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K$^-$ INTERACTIONS IN HYDROGEN

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ABSTRACT

K^- mesons from the Bevatron have been stopped in a 10-in. hydrogen bubble chamber. This is a preliminary report on the first 137 interactions. There are photographs confirming the existence of the $\overline{\theta}^0$ and the Σ^0, which must be lighter than the Σ^- by at least several Mev. Σ's are produced more profusely than Λ's in the absorption of K^- by protons; we observe the production ratios $\Sigma^-:\Sigma^+:\Sigma^0:\Lambda \simeq 4:2:2:1$. The large observed absorption cross section of slow K^- by protons suggests that the interaction takes place in p states as well as in s states. There is evidence that the spin of the Σ is greater than 1/2. There is no evidence for parity doublets. Our data rule out the proposed selection rule $\Delta I = \pm 1/2$. The accepted value for the mean life τ_Λ is checked, and we find $\tau_{\Sigma^-} = (1.86 \pm 0.26) \times 10^{-10}$ sec and $\tau_{\Sigma^+} = (0.86 \pm 0.17) \times 10^{-10}$ sec.

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I. INTRODUCTION

From examination of the interaction of slow K mesons with hydrogen and deuterium a great deal can be learned about the properties of not only the K mesons, but also the Σ and Λ hyperons and the $\bar{\theta}^0$ mesons that are produced. Many authors have pointed out the experimental importance of stopping K^- in hydrogen,[1, 2, 3, 4] but this experiment became feasible only this year when hydrogen bubble chambers were operated successfully at the Bevatron.

This is a preliminary report on the first 137 interactions seen in the Berkeley 10-inch hydrogen chamber. Because of the limited statistics most of the quantitative analysis is still uncertain; however, there are enough data to permit the following conclusions:

a. $\Sigma^0, \bar{\theta}^0$

The experiment furnishes excellent evidence for the existence of a neutral Σ hyperon and of a neutral K meson ($\bar{\theta}^0$) with the strangeness of the K^- and decaying into two charged pions. The Σ^0 must be lighter than the Σ^- by at least several Mev.

b. Strong interactions involving strange particles

No violation of the Gell-Mann - Nishijima scheme was observed in the absorption of the K^- mesons by protons. Σ's are produced somewhat more profusely than Λ's in these absorptions. We observe the production ratios $\Sigma^-:\Sigma^+:\Sigma^0:\Lambda \cong 4:2:2:1$.

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*On leave from C. E. A., Saclay, France.

[1] Case, Karplus, and Yang, Phys. Rev. 101, 358 (1956).

[2] R. Gatto, Nuovo Cimento 3, 5 (1956).

[3] T. D. Lee, Phys. Rev. 99, 337 (1955).

[4] Stephen Gasiorowicz, Isotopic Spin Conservation in K^- Interactions with Nuclear Matter, UCRL-3074, July 1955.

The large observed cross section of slow K^- by protons suggests that the interaction takes place in p states as well as in s states.

The absorption of Σ^-'s by protons leads to comparable numbers of Σ^0's and Λ's.

c. Hyperon spins

The angular distribution of the decay products of the charged Σ's suggests that the Σ has a spin greater than 1/2; this suggestion is strengthened by similar evidence from emulsion experiments. The corresponding evidence for Λ's is still quite inconclusive.

d. Parity doublet question

If the Σ's and Λ's exist in parity doublets, one would expect to observe two lifetimes (for Σ^+, Σ^-, and Λ) and forward-backward asymmetries in the decay distributions. No evidence for either one of these effects was found.

e. Hyperon decay mechanism

The observed lifetime ratio $(\tau_{\Sigma^-}/\tau_{\Sigma^+}) = 2.2 \pm 0.5$ and the branching ratio $\frac{\Sigma^+ \to p + \pi^0}{\Sigma^+ \to n + \pi^+} = 1.0 \pm 0.2$ are in conflict with the predictions based on the I-spin selection rule $\Delta I = \pm 1/2$.

f. Hyperon lifetimes

The accepted value of the Λ^0 lifetime is checked, and our knowledge of the Σ^+ and Σ^- lifetimes is considerably improved by this experiment. We find:

$$\tau_{\Lambda} = (3.25 \pm 0.6) \times 10^{-10} \text{ sec.},$$
$$\tau_{\Sigma^+} = (0.86 \pm 0.17) \times 10^{-10} \text{ sec.},$$
$$\tau_{\Sigma^-} = (1.86 \pm 0.26) \times 10^{-10} \text{ sec.}$$

The experiment is still in progress: There are plans to observe K^- absorption in deuterium.

II. EXPERIMENTAL

The experimental arrangement is shown in Fig. 1. The "K^- beam" consists mainly of μ-mesons and electrons with a slight contamination of K^-. We find one stopping K^- per 250 pictures. A K coming to rest in our chamber is three mean lives old. Further experimental details are given in the Appendix. About 100,000 pictures have been taken so far; this report summarizes the results from the first 35,000.

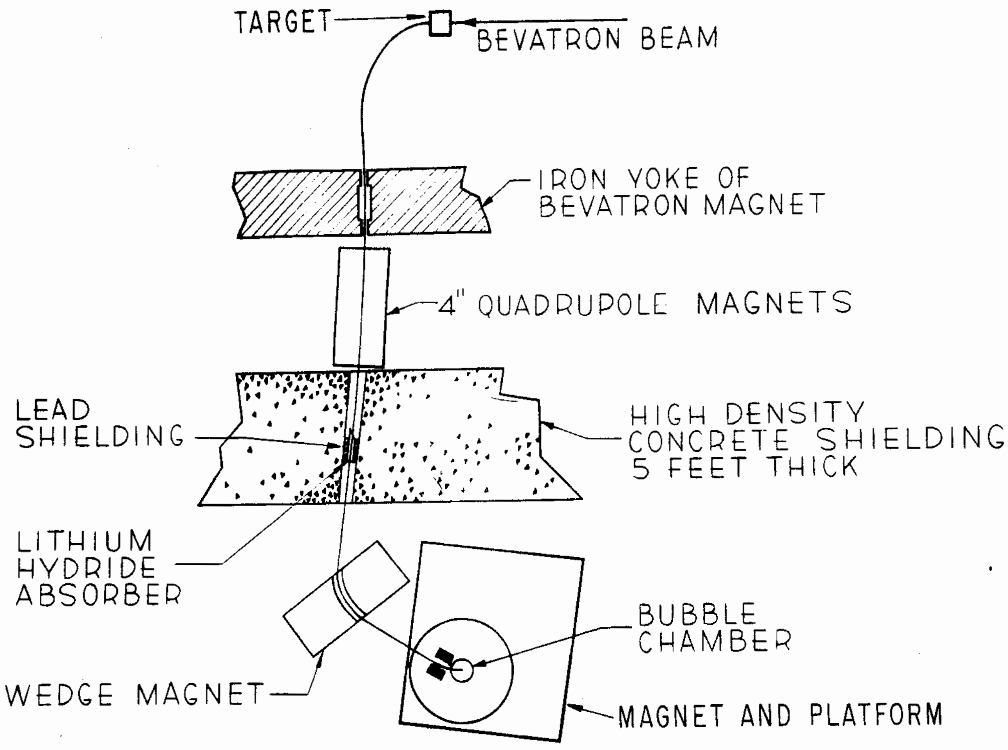

Fig. 1. K^- meson beam.

The 10-inch-diam bubble chamber is 6.4 inches deep.[5] It is in a dc magnetic field of 11 kilogauss and is expanded at the Bevatron repetition rate, which is ten times per minute.

We believe that careful scanning of our photographs can detect with nearly 100% efficiency K^- interactions leading to charged secondaries. However some of the data in this preliminary report are based on a quick scan (~80% efficient) which was done while the run was in progress.

III. DISTRIBUTION OF EVENTS

Seventeen of the K's decayed in flight; the rest interacted with protons, either in flight (11 cases) or after the K had come to rest and formed a K-mesic atom (126 cases).

Table IA lists the eight possible reactions compatible with the energy available and with conservation of strangeness[6,7] and involving previously identified or postulated particles. We have not yet considered the relatively rare electromagnetic decays or interactions involving charged particles. We have observed all the reactions listed in Table I (except VII and VIII) and no others.

The K^- mesons produced 83 charged Σ hyperons. All the Σ^+ and 48 Σ^- decayed; 7 Σ^- interacted with protons--one in flight, and six after they had come to rest and formed an atom with hydrogen.

In analogy with Table IA, Table IB lists the possible reactions for $\Sigma^- + P$.

Some of the bubble chamber pictures are reproduced in Figs. 2, 3, and 4.

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[5] Luis W. Alvarez, Berkeley Bubble Chamber, 1956 CERN Symposium.

[6] M. Gell-Mann, Phys. Rev. 92, 833 (1953); M. Gell-Mann and A. Pais, Proceedings of the Glasgow Conference, Pergamon Press, 1955, London and New York.

[7] K. Nishijima, Progr. Theor. Phys. 12, 107 (1954).

