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ABSTRACT

277 K^- mesons have been stopped in a hydrogen bubble chamber, roughly doubling the number reported previously. Hyperon production ratios, lifetimes, decay-mode ratios, and decay angular distributions are statistically improved. Cross sections for K^- interactions in flight are reported.

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I.   Introduction

A report on the first 137 K⁻ interactions observed in the Berkeley 10-inch hydrogen bubble chamber has appeared previously.[1]   We shall refer to this original report as Ref. 1.   Subsequent Bevatron runs have roughly doubled the available data.   The new data (combined with the older data) are here presented in the form of tables and graphs.

No new types of events have been identified.

There are two noticeable deviations from the earlier reported results: The decay distributions of the hyperons are now much more consistent with isotropy.   The ratio of Λ to Σ^0 production appears to be less than 1/2, possibly much less.

Cross sections for K⁻ elastic scattering and $\Sigma^+ + \Sigma^-$ production in flight as a function of momentum are reported.   Up-down asymmetries in Σ^- and Σ^+ decays from hyperons produced from K⁻ interactions in flight are discussed.

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[1] Alvarez, Bradner, Falk-Vairant, Gow, Rosenfeld, Solmitz, and Tripp, Nuovo Cimento 5, 1026 (1957); K⁻ Interactions in Hydrogen, UCRL-3583, Nov. 1956.

II. Distribution of Events

Table I lists all the strange-particle interactions and decays observed so far. In cases of neutral particles resulting from K^- capture, differentiation between events in flight and those at rest is generally not possible, so that only the total number of such events is noted. In Ref. 1 the number of K_p events was estimated. Subsequent runs were performed under such a variety of experimental conditions that the number of K_p events is now considerably harder to estimate. However, the branching ratio between neutral and charged decays for Λ and K^0 is quite well known, from associated production experiments,[2] to be

$$\frac{R(\Lambda \mid p\pi^-)}{R(\Lambda \mid p\pi^-)+R(\Lambda \mid n\pi^0)} = 0.68 \pm 0.05,[*]$$

$$\frac{R(K^0 \mid 2\pi^0)}{R(K^0 \mid 2\pi^0)+R(K^0 \mid \pi^+ +\pi^-)} = 0.07 \pm 0.03.$$

Using these numbers we can infer the number of $\overline{K}^0$, Σ^0, and Λ produced that decay by a neutral mode. These are indicated by the letter (c).

Beta-decay modes of the $\Sigma^\pm$ hyperons were investigated by studying the momentum distribution of the decay products. Within the uncertainty of the momentum measurements no events were found that would have necessitated invoking this alternative decay mechanism. On this basis the rate of beta decay is found to be less than 5% of the charged-pion decay.

Calculations of the rate of beta decay of the $\Sigma^\pm$, based on the same beta-decay interaction constant as found for the neutron decay, indicate that the rate of decay via this mode should be between 1% and 4% (depending on the choice of interactions) of the observed charged-pion mode of Σ^+ decay[3]).

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[*] We obtain a value of 0.70 ± 0.15 for this ratio, when we use our observed number of Λ's arising from Σ^- capture.

[2] Plano, Samois, Schwartz, Steinberger, Eisler, Phys. Rev. (to be published, 1957).

[3] R. Behrends and C. Fronsdahl, Phys. Rev. 106, 345 (1957).

