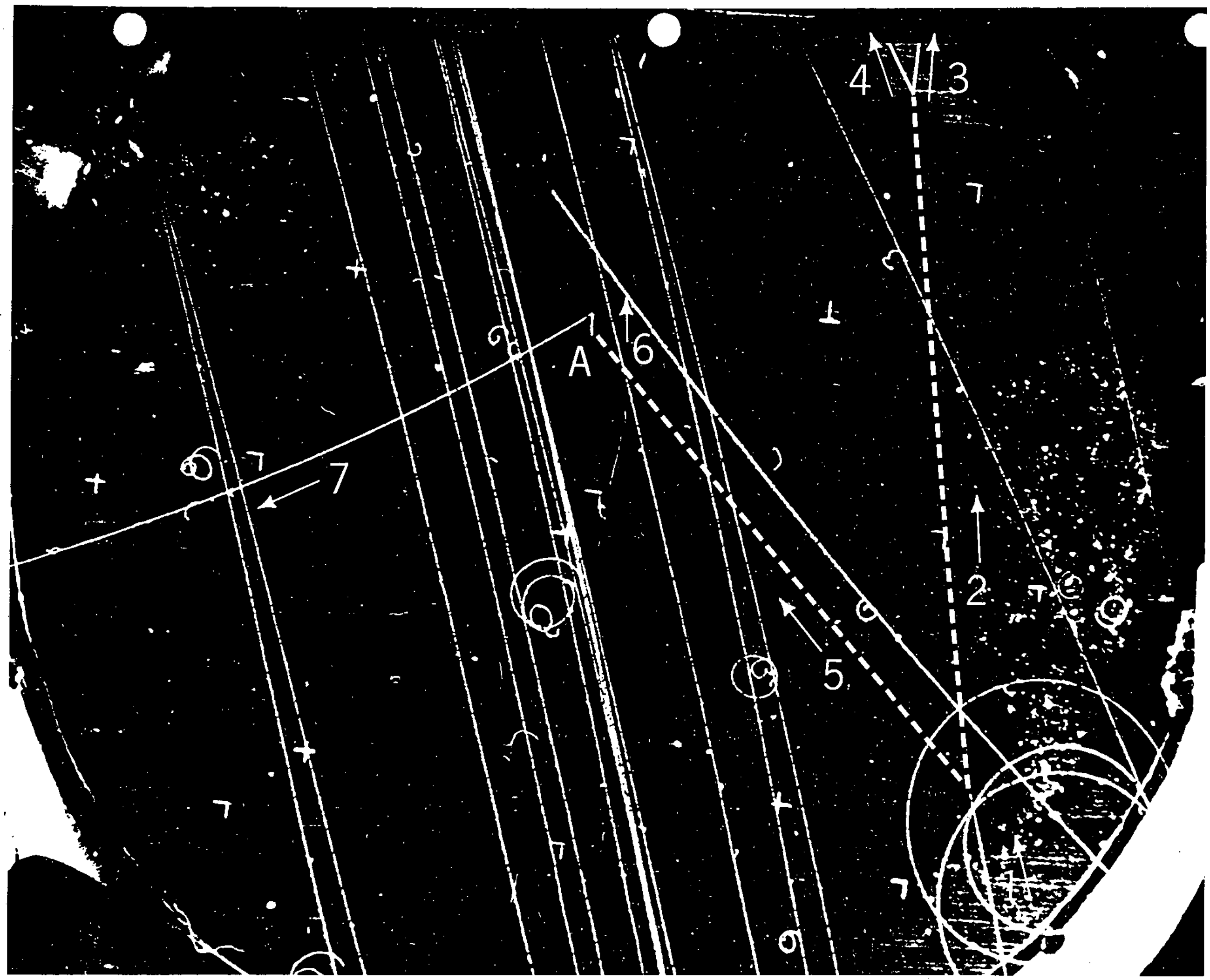

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Fig. 2.