Table I

Distribution of Events

A. K^- Interactions

$K^- + p \longrightarrow$	Circumstances of K^- interactions: In flight	At rest	Total
I $K^- + p$ (elastic scatter)	3	-	3
II $\overline{K}^0 + n$; $\theta_1 \longrightarrow \begin{cases} \pi^+ + \pi^- \\ \pi^0 + \pi^0 \end{cases}$	(1)[a]	(2)[a]	3
		$K\rho$[b]	
θ_2 or τ^0 decay		None observed	
III $\Sigma^+ + \pi^-$; $\Sigma^+ \longrightarrow n + \pi^+$	0	14	28
$\Sigma^+ \longrightarrow p + \pi^0$	1	13	
IV $\Sigma^- + \pi^+$; $\Sigma^- \longrightarrow n + \pi^-$	4	44	55
Σ^- interacts	0	7	
V $\Sigma^0 + \pi^0$; $\Sigma^0 \rightarrow \gamma + \Lambda$, $\Lambda \rightarrow \begin{cases} p + \pi^- \\ n + \pi^0 \end{cases}$	0	14	14
		$K\rho$[b]	
VI $\Lambda + \pi^0$; $\Lambda \rightarrow \begin{cases} p + \pi^- \\ n + \pi^0 \end{cases}$	1	7	8
		$K\rho$[b]	
VII $\Lambda + \pi^0 + \pi^0$		None observed	
VIII $\Lambda + \pi^+ + \pi^-$	0	0	0
Total excluding $K\rho$	10	101	111
$K\rho$[b]			26[b]
Total Interactions			137

B. Σ^- Interactions

$\Sigma^- + p \longrightarrow$	Circumstances of Σ^- interactions: In flight	At rest	Total
IX $\Sigma^- + p$ (elastic scatter)	0	-	0
X $\Sigma^0 + n$; $\Sigma^0 \rightarrow \gamma + \Lambda$; $\Lambda \rightarrow \begin{cases} p + \pi^- \\ n + \pi^0 \end{cases}$	0	2	2
		$\Sigma\rho$[b]	
XI $\Lambda + n$; $\Lambda \rightarrow \begin{cases} p + \pi^- \\ n + \pi^0 \end{cases}$	0	2	2
		$\Sigma\rho$[b]	
Σ_ρ^- events[b]	1	2	3
Total	1	6	7

(a) Indicates identification uncertain.

(b) Between 20 and 40 K's disappear in the chamber, yielding no visible interaction or decay products. We call these "Kρ" endings, and assume that there are 26 of them. Σρ are defined analogously.

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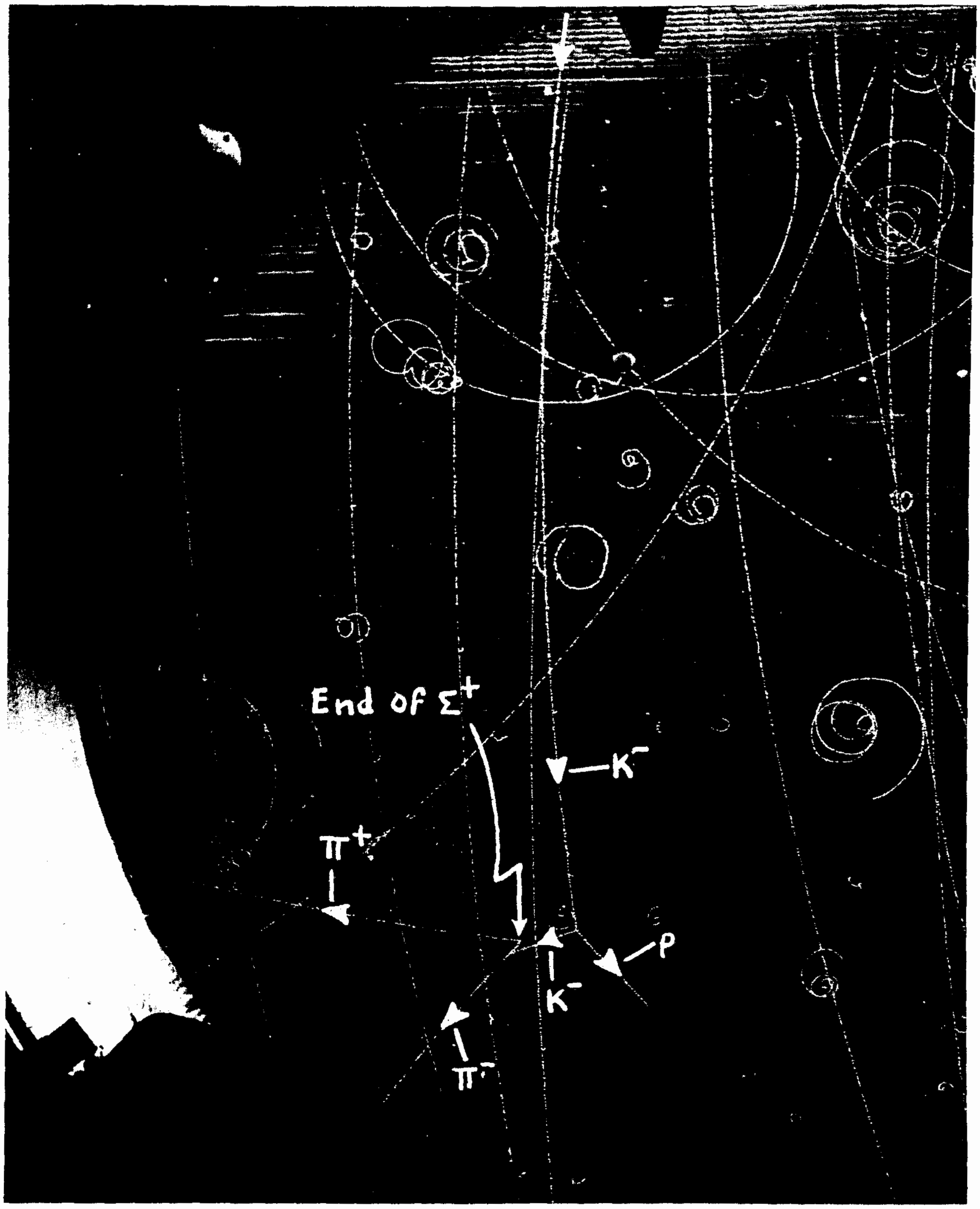
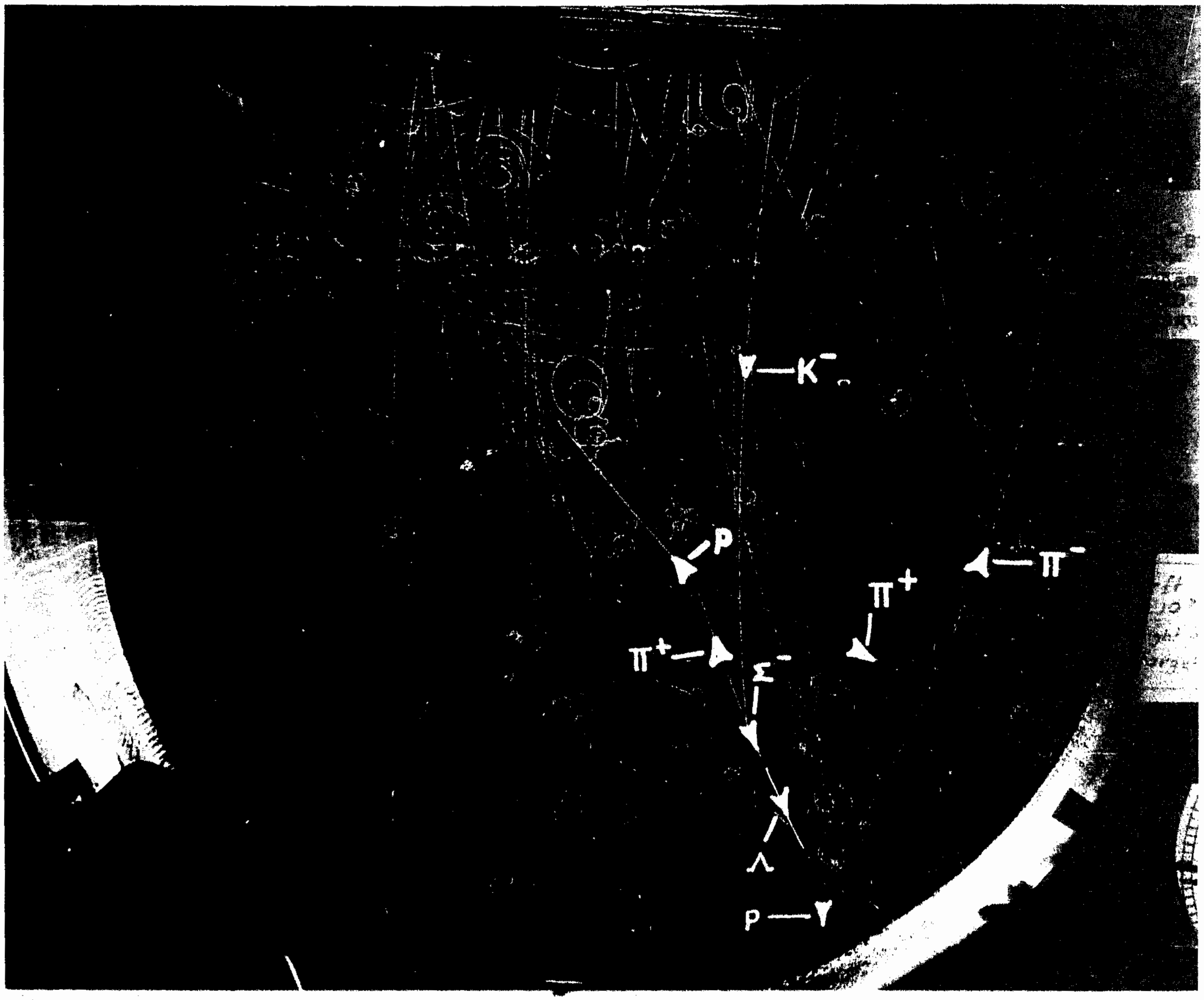