Table I

Distribution of Events

A. K⁻ + p interactions

Final State		In flight		At rest	Subtotal	Total
I	$K^- + p$ (elastic scatter)	6		-	6	6
II	$\overline{K}^0 + n \quad K_1^0 \to \begin{cases} \pi^+ + \pi^- \\ \pi^0 + \pi^0 \end{cases}$	2(?)		1(?)	3	6
			K_ρ(a)		0(c)	
	K_2^0 Decay	none observed (b)			3(c)	
III	$\Sigma^+ + \pi^-, \quad \Sigma^+ \to \begin{cases} \pi^+ + n \\ \pi^0 + p \end{cases}$	3 1		31 27	62	62
IV	$\Sigma^- + \pi^+ \begin{cases} \Sigma^- \to \pi^- + n \\ \Sigma^- \text{ interacts with p} \end{cases}$	10 0		102 9	121	121
V	$\Sigma^0 + \pi^0 \quad \Lambda \to \begin{cases} \pi^- + p \\ \pi^0 + n \end{cases}$ $\downarrow \Lambda + \gamma$	(?)	K_ρ(a)	(?)	44±6 22±5(c)	66±9
VI	$\Lambda + \pi^0 \quad \Lambda \to \begin{cases} \pi^- + p \\ \pi^0 + n \end{cases}$	(?)	K_ρ(a)	(?)	10∓6 5∓3(c)	15±9
VII	$\Lambda + \pi^0 + \pi^0, \quad \Lambda \to \begin{cases} \pi^- + p \\ \pi^0 + n \end{cases}$	(?)	K_ρ(a)	(?)	1(?) 0 (c)	1
VIII	$\Lambda + \pi^+ + \pi^-$	0		0	0	0
				Total	247	277

B. $\Sigma^- + p$ interactions

Final state		In flight	At rest	Total
			Circumstances of Σ^- interaction	
IX	$\Sigma^- + p$ (elastic scatter)	0	--	0
X	$\Sigma^0 + n \qquad \Lambda \to \begin{cases} p + \pi^- \\ n + \pi^0 \end{cases}$ $+ n$	0 Σ^-_ρ (a)	3	3
XI	$\Lambda + n \qquad \Lambda \to \begin{cases} p + \pi^- \\ n + \pi^0 \end{cases}$	0 Σ^-_ρ (a)	4	4
	Σ^-_ρ events (a)	1	2	3
Total		1	9	10

(?) Indicates assignment of occurrence in flight or at rest is uncertain.

(a) A "K_ρ" is a K disappearing in the chamber, yielding no visible interaction or decay.
"Σ_ρ" are defined analogously.

(b) Since the θ_2^0 mean life is known to be $> 3 \times 10^{-8}$ sec, less than 3% would decay in the chamber.

(c) Inferred from other experiments. (See text and Ref. 2.)

III.   Hyperon Lifetimes

Additional events have improved the accuracy of measurement of hyperon mean lives.

Not all the hyperons decayed in the chamber; some Σ^- interacted with protons and some Λ escaped.   Under such conditions the mean life τ is given by

$$\frac{1}{\tau} = \frac{n_d \pm \sqrt{n_d}}{T} , \tag{1}$$

when n_d is the number of hyperons that decay, but T is the total time of flight of all hyperons observed, including those that did not decay, i.e., $T = T_{decay} + T_{escape} + T_{interact}$. For Λ's, T_{escape} cannot be measured directly but can be calculated from the probability of escape of the observed Λ's that do decay. (For our chamber size and momentum spectrum we find $T_{escape} = 0.05\ T_{decay}$.) The mean lives are

$$\Sigma^+ = 0.7 \pm 0.1 \times 10^{-10} \text{ sec,}$$

$$\Sigma^- = 1.6 \pm 0.2 \times 10^{-10} \text{ sec,}$$

$$\Lambda = 2.95 \pm 0.4 \times 10^{-10} \text{ sec.}$$

The errors are standard deviations; they include the statistical uncertainty given by Eq. (1) and estimated experimental uncertainty.   A new value for the density of liquid hydrogen (now measured[4] as $\rho = 0.0586 \pm 0.0006$ g/cm^3) at the time of bubble formation is used in the computation of the mean life of the charged hyperons. Decay curves for the three hyperons are shown in Figs. 1, 2, and 3.   Again, no evidence is found for the existence of two life-times for each hyperon, as would be expected on the basis of the parity-doublet hypothesis.