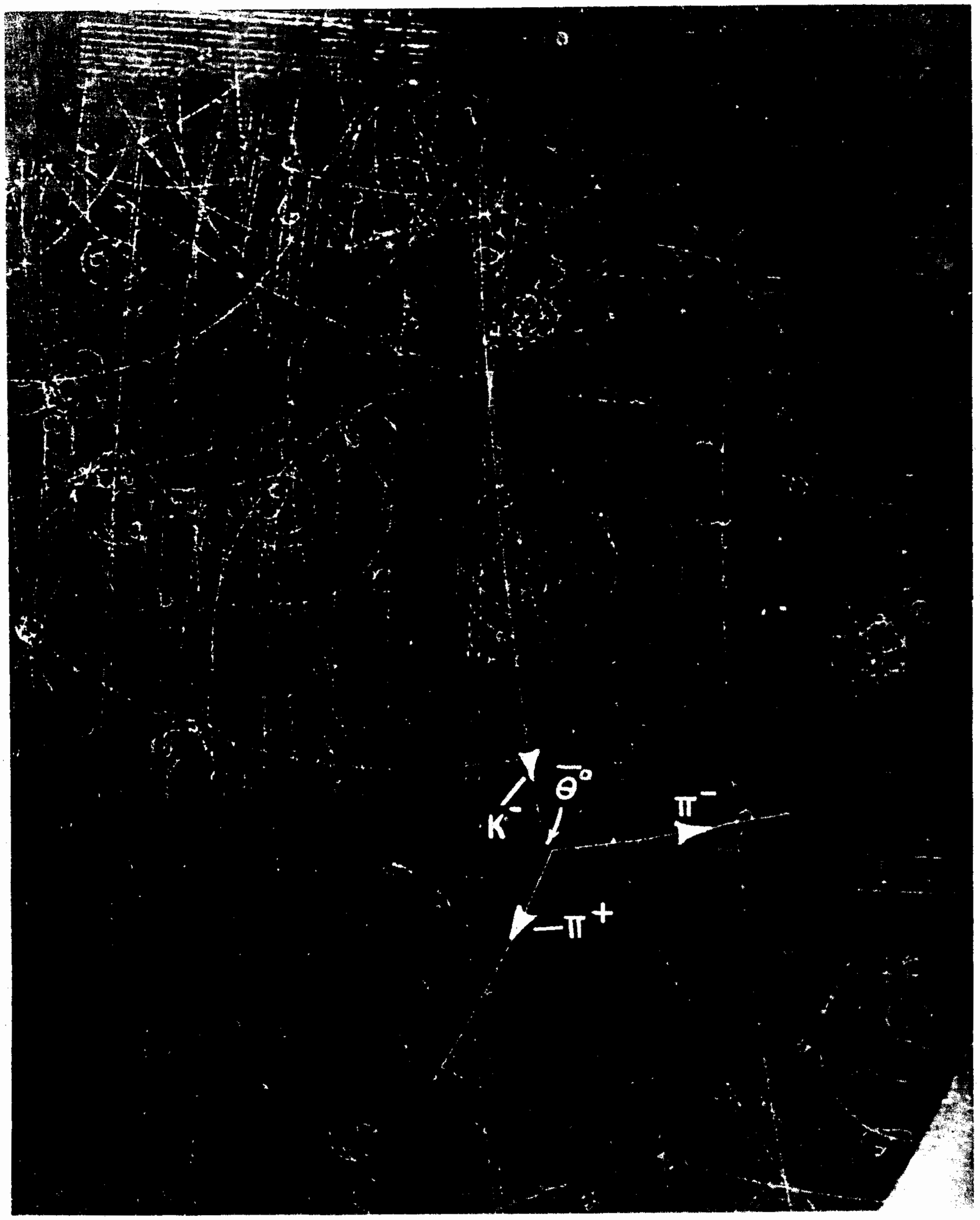
ZN-1625

Fig. 2. A K^- scatters elastically on a proton before coming to rest and forming a K-mesic atom. Then $K^- + p \rightarrow \pi^- + \Sigma^+$; $\Sigma^+ \rightarrow \pi^+ + n$. The horizontal lines spaced about 1 mm apart in the chamber are caused by light scattered in passing through a "Venetian blind" used in the dark-field illumination system.



ZN-1628

Fig. 3. A K-mesic atom disintegrates into $\Sigma^- + \pi^+$. The Σ^- goes its full range, comes to rest, and is captured by a proton, whereupon it produces $\Sigma^0 \rightarrow \Lambda + \gamma$. The π^+ is scattered by a proton.



ZN-1626

Fig. 4. Production of a $\overline{\theta}^0$.

IV. THE CHARGED Σ HYPERONS

The Σ^+ coming from stopped K's (Reaction III) have a kinetic energy t_{Σ^+} of 13.8 Mev (181.2 Mev/c).[8] We have 27 such Σ^+, all of which decay in flight. The distribution of the times in flight is given in Fig. 5. The mean life is

$$t_{\Sigma^+} = (0.86 \pm 0.17) \times 10^{-10} \text{ sec.}$$

There are no accurate measurements with which this result may be compared; there are several estimates by nuclear emulsion workers.[9]

We have taken the density of liquid hydrogen at the time of bubble formation to be 0.055 g/cm^3; this leads to a Σ^+ range of 1.42 cm and a moderation time of 4.34×10^{-10} sec, or 5.7 mean lives.

The Σ^- is 7.3 ± 0.9 Mev heavier than the Σ^+.[8] The Σ^- coming from stopped K's (Reaction IV) should have $t_{\Sigma^-} = 12.6$ Mev (173.8 Mev/c), a range $R_{\Sigma^-} = 1.17$ cm,[10] and a moderation time of 3.76×10^{-10} sec.

As shown in Table I, 44 such Σ^-'s decay and seven interact. We can use these events to calculate a mean life

$$t_{\Sigma^-} = 1.86 \pm 0.26 \times 10^{-10} \text{ sec.}$$

This agrees with the mean life reported by Budde et al,[11] who observed the reaction $\pi^- + P \rightarrow \Sigma^- + K^+$, using a propane bubble chamber. They found $t_{\Sigma^-} = 1.4 {}^{+1.6}_{-0.5} \times 10^{-10}$ sec.

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[8] Chupp, Goldhaber, Goldhaber, and Webb (The Mass of the Negative K Meson and Negative Σ Hyperon, UCRL-3584, Nov. 1956) have used their own events plus some found by other emulsion groups (Fry, Schneps, Snow, and Swami, Phys. Rev. 103, 226 (1956)) to compute the following masses (in Mev):

$$m_{K^-} = 493.7 \pm 0.7\,, \qquad m_{\Sigma^+} = 1189.3 \pm 0.5\,,$$
$$m_{\Sigma^-} = 1196.5 \pm 0.9\,, \quad m_{\Sigma^-} - m_{\Sigma^+} = 7.3 \pm 0.8\,.$$

[9] See, for example, Fry, Schneps, Snow, and Swami, Phys. Rev. 100, 950 (1955).

[10] Actually the six Σ^- that come to rest have a range of 1.07 ± 0.03 cm. This suggests that our nominal density is about 10% too low (see Appendix).

[11] Budde, Chrétien, Leitner, Samios, Schwartz, and Steinberger, Phys. Rev. 103, 1827 (1956).

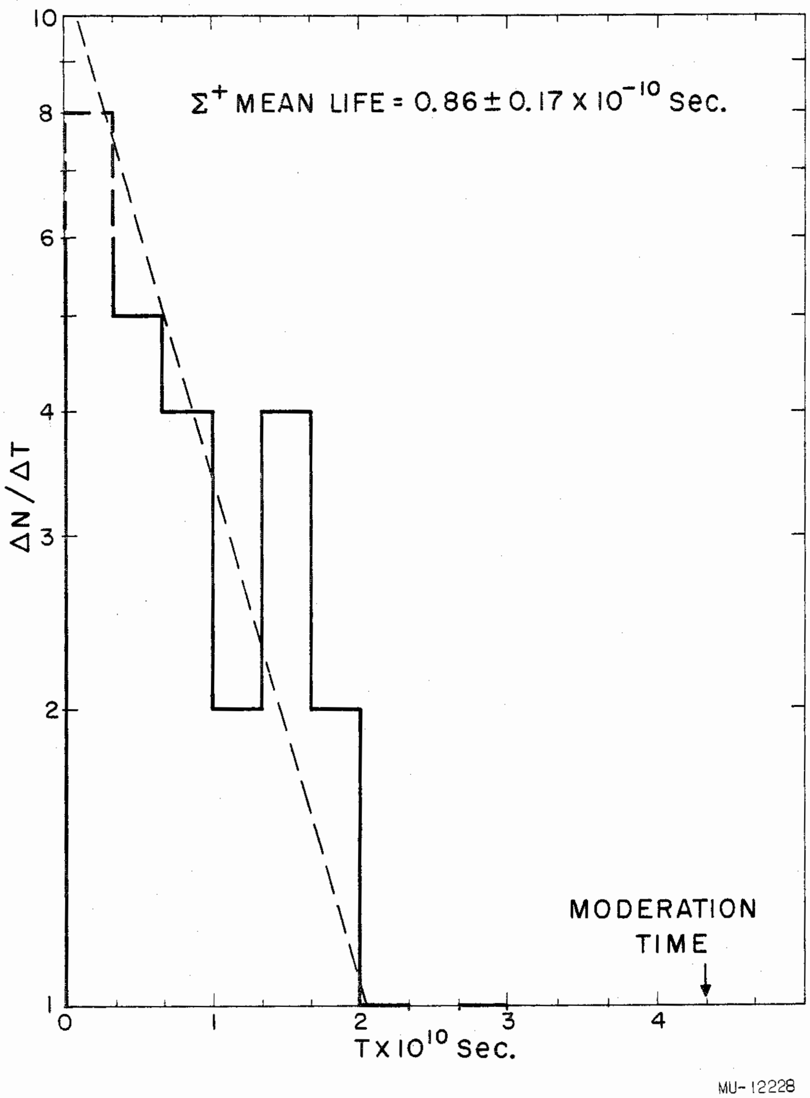

Fig. 5. Distribution in time of the Σ^+ decays. Four short Σ's were found whose charge could not be determined. Two of these were arbitrarily called Σ^+ and are represented by a dashed area.

The mean life was calculated on the assumption that all 44 decays occurred in flight. Actually the uncertainty in range measurement is such that we cannot rule out the possibility that as many as six of the Σ^- could have come to rest before decaying. If all six come to rest, our mean life should be increased by a factor 44/38, i.e., by ~ 15%.

The total path traversed by the 55 Σ^- was 27 cm. In our liquid hydrogen, a cross section of 1 barn corresponds to a mean free path of 30 cm. These facts give some idea of the cross section associated with the one Σ^- that interacted in flight.

V. CAN THERE BE TWO Σ LIFETIMES?

There have been many attempts to explain how two particles with apparently different parity (the τ and the θ) can have the same mass.

Lee and Yang and Gell-Mann[12] have suggested the idea of parity doublets. If the K mesons are doublets, then Σ and Λ hyperons must also be doublets--specifically there should be two Σ^+ (and two Σ^-) of opposite parity and presumably with different lifetimes.[13]

We have tried to fit our observed distribution of Σ^+ lifetimes by assuming that we have equal numbers of Σ^+ of each parity, and that the mean lives for the two cases are τ and $B\tau$. Specifically, we have assumed that the probability for any Σ^+ to decay at a time t is

$$P(t, \tau, B) = 1/2 \left[\frac{1}{\tau} e^{-\frac{t}{\tau}} + \frac{1}{B\tau} e^{-\frac{t}{B\tau}} \right], \quad (1 < B < \infty) . \qquad (1)$$

[12] T. D. Lee and C. N. Yang, Phys. Rev. 102, 290 (1956); Murray Gell-Mann (private communication).

[13] Moreover, according to this theory there should be equal numbers of the two sorts of K's produced at the target. There is good evidence that the mean lives of the charged K's of both parities are indeed very similar, so that the two parities of K should come to rest in our chamber in about equal numbers and make comparable numbers of even- and odd-parity Σ's.

The relative likelihood function[14] L(B) is very nearly of the form $L(B)/L(1) = 10^{-B/3.7}$. We can thus say that the most probable value of B is about unity (corresponding to a unique lifetime), and that a B greater than 3 or 4 is quite improbable.

The Σ^- can be treated the same way as the Σ^+, and the conclusions are qualitatively the same. The Σ^- lifetime distribution does not extend over so many mean lives as that for the Σ^+, therefore our 55 Σ^-'s are no more valuable for this analysis than our 28 Σ^+'s.

A different test for the existence of parity doublets is considered below.

VI. ANGULAR DISTRIBUTION OF Σ DECAY PRODUCTS

The angular distribution of hyperon decay products with respect to the hyperon direction of flight is of interest both because it may yield some information on the spin of the Σ and because a fore-aft asymmetry would confirm the existence of parity doublets.[15] The two aspects of the problem may conveniently be separated for the following reason. If the Σ has a well-defined parity, the angular distribution of its decay products can contain only terms which are even in cos θ. If the Σ is a parity doublet, then additional odd terms are allowable. If the angular distribution is folded about 90°, these odd terms must cancel, and one is left with a folded angular distribution that is independent of the existence or nonexistence of parity doublets.

A. Spin of the Σ

The folded angular distribution for the Σ^+ decay products is independent of the decay mode of the Σ^+ ($\rightarrow N + \pi^+$ or $P + \pi^0$) but it is not in general the same as the angular distribution of the Σ^- decay products. If, however, the K^- has spin zero and is captured from an s-state or a $p_{1/2}$ state of the K-mesic atom, then both Σ^+ and Σ^- must be produced in the same angular momentum and spin states, leading to the same angular distribution of their decay products.

---

[14] L(B) is defined in the following way: Let $L(\tau, B) = \prod_{i=1}^{28} P(t_i; \tau, B)$, where P is given by Eq. (1); for each assumed value of B, a value of τ called τ_B is calculated such that $L(\tau_B, B) = L(B)$ is a maximum.

[15] T. D. Lee and C. N. Yang, Possible Interference Phenomena between Parity Doublets (submitted to Phys. Rev.).

1. $S_\Sigma = 1/2$

The folded distribution for the decay of a spin 1/2 particle must be isotropic. If we can show that our (folded) data are inconsistent with isotropy, then S_Σ must be $> 1/2$. In order to make this test quantitatively it is convenient to analyze the events (total number = N) into n_p polar events ($|\cos\theta| > 1/2$) and n_e equatorial events, with $n_p + n_e = N$. The data are given in Table II. For the Σ^- we find $n_p^-/N^- = 25/41 = 0.61 \pm 0.08$, and for the $n_p^+/N^+ = 15/24 = 0.625 \pm 0.10$.

These values are to be compared with the expected value $n_p/N = 1/2$ for an isotropic distribution. The result for either the Σ^- or the Σ^+ taken separately is almost consistent with isotropy; however, the argument against isotropy becomes stronger if both results are considered together. Let us therefore assume that the true distributions of the decay products of Σ^+ and of Σ^- are both isotropic (for example because $S_\Sigma = 1/2$), and calculate the probability that the data should fit this assumption as badly as they do, or worse. Since both Σ^+ and Σ^- are here assumed to have identical (isotropic) distributions, we can combine the data, and we then find $n_p/N = 0.615 \pm 0.06$, and the probability of finding a deviation from 0.50 this large or larger is 8.2%.[16] The combined distribution is plotted in Fig. 6.

Since receipt of a private communication from Professor W. F. Fry (University of Wisconsin), we attach added significance to the evidence against isotropy for Σ decay. The Madison emulsion group find the same ratio n_p/N, based on 84 hyperon decays, as we do from our 65 cases.

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[16] For the binomial distribution $P(n_p, N) = C_{n_p}^N \left(\frac{1}{2}\right)^N$, the probability $P(n \geq 40, N = 65)$ is 4.1% (see <u>Tables of the Cumulative Binomial Probability Distribution</u>, Harvard University Press, Cambridge, Mass., 1955). The distribution is of course symmetric in n_p and n_e, and we must take into account the additional 4.1% probability that $n_e \geq 40$, i.e., that $n_e \leq 25$. Therefore the total probability of finding a fit this bad or worse is 8.2%. It may be noted that the above formulation reduces to the usual χ^2 test in the limit of large statistics.

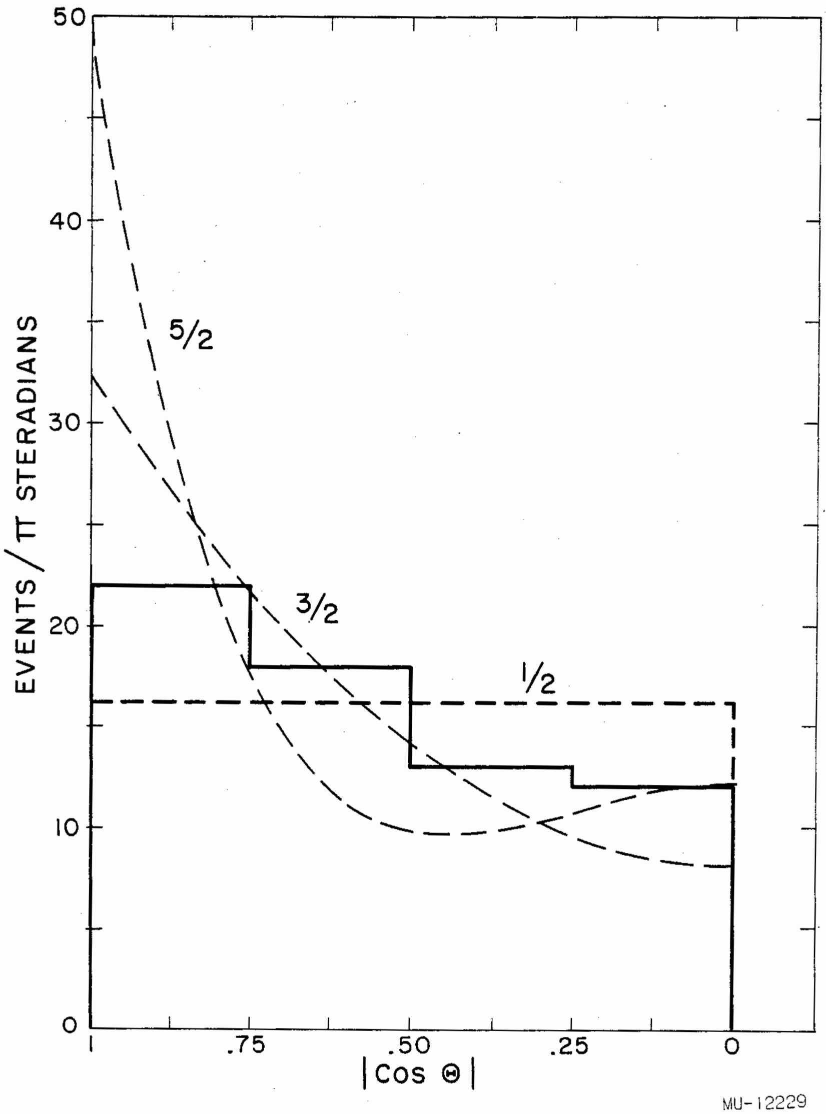

Fig. 6. Angular distribution of the pion produced in Σ decay. The histogram represents the sum of Σ^+ and Σ^- events, folded through 90°. The three dashed curves represent the theoretical distributions for Σ's of spin 1/2, 3/2, and 5/2 (the latter two are valid only if K^- captured in a state of angular momentum 1/2). The thin solid line is the best fit to our data on the assumption that the distribution is of the form $(1 + A \cos^2 \theta)$.

Table II

Angular distribution (c. m.) of the pions from Σ decay.[a]

$x = \cos\theta_{\Sigma\pi}$	Forward				Backward				Total	Probability
	1 – 3/4	3/4 – 1/2	1/2 – 1/4	1/4 – 0	0 – 1/4	1/4 – 1/2	1/2 – 3/4	3/4 – 1		
Experimental distribution:										
$\Sigma^- \rightarrow \pi^- + n$	9	3	7	3	4	2	7	6	41	-
$\Sigma^+ \rightarrow \pi^+ + n$	1	3	1	1	2	0	2	1	11	-
$\Sigma^+ \rightarrow \pi^0 + p$	3	2	3	2	0	0	1	2	13	-
Total	13	8	11	6	6	2	10	9	65	-
Folded through 90°	-	-	-	-	12	13	18	22	65	-
Theoretical distribution:										
$S_\Sigma = 1/2$	$f(\theta)$ = constant				16.25	16.25	16.25	16.25	65	8.2%
$S_\Sigma = 3/2$	$f(\theta) = 1 + 3x^2$				8.6	11.7	17.8	26.9	65	21 %
$S_\Sigma = 5/2$	$f(\theta) = 1 - 2x^2 + 5x^4$				11.7	10.1	12.6	30.6	65	18 %

[a] We have included only the Σ's from K's that came to rest. The theoretical distributions for $S_\Sigma = 3/2$ and 5/2 are calculated on the assumption that the Σ originates from a K-mesic atom with angular momentum 1/2 (for example, capture of a spinless K from an s state). The calculation of the probability that our data are consistent with isotropy is discussed in the text and in footnote 16. The probability associated with the angular distributions assumed for $S_\Sigma = 3/2$ is calculated in similar fashion. For $S_\Sigma = 5/2$ we applied the χ^2 test for the four separate units of solid angle given in the table, instead of further grouping the data into two intervals as done for $S_\Sigma = 1/2, 3/2$. This was done because any lumping would tend to wash out the sharp forward peaking of the theoretical distribution.