IV.   Angular Distribution of Hyperon Decay Products

The decays of hyperons produced by the capture of K^- from atomic orbits comprise all but 14 of our decays.   The angular distribution of these decay products is of interest both because any anisotropy would indicate that the hyperon spin is $> 1/2$ and because a fore-aft asymmetry would confirm the existence of parity doublets.   In Ref. 1 the angular distribution of decay products of Σ^- and Σ^+ had only an 8.2% chance of being consistent with isotropy.   Our more recent data have tended to wash out the anisotropy,

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[4]G. Clark and W. Diehl, Range-Energy Relation for Liquid Hydrogen Bubble Chambers, UCRL-3789, May 1957.
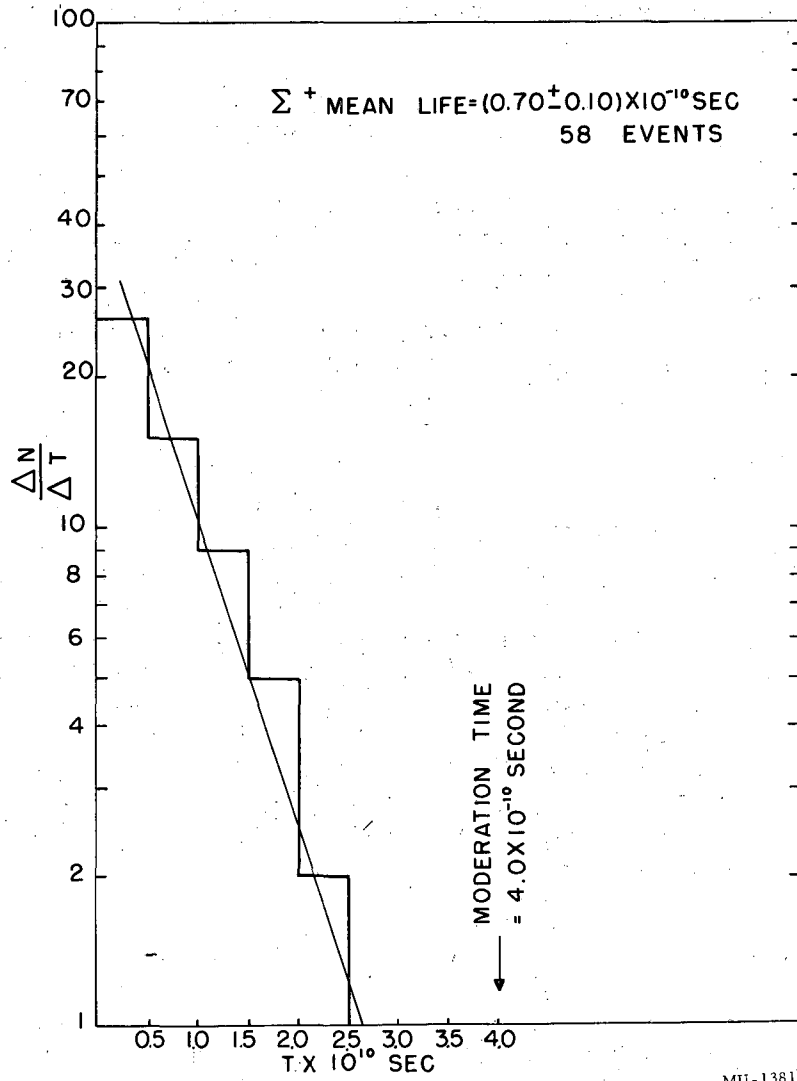
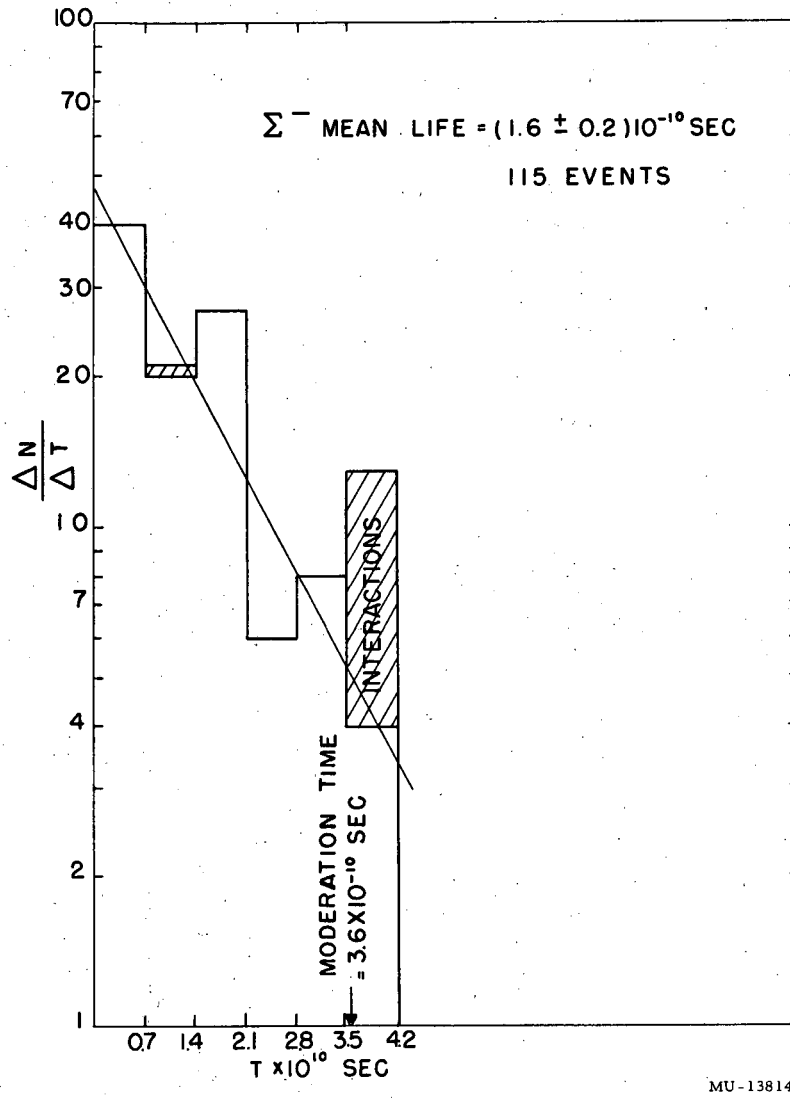Fig. 1. Distribution in time of flight for the Σ^+ decays.