2. $S_\Sigma = 3/2$

It can be shown in general that in the angular distribution of decay products of a particle of spin S no term in $\cos\theta$ raised to a power greater than the $(2S - 1)^{th}$ can appear. If we take $S_\Sigma = 3/2$, the angular distribution must be of the form $(1 + A\cos^2\theta)$. For the combined Σ^+ and Σ^- decays our experimental result $n_p/N = 0.615 \pm 0.06$ leads to $A = 1.3^{+1.3}_{-0.8}$. This angular distribution is plotted as a thin solid line in Fig. 6, and it can be seen that it fits the data well within our statistical errors.

Let us, therefore, consider this case $S_\Sigma = 3/2$ in more detail. The angular distribution is governed by the total angular momentum J of the K-mesic atom from which the Σ originates.[17] Gatto has pointed out that K's are quite possibly absorbed from p states as well as from s states.[2] We shall assume that the spin of the K is zero; then we need discuss only the two cases $J = 1/2$ and $J = 3/2$.

a. $J = 1/2$. (if the K is captured from an s-state, this is the only case we need consider). For this simple case, the folded angular distribution is unique,[17] namely, it is proportional to $1 + 3\cos^2\theta$. It can be seen from Fig. 6 and from Table II that the fit is only moderately good.

b. $J = 3/2$. The angular distribution is no longer unique, but depends upon the amplitudes of various angular momentum states in which the Σ is produced (and A_+--for the Σ^+ decays--and A_- could be different). Although A is not unique, it must lie in the range -1 to $+3$ (as must A_+ and A_-).

Since $J = 1/2$ forces A to be 3, we conclude that if the K absorption takes place partly from s state and partly from p states A must lie in the range -1 to $+3$. Our best value of $A = 1.3$ evidently falls within this range. Our individual values of A_+ and A_- are almost equal to A, and individually pass this test.

3. $S > 3/2$

On the basis of our data we certainly cannot rule out $S > 3/2$. However, it may be of some interest to note that if S_Σ is large and J small the angular distribution becomes sharply peaked towards 0° and 180°. Our data show no sharp peaking. This peaking is already apparent for the case $J = 1/2$, $S_\Sigma = 5/2$, which is included in Table II and in Fig. 6.

[17] S. B. Treiman, Phys. Rev. 101, 1216 (1956).

B. Fore-aft Asymmetry

Lee and Yang[15] have shown that if the Σ has mixed parity (see Section V) its decay products could show a fore-aft asymmetry. This asymmetry need not be the same for each of the three possible modes of decay: $\Sigma^- \rightarrow N + \pi^-$, $\Sigma^+ \rightarrow N + \pi^+$, and $\Sigma^+ \rightarrow P + \pi^0$ should be considered separately. The data are displayed in Table III:

Table III

Evidence for possible asymmetries in Σ decay. Forward and backward refers to the pion direction in the center-of-mass system relative to the Σ direction.

	No. in forward hemisphere	No. in backward hemisphere	Total	
	n_f	n_b	N	n_f/N
$\Sigma^- \rightarrow \pi^- + N$	22	19	41	0.536 ± 0.08
$\Sigma^+ \rightarrow \pi^+ + N$	6	5	11	0.545 ± 0.15
$\Sigma^+ \rightarrow \pi^0 + P$	10	3	13	0.769 ± 0.12

There is some preference for forward over backward, but only one of the three modes is peaked forward by more than one standard deviation. Any conclusion drawn from this single mode is weakened by data from the Wisconsin emulsion group, who inform us that they have 38 examples of this mode of decay, divided equally between forward and backward.

VII. Σ^0 AND Λ HYPERONS

A Σ^0 is expected to decay rapidly ($\sim 10^{-20}$ sec) into $\Lambda + \gamma$; thus the Σ^0 should be detectable via its secondary gamma or Λ originating essentially from the point of production of the Σ^0. We have as yet no gamma-ray converter inside the bubble chamber, but if the Λ decays through its charged mode, then we can detect it with high efficiency (the bubble chamber is large compared with the mean decay distance of a slow Λ).

Both Σ^0 and Λ can be made by the interactions of K^- with protons (Reactions V through VIII) or of Σ^- with protons (Reactions X and XI), but the primary Λ's can be distinguished from those which are the daughters of Σ^0's by measurements of the Λ energy.

A. Hyperons from K^-

For neutral hyperons coming from a K^- mesic atom, $T_{\Sigma^0} =$ 13.5 Mev (179.8 Mev/c),[18] $T_\Lambda = 28.7$ Mev (253.0 Mev/c), for the two-body Reaction VI. For the three-body Reactions VII and VIII, $0 < T_\Lambda < 8$ Mev.

The energy spectrum of the Λ's coming from K^- mesic atoms is given in Fig. 7. The various contributing spectra are drawn schematically in the upper part of the figure and the experimental distribution is given below. Our best estimate is that of the 21 events 14 ± 2 are Σ^0's and 7 ∓ 2 are primary Λ's.

We shall now discuss the experimental spectrum in more detail: with our present technique, we can measure the kinetic energy of a Λ to about 2 Mev if the secondary proton stops in the chamber--if it does not stop the uncertainty is greater. With this coarseness of measurement, we cannot resolve the line from the continuum. Not only do the two merge, but also the mixing makes the peak in the experimental spectrum appear at a slightly lower energy than that of the line. We attribute the one at 47 Mev to a $K^- - p$ interaction in flight. It is not surprising that we should observe one such interaction: for the 78 $\Sigma^\pm$ from K's that have come to rest, we see five made by K's still in flight; therefore for 21 (primary and secondary) Λ's coming from K's at rest, there should be about one made by a K still in flight.

We feel that the contribution of Reaction VII to the spectrum is quite small because the phase space is an order of magnitude less than that available to Reactions V and VI. Moreover there is the experimental evidence that we do not see the easily detectable Reaction VIII, which should show up more strongly because (a) we can detect it even if $\Lambda \rightarrow N + \pi^0$, (b) it can proceed through states in which the two pions have either I-spin 1 or 0, whereas Reaction VII is limited to I = 0.

B. Hyperons from Σ^- Interactions; Mass of the Σ^0

When a Σ^- comes to rest and is captured by a proton, it can yield primary Λ's (Reaction XI) with a kinetic energy $T_\Lambda = 36.9$ Mev. If $m_{\Sigma^-} - m_{\Sigma^0} > m_N - m_P = 1.3$ Mev, the Σ^- can also give Σ^0's by Reaction X. These Σ^0's will give rise to a spectrum of secondary Λ's, and the limits of this spectrum depend sensitively on $m_{\Sigma^-} - m_{\Sigma^0}$.

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[18] We have taken $m_{\Sigma^0} = 1193$ Mev; this guess is based on the evidence presented in Section VII B.

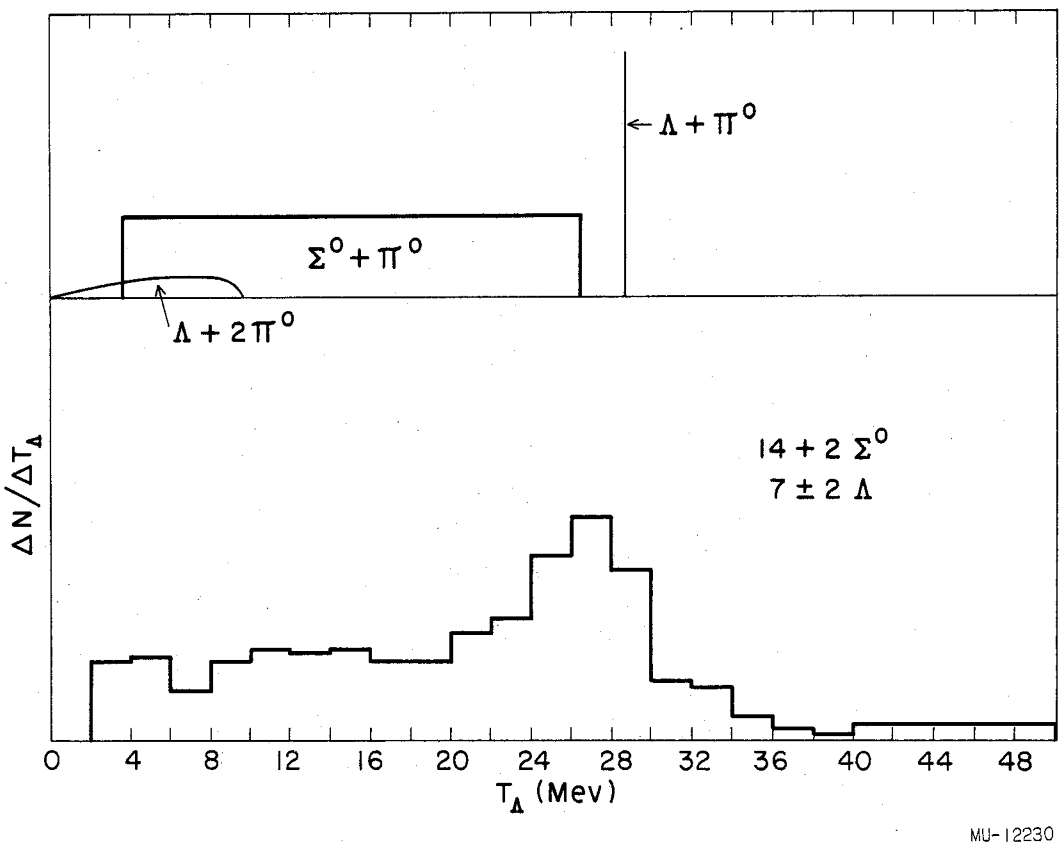

Fig. 7. Energy spectrum of Λ's from K^- captured by protons. The spectrum of secondary Λ's from Σ^0's will be a rectangle (as drawn) if the Σ^0 has spin 1/2; in any case this spectrum must be symmetric about its average energy. The histogram is constructed by assigning to each event a rectangle of unit area (indicated in black); the width of the rectangle shows the energy uncertainty of that Λ.