Fig. 2. Distribution in time of flight for the Σ^- decays. The
shaded areas represent Σ^- that interact rather than
decay. The mean life is $\tau = T/n_d$, when T = total ob-
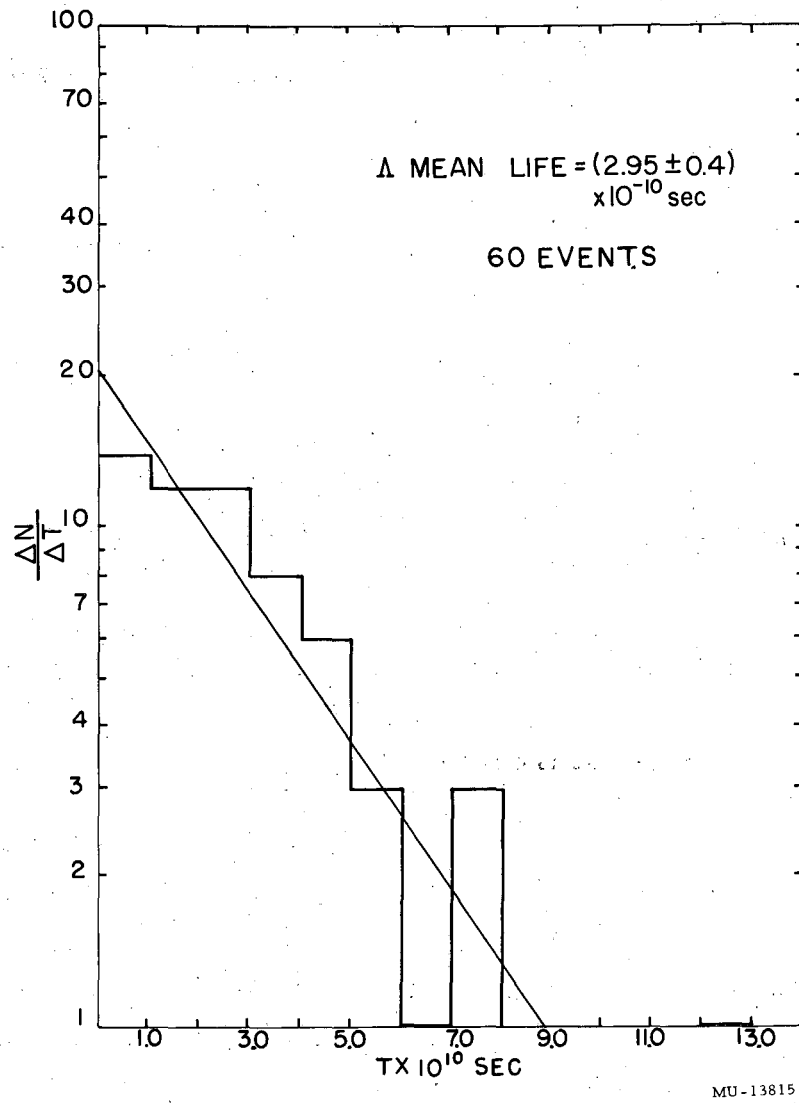served time of flight, n_d = number of observed decays.

Fig. 3. Distribution in time of flight for Λ decays.

although "polar" decays (i.e., $|\cos\theta| \geq 1/2$, θ = c.m. angle between directions of π andΛor Σ) are still slightly favored. A plot of the folded distribution for Λ, Σ^+, and Σ^- is given in Fig. 4. For an isotropic distribution we expect

$$\frac{n_{polar}}{n_{total}} = 0.500;$$

we find for $\Sigma^+ + \Sigma^-$ $n_{polar}/n_{total} = 88/159 = 0.55 \pm 0.04$. A compilation of all available emulsion data on Σ made for the 1957 Rochester Conference by G. Snow[5] shows

$$n_{polar}/n_{total} = 237/432 = 0.55 \pm 0.024;$$

the combined hydrogen and emulsion data give

$$n_{polar}/n_{total} = 324/591 = 0.55 \pm 0.021.$$

The probabilities of these three ratios' being consistent with isotropy are respectively 27%, 2.1%, and 1.7%. This is rather weak evidence for hyperon spins $> 1/2$.

No statistically significant fore-aft asymmetry has been observed.

V. Λ Energy Distribution

The Λ produced by K^- capture at rest (reaction VI of Table I) have a unique energy of 28.7 Mev, whereas those Λ^0 which are decay products of Σ^0 produced from K^- capture at rest have a spectrum from 5 to 27 Mev. The energy spectrum should be symmetrical about the mid energy if parity is conserved in the strong and electromagnetic interactions. By comparing the energy distribution shown in Fig. 5 with the kinematic limits we can say that 44 ± 6 events arose from Σ^0 and that 10 ∓ 6 were Λ produced directly. This differs somewhat from the ratio

$$\frac{\Sigma^0}{\Lambda} = \frac{14\pm2}{7\mp2} \qquad \text{reported in Ref. 1.}$$

The spectrum is slightly higher (by about 3%) at the upper energy end, because of high-energy Λ preferentially escaping from the chamber. Except for the lifetime correction discussed in Section III, the curves and tables are not adjusted for this effect.

For Σ^0 and Λ produced from Σ^- capture the kinematic division is much cleaner, so that the identification as a Σ^0 or Λ is free of uncertainty. From the kinetic energies of three Λ from Σ^0 we obtain a likelihood function for the $\Sigma^- - \Sigma^0$ mass difference shown by the dashed line in Fig. 6. The figure also shows the data of Plano et al.[6] (dotted curve) and a combined curve (solid curve) for the $\Sigma^- - \Sigma^0$ mass difference of 7.6^{+3}_{-2} Mev. We have measured the mass of Σ^- by measuring the range of stopped Σ^- produced from K^- capture. Our value of 1198.5 ± 1.4 Mev is not in disagreement with the more accurate emulsion value of 1196.5 ± 0.5 Mev.

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[5] Proceedings of the Seventh Rochester Conference (to be published, 1957).