We have observed four Λ's from stopped Σ^-; two of them had T_Λ consistent with 36.9 Mev and were evidently primaries; for the other two, T_Λ was 2.8 ± 0.5 and 4.5 ± 0.5 Mev, and these we interpret as secondaries. These two events show that 1.7 Mev $< (m_{\Sigma^-} - m_{\Sigma^0}) <$ 22.7 Mev. Figure 8 shows the likelihood function for $m_{\Sigma^-} - m_{\Sigma^0}$ based on these two events under the assumption that the Σ^0 decays isotropically. It can be seen that the most probable value of m_{Σ^0} is somewhere between m_{Σ^-} and m_{Σ^+}.

C. Mean Life of the Λ

On the assumption that the Λ has a unique mean life, we calculate from our 25 Λ's

$$\tau_\Lambda = 3.25 \pm 0.6 \times 10^{-10} \text{ sec.}$$

This is in a good agreement with the values $3.7\,^{+0.6}_{-0.5}$ given by Page,[19] and $2.0\,^{+1.3}_{-0.7}$ by Budde et al.[11] The distribution of these 25 events in flight time is consistent with a unique mean life. The average K stops about 10 cm from the wall of the chamber, and the flight time for a typical Λ (20 Mev) to reach the walls (if it does not first decay) is a little more than 10^{-9} sec. We could therefore miss extremely long-lived Λ's. If short- and long-lived Λ's are assumed to be produced in equal numbers, then we can put a lower limit of $\sim 5 \times 10^{-9}$ sec. on the lifetime of the long-lived component.

VIII. ANGULAR DISTRIBUTION OF Λ DECAY PRODUCTS

The angular distribution of Λ decay products gives information on the Λ spin. The considerations are analagous to those in the preceding section. Experimentally, the analysis is more difficult because of our inability to distinguish (except on a statistical basis) many of the primary Λ's and those coming from Σ^0's. About all that can be done at this time is to add the angular distribution from all our Λ's (primary and secondary) coming from stopped K's and to see whether the distribution is consistent with isotropy.

We find $n_p/N = 15/24 = 0.62 \pm 0.10$.

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[19] D. I. Page, Phil. Mag. 45, 863 (1954).

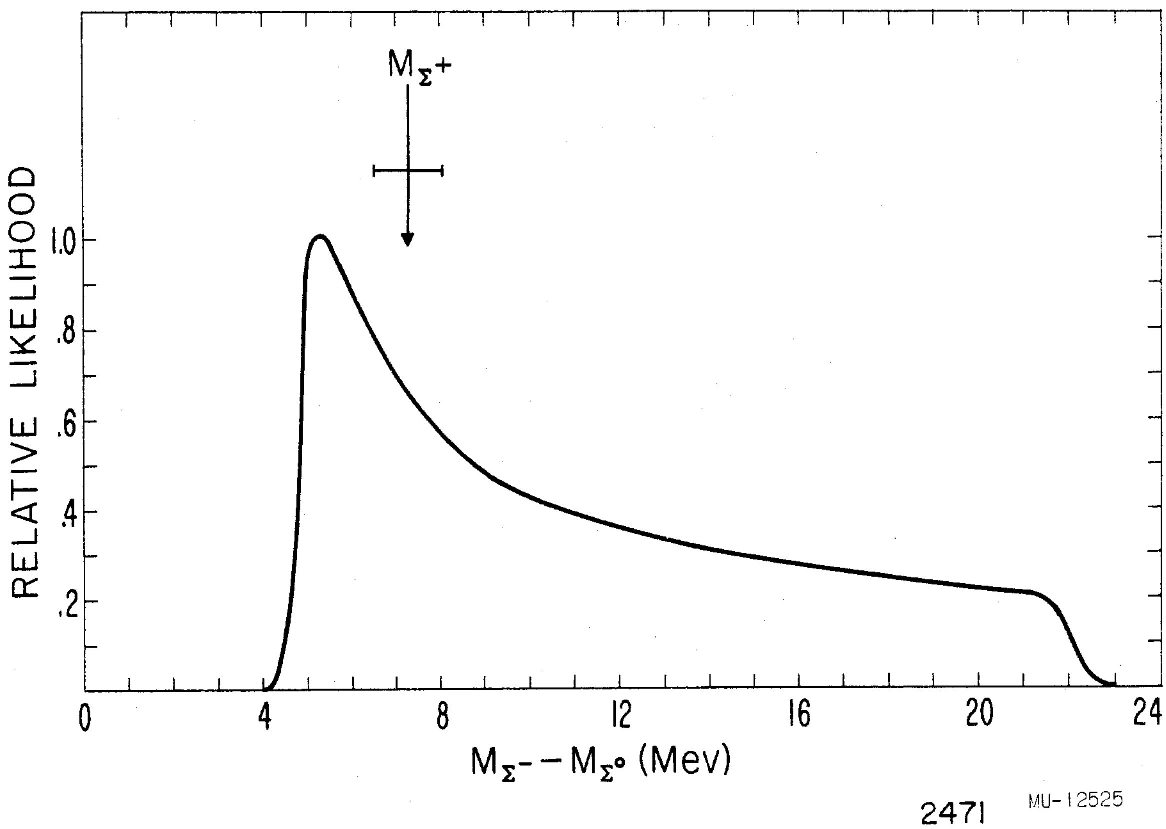

Fig. 8. Relative likelihood for Σ^0 mass values based on the kinetic energies of three Σ^0's coming from Σ^- absorptions. One additional event, found after the text was completed, has been included in computing the likelihood function.

There have been a number of experiments on the production and subsequent decay of Λ's[11, 20, 21] that should shed some light on the spin on the Λ; however the evidence still seems inconclusive. Considerations of the ratio of mesonic to nonmesonic decay of light hyperfragments do suggest that $S_{\Lambda} = 1/2$.[22, 23] Our value of n_p/N is not inconsistent with this conclusion.

IX. THE $\overline{\theta}^0$ MESON

Three events have been observed in which a neutral particle is produced in a K^- + p interaction and decays into two charged light particles (one of these is shown in Fig. 4). The kinematics suggest the θ_1 decay: $\theta_1 \rightarrow \pi^+ + \pi^-$. In order to conserve strangeness the neutral heavy meson that was produced must have been a $\overline{\theta}^0$, which then decayed as a θ_1.[24, 25]

The kinetic energies of the 3 $\overline{\theta}^0$'s are 10 ± 2, 9 ± 2, and 1.5 ± 1 Mev.[26] Since they are not of unique energy, at least one of them, and possibly all, must have been produced by a K^- in flight. We cannot rule out interactions in flight because Coulomb scattering of a stopping particle produces fluctuations of track curvature such that occasionally a K could disappear 10 cm before the end of its range (when it still has ~30 Mev kinetic energy) and still look as if it had come to rest. Bubble counting leads to a comparable uncertainty.

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[20] Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. 98, 121 (1954).

[21] W. Walker and W. Shephard, Phys. Rev. 101, 1810 (1954).

[22] M. A. Ruderman and R. Karplus, Phys. Rev. 102, 247 (1956).

[23] H. Primakoff, Nuovo Cimento 3, 1394 (1956).

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

[25] A reaction has been reported by Fowler, Maenchen, Powell, Saphir, and Wright (Phys. Rev. 103, 208 (1956)) in which the production of a $\overline{\theta}^0$ was required for kinematical reasons and in order to preserve strangeness. However the postulated $\overline{\theta}^0$ was not observed to decay. Also R. G. Glasser and N. Seeman (abstract submitted for APS meeting, Chicago, Nov. 1956) report evidence for neutral particles which may be $\overline{\theta}^0$'s and which are capable of producing hyperons in an interaction.

[26] The mass of the $\overline{\theta}^0$ enters into the calculation of the kinetic energies, but in a very insensitive way. For this calculation we assume $m_{\overline{\theta}^0} = m_{K^-}$.

It must be remarked that the low-energy $\overline{\theta}^0$ was found in one of our most unsatisfactory photographs, where the beam was many times as intense as it should have been. This event could possibly be just a small-angle pion-proton scattering.

If our two high-energy $\overline{\theta}^0$'s come from stopped K's, then the mass of the $\overline{\theta}^0$ must be smaller than that of the K^- by about 15 Mev. This is in disagreement with Thompson's finding that the mass of the θ^0 and the K^+ are equal within ± 5 Mev.[27] Our two high-energy θ's both come forward from the place where the K^- disappears, so we can get agreement with Thompson's mass by postulating that the K^- charge-exchanged when it still had a kinetic energy of about 10 Mev ($R \sim 1.5$ cm).

On the assumption that there are no parity doublets, half the $\overline{K}^0$'s produced should decay in the chamber as θ_1's, and about 90% of the other half should escape from the chamber before decaying as θ_2's. We may not observe all the θ_1's however, since there may be a decay mode $\theta_1 \rightarrow \pi^0 + \pi^0$ (although there is some evidence that this is absent). In summary, if the K is not a parity doublet we can expect to detect one-half or less of the $\overline{K}^0$'s. (If K's are a parity doublet, half of them will be long lived τ's, and we can then expect to detect $\leq 1/4$ of the total number produced.) Budde et al.[11] find experimentally that a fraction $\alpha \sim 1/3 \pm 1/6$ of the θ^0's produced in high-energy $\pi + p$ collisions decay in their bubble chamber. We have identified three θ_1 events; dividing three by α we suggest that there are probably 9 ± 3 K^0's made altogether, 6 of them showing up as $K\rho$'s.

X. MATRIX ELEMENTS AND PHENOMENOLOGY

A. Production of Σ's

We assume conservation of isotopic spin I during the production of Σ^+, Σ^-, and Σ^0 via Reactions III, IV, and V. Both the states I = 1 and I = 0 are involved; our data permit us to estimate the relative strength and phase of the matrix elements J_1 and J_0.[4] We shall show that $|J_1| \lesssim |J_0|$, and $\phi \approx 70^\circ$.

Let
$$\frac{J_1}{J_0} \equiv \tau e^{i\phi}$$

[27] Thompson, Burwell, Cohn, Huggett, and Karzmark, Phys. Rev. 95, 661 (1954).

and let $\Sigma^{+,-,0}$ stand for the number of hyperons produced. Then we have

$$\frac{\Sigma^-}{\Sigma^+} = \left| \frac{r e^{i\phi} + \sqrt{\frac{2}{3}}}{-r e^{i\phi} + \sqrt{\frac{2}{3}}} \right|^2 \qquad (1)$$

and

$$\frac{\Sigma^- + \Sigma^+}{2\Sigma^0} = \frac{3}{2} r^2 + 1 \geq 1 \, . \qquad (2)$$

From the experimental numbers $\Sigma^{+,-,0}$ let us now calculate r and ϕ.

From Eq. (1) and the value $\Sigma^-/\Sigma^+ = 2$ (see Table I), we obtain the lower limit $r \geq 0.14$.

There is considerable uncertainty about the total numbers of Σ^0's produced because the secondary Λ's may decay by the neutral mode or there could also be a long-lived type of Λ. If a is the fraction of Λ's decaying by the charged mode, then $a\Sigma^0$ is the number of observed Σ^0 (14 according to Table I).

The value a is subject to the following considerations:

1. Inserting the lower limit $r \geq 0.14$ into Eq. (2), we find

$$(\Sigma^- + \Sigma^+) = 83 \geq 1.03 \times 2\Sigma^0 = 1.03 \times 2 \times 14/a \, ,$$

hence $a \geq 0.35$.

2. From the number of Kp endings we estimate $0.4 < a < 0.6$.
3. Budde et al.[11] have examined the associated production of Λ's in high-energy $\pi + p$ collisions and find $0.18 < a < 0.45$.
4. The proposed I-spin selection rule for strange-particle decays, $\Delta I = \pm 1/2$,[6] requires $a = 2/3$.

Figure 9 gives r and ϕ as functions of a. J_1/J_0 can be used to calculate the relative abundance of Σ's produced by K^- interactions with neutrons.

B. Relative Production of Λ's and Σ's

Since Λ's are assumed to have I-spin 0, Reaction VI can proceed only in an I = 1 state; we shall call the matrix element for this process G_1. We wish to compare G_1 with the matrix element J_1 responsible for Σ production, which has already been discussed in paragraph A. Again assuming conservation of isotopic spin, we find

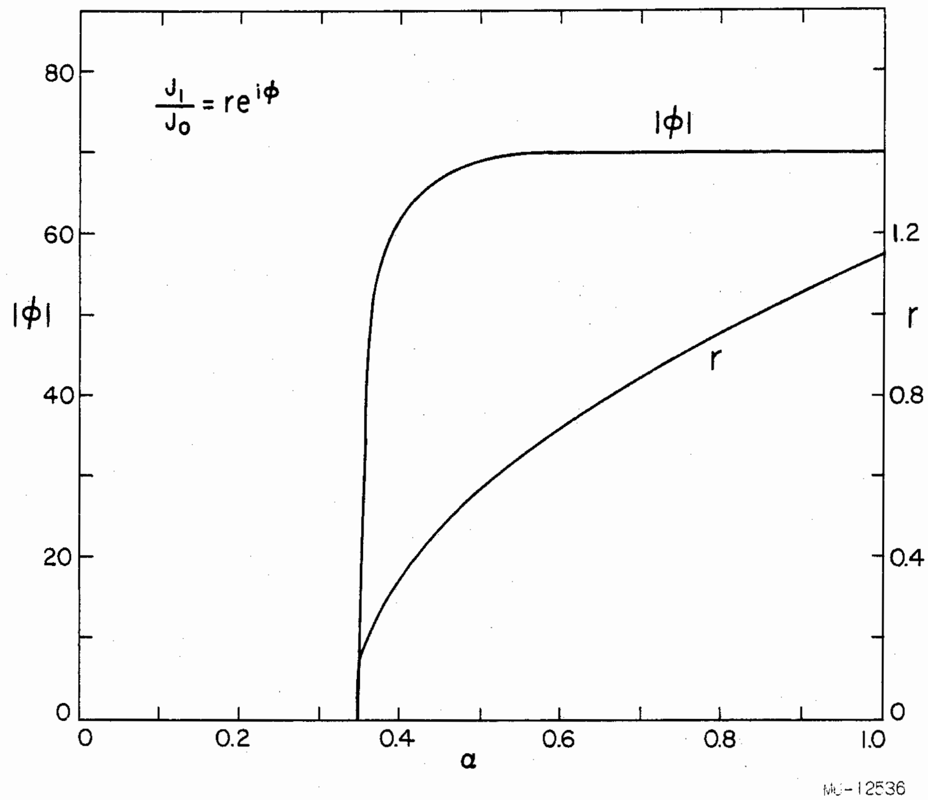

Fig. 9. Ratio of the I spin 1 and I spin 0 matrix elements (J_1 and J_0) for the reaction $K^- + p \rightarrow \Sigma + \pi$ as a function of a, the fraction of Λ's decaying into $\pi^- + p$ in the chamber.

$$\left|\frac{G_1}{J_1}\right|^2 = \frac{\Lambda}{\Sigma^+ + \Sigma^- - 2\Sigma^0} = \frac{\Lambda_{\text{observed}}}{\alpha(\Sigma^- + \Sigma^+) - 2\Sigma^0_{\text{observed}}} ;$$

here α is, as before, the fraction of Λ's observed to decay into charged particles. Our data suggest that $\alpha = 0.5 \pm 0.1$; inserting this into Eq. (3), we find

$$\left|\frac{G_1}{J_1}\right|^2 = \frac{7 \pm 3}{11 \pm 11} \sim \frac{2}{3}$$

Observations of K^- stars in nuclear emulsion have already led to the suggestion that the production of Σ's may be more intense than that of Λ's.[28]

XI. DECAY OF THE Σ HYPERON

The decay products of the Σ^+ represent mixtures of $I = 1/2$ and $I = 3/2$ states, whereas for Σ^- the final state is entirely $I = 3/2$. If we define the ratio of the $I = 1/2$ to the $I = 3/2$ matrix elements for the Σ^+ as

$$R_{1/2}/R_{3/2} = x\, e^{i\psi} ,$$

we have the branching ratio

$$f \equiv \frac{\Sigma^+ \to P + \pi^0}{\Sigma^+ \to N + \pi^+} = \frac{2 + x^2 - 2\sqrt{2}\, x\cos\psi}{1 + 2x^2 + 2\sqrt{2}\, x\cos\psi} ; \tag{4}$$

experimentally we find $f = 1.0 \pm 0.2$. Solving for x, we get

$$x = \frac{-\sqrt{2}\,(f + 1)\cos\psi \pm \left[2(1 + f)^2 \cos^2\psi - (2f - 1)(f - 2)\right]^{1/2}}{2f - 1} \tag{5}$$

A number of authors have pointed out that the symmetry and unitarity of the S-matrix implies that $\psi = (\delta_{3/2} - \delta_{1/2})$;[29, 30, 31] here $\delta_{3/2}$, $\delta_{1/2}$ are the $I = 3/2$, $1/2$ π - p phase shifts appropriate to the parity and angular momentum

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[28] Sulamith Goldhaber, Proceedings of the Sixth Annual Rochester Conference, April 1956.

[29] G. Takeda, Phys. Rev. 101, 1547 (1956).

[30] M. Kawaguchi and K. Nishijima, Progr. Theor. Phys. 15, 182 (1956).

[31] B. D'Espagnat and J. Prentki, Nuovo Cimento 3, 1045 (1956).

of the final state; these are determined uniquely by the spin and parity of the Σ^+. Table IV lists the values of $|x|$ we find by using Eq. (5) and our experimental branching ratio f = 1 for various spin and parity assignments.

Several authors have discussed the decay of hyperons.[29, 31, 32, 33] One suggestion is to demand that the interaction responsible for the decay be a spinor in I space (implying $\Delta I = \pm 1/2$ in the decays).[30, 31, 32]

This assumption leads to the relationship

$$\frac{\tau_{\Sigma^-}}{\tau_{\Sigma^+}} = \frac{1}{3}(1 + x^2) . \tag{6}$$

From the last column of Table IV we see that our observed lifetime ratio ($\tau_{\Sigma^-}/\tau_{\Sigma^+} = 2.2 \pm 0.5$) conflicts with Eq. (6) for all possible spin and parity assignments.[34]

XII. K^- INTERACTIONS IN FLIGHT

Nine K^- interactions in flight have been definitely identified, three of these as elastic scatterings. The number of interactions in flight should probably be increased by about six for the $\overline{K}^0$ contribution.[35] In order to calculate a cross section based on the observed track length of stopping K^-'s, one must count only those interactions (about 3/4 of the total) in which the K would have stopped in the chamber if it had not interacted. We obtain an absorption cross section of (210 ± 100) mb and a scattering cross section of (45 ± 30) mb; the average K^- enters the chamber with about 30 Mev. The uncertainties are evidently too large to permit any clear-cut conclusions, but it is interesting to note that complete S-wave absorption ($\pi\lambda\!\!\!^{-2}$ averaged over the K^- path) is about 200 mb; complete S-wave absorption implies an equal elastic cross section. Our large absorption cross section suggests that P waves as well as S waves contribute to the interaction.