[6] Private communication from M. Schwartz and R. Plano (Brookhaven Nat'l Lab.)
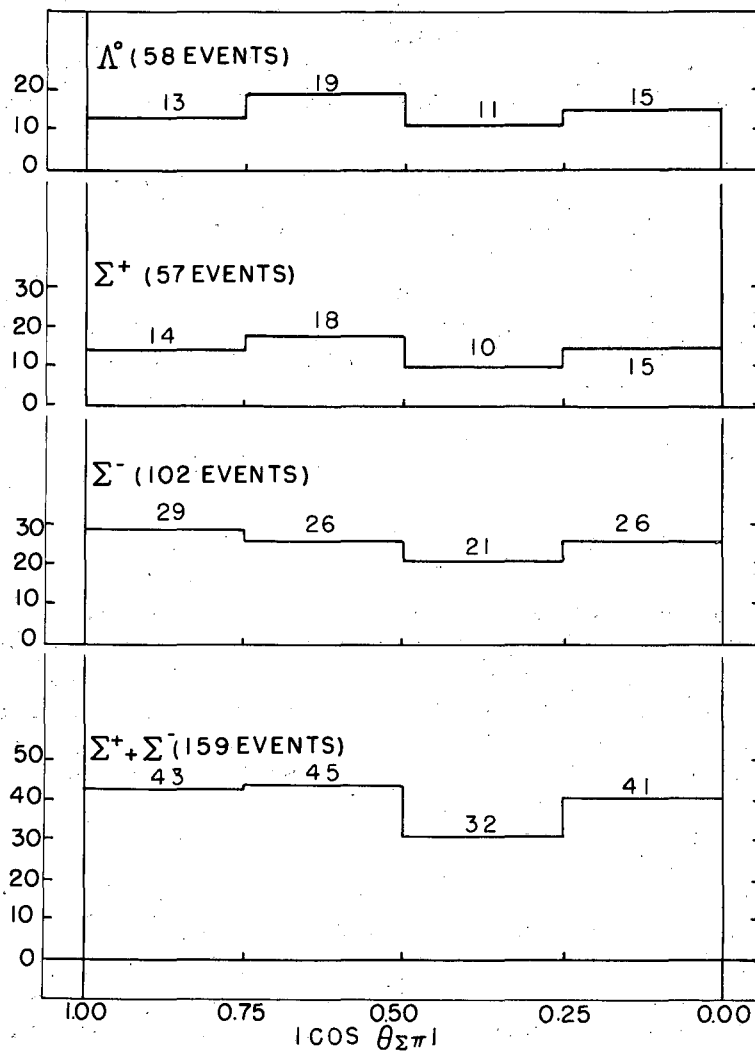
Fig. 4. Angular distribution of the decay products of hyperon decay with respect to direction of motion of hyperon. The results have been folded about 90° and plotted against the cosine of the center-of-mass angle.
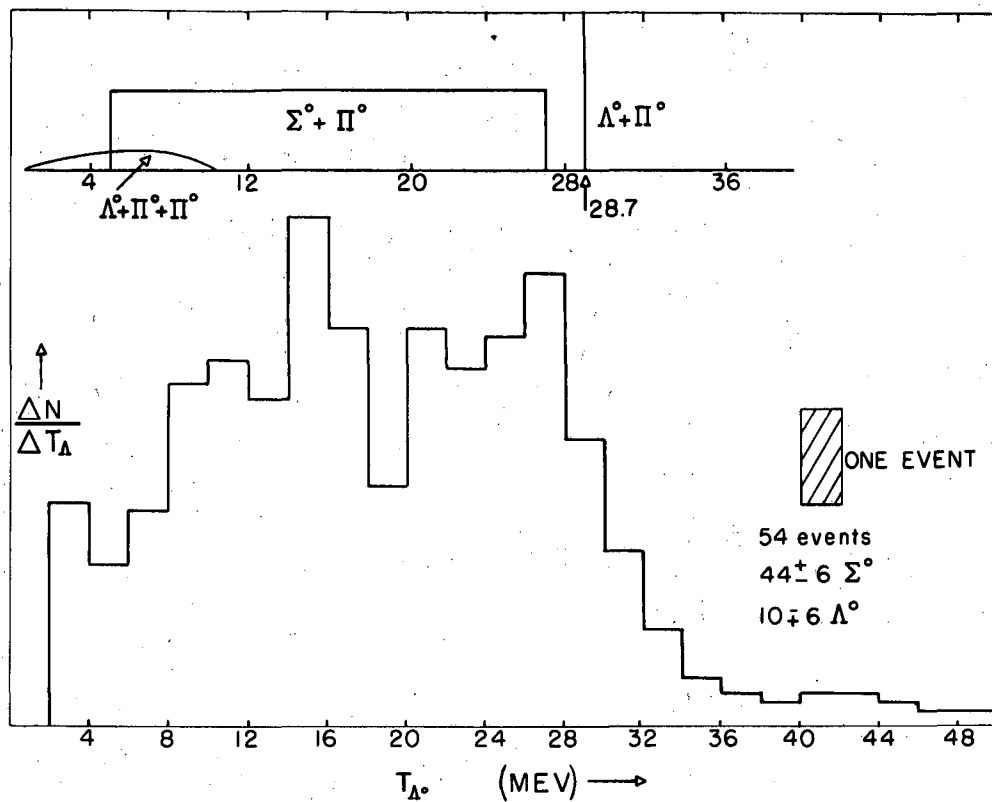
Fig. 5. Energy spectrum of Λ's from K⁻ capture by protons.
The spectrum of decaying Λ's from Σ⁰'s should be