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[32] M. Kawaguchi and K. Nishijima, Progr. Theor. Phys. 15, 180 (1956).

[33] C. Iso and M. Kawaguchi, Progr. Theor. Phys. 16, 177 (1956).

[34] The conflict is smallest for the $(3/2)^+$ assignment, and in that case would be removed if the branching ratio were as large as 1.4 and $\tau_{\Sigma^-}/\tau_{\Sigma^+}$ as large as 3.2. However, these values are both two standard deviations away from our best values; this can be seen with the help of the plot of f versus $1/3\,(1 + x^2)$ given by Iso and Kawaguchi.[33]

[35] We assume that two observable and four unobservable $\overline{\theta}^0$'s are produced in flight (see Section IX).

Table IV

Σ Decay								
Type of Σ	π-p system	$\cos(\delta_{3/2}-\delta_{1/2})$[a]	$\lvert x\rvert = \lvert (R_{1/2})/(R_{3/2}) \rvert$[b]			$\frac{1+x^2}{3} \left(= \frac{\tau_{\Sigma^-}}{\tau_{\Sigma^+}} \text{ if } \Delta I = \pm\frac{1}{2}\right)$		
$1/2^-$	$S_{1/2}$	0.95	0.18	or	5.5	0.34	or	11
$1/2^+$	$P_{1/2}$	1.00	0.17	or	5.8	0.34	or	12
$3/2^+$	$P_{3/2}$	0.76	0.22	or	4.5	0.35	or	7
$3/2^-$	$d_{3/2}$	1.00	0.17	or	5.8	0.34	or	12
higher spins	d and higher	1.00	0.17	or	5.8	0.34	or	12

[a]Phase shifts from Proceedings of the Sixth Annual Rochester Conference, April 1956.

[b]$R_{1/2}$ and $R_{3/2}$ are the matrix elements for decay into I = 1/2 and I = 3/2 states.

XIII. DECAYS IN FLIGHT

Seventeen K^- mesons decay in the chamber before coming to rest. This number is consistent with the number of expected decays from the known K lifetime. At present our momentum measurements are not sufficiently precise to distinguish between most of the K decay modes; however, 4 τ^- decays were observed (Fig. 10). They have been analyzed by Bernard Waldman, who finds $m_{\tau^-} = 492 \pm 5$ Mev ($963 \pm 10\ m_e$).[36] As early as 1953 Van Lint and Trilling observed a τ^- whose mass they calculated as 493 ± 3 Mev.[37] Our mass value corroborates theirs but is of little help in reducing the uncertainty. These masses for the τ^- agree with the better-known mass (494 ± 0.5 Mev) of the positively charged K.[38]

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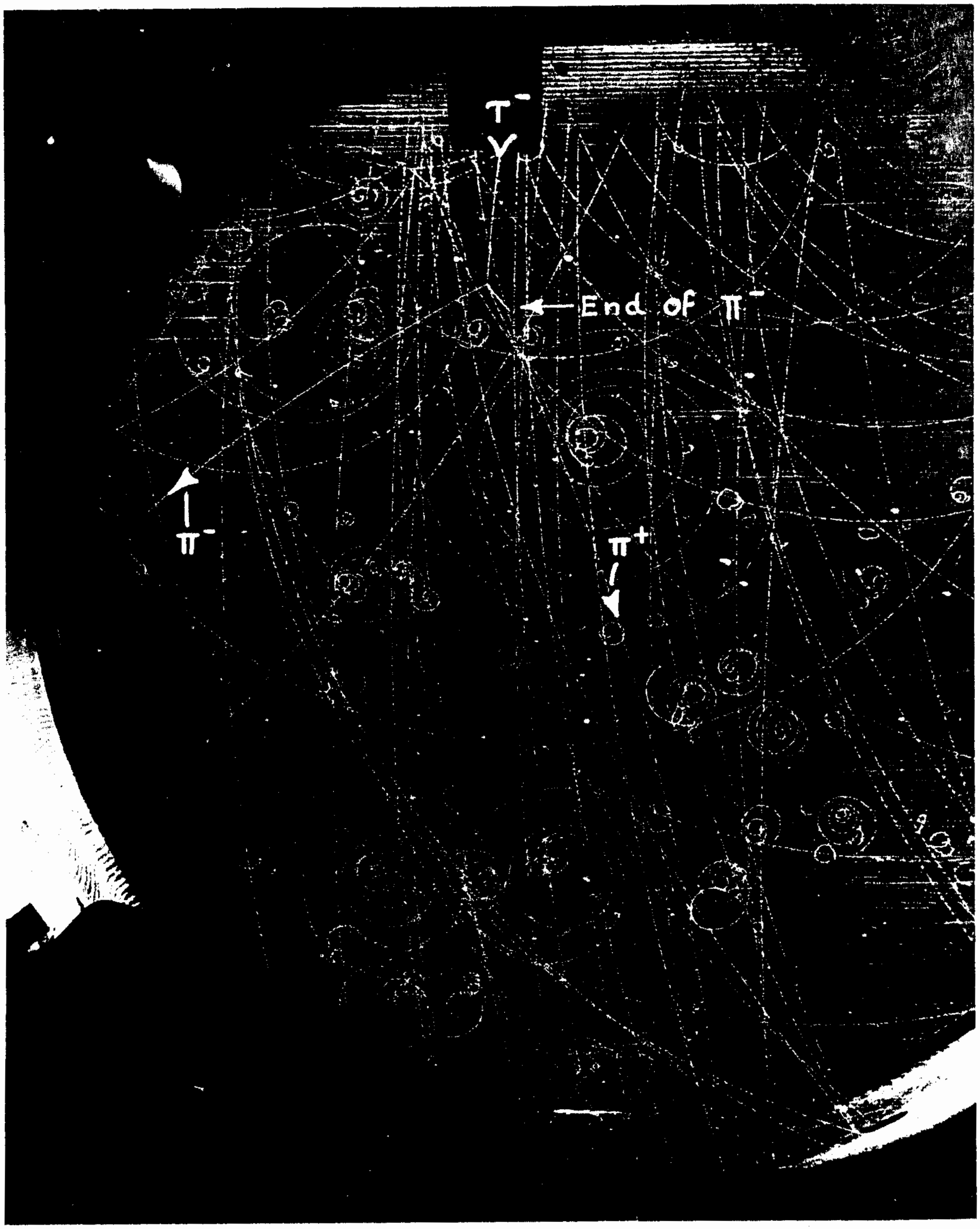
[36] Bernard Waldman, A Mass Determination of a τ^- Meson, UCRL-3507, Aug. 1956.

[37] V. A. J. Van Lint and G. H. Trilling, Phys. Rev. 92, 1089A (1953).

[38] Heckman, Smith, and Barkas, Nuovo Cimento 4, 51 (1956).



ZN-1627

Fig. 10. K^- decay in flight: $\tau^- \rightarrow \pi^- + \pi^- + \pi^+$.

ACKNOWLEDGMENTS

It would have been impossible to carry out the work described in this paper without the cooperation of many individuals and groups, some members of the Radiation Laboratory and some not. Often this experiment required extraordinary effort by supporting personnel. Space does not permit us to acknowledge the help of each person by name. Among those who contributed in large measure, however, we wish to acknowledge the work of the bubble chamber operating crews, under the direction of Richard L. Blumberg, Robert Watt, and Glen Eckman. The personnel of the University of California Chemistry Department Liquified Gases Plant, under the direction of Dr. David Lyon, provided large quantities of liquid hydrogen and nitrogen, operating for long hours, often at plant capacity.

We wish also to thank the Bevatron operating staff, as directed by Dr. Edward J. Lofgren and Mr. Harry Heard; the scanners; and also Prof. Bernard Waldman, who worked with us during the summer. Professors Robert Karplus, T. Kotani, Malvin Ruderman, and many others provided very helpful discussions on the theoretical aspects of this experiment.

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APPENDIX

EXPERIMENTAL DETAILS

We are convinced that a careful, experienced scanner detects K mesons stopping in the chamber with very nearly 100% efficiency (providing beam and bubble chamber conditions are reasonably good). Sometimes a fast scan is done during a run to check on conditions; this is only about 80% efficient.

The identification of most of the events is very simple and can be done by inspection. Thus when a K^- stops, leading to a Σ, one observes the characteristic collinear Σ and π tracks, with a secondary π track originating from the end of the Σ; the stopping K^- and the Σ are heavily ionizing, the two π's minimum ionizing; one can get additional kinematic checks by making rough curvature (and hence momentum) measurements with the help of templates. For K endings leading to Λ's the identification is just as easy. Only in the case of K_ρ's (i.e., K endings giving no visible products) is there some difficulty in identification: A short, fairly straight, heavily ionizing track going through the entrance window can be either a K^- or a proton going in the opposite direction; a π^- charge-exchange scattering may also look like a K^- ending if the chamber is oversensitive (since in that case minimum and heavily ionizing tracks tend to have similar appearance).

Lengths, angles, and curvatures were measured with ruler, protractor, and templates on projections of the two stereophotographs; then the corresponding spatial quantities were obtained by desk calculation (a faster and more accurate method of analysis is being developed). These measurements are adequate for obtaining the lifetimes of the hyperons and the angular distribution of their decay products.

The Q values of the various reactions and decays observed could in principle be determined from the range and curvature measurements. For instance, the Q value of the reaction $K^- + p \rightarrow \Sigma^- + \pi^+$ could be determined either from the curvature of the π^+ track or from the range of the Σ^- in case it stops. If the measurement accuracy were limited by multiple scattering or by Bohr straggling, we could determine the Q value to about 1 Mev from a single event. However, at present we have some difficulty in getting accurate momentum measurements from either curvature or range. We suspect that curvature is not reliable to better than about 10% because of turbulence; the range-energy relation is not well known because of the present uncertainty of the density of the superheated liquid hydrogen. Our best guess for the density, based on van der Waals' equation, is (0.055 ± 0.005) g/cm^3; there is a program under way to establish a point on the range-energy relation by measuring ranges of μ^+'s from π-μ decays.