symmetric about the average energy.   The histogram
is constructed by assigning to each Λ a rectangle of
unit area (indicated by the shaded rectangle) whose
width shows the energy uncertainty of that Λ.
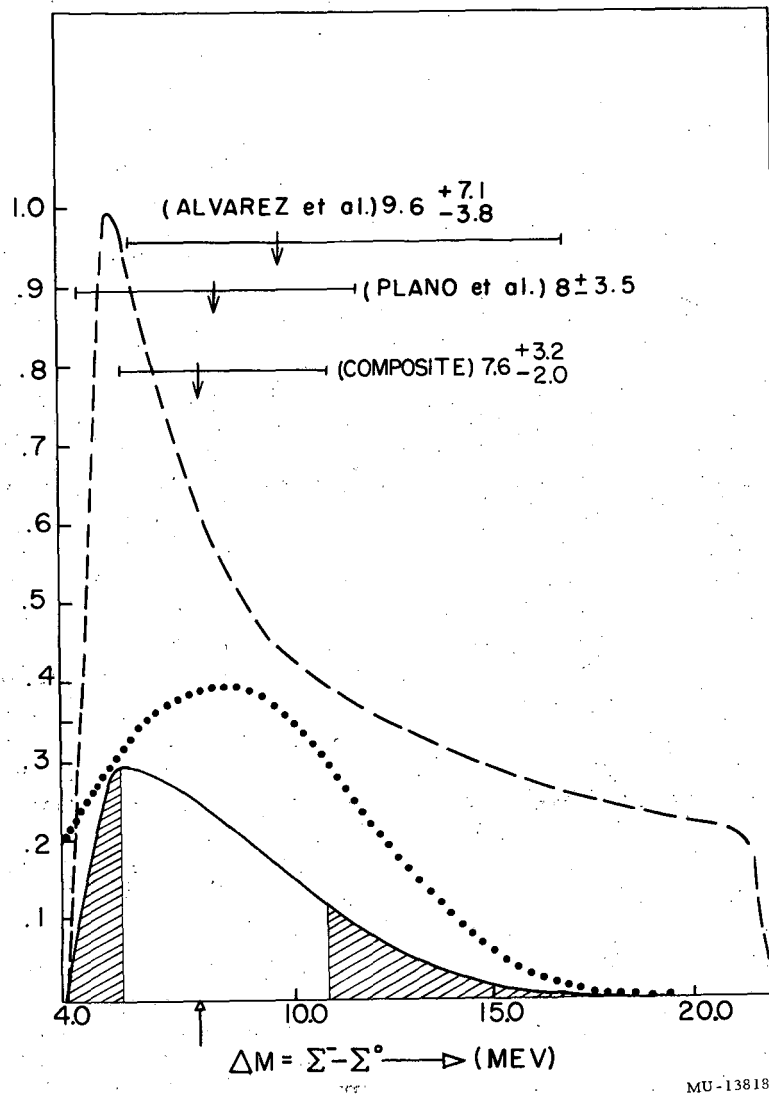
Fig. 6. The dashed curve is the relative-likelihood function
for the $\Sigma^- - \Sigma^0$ mass difference based upon three Σ^0's
coming from Σ^- absorption. The dotted curve is the
mass difference from Plano et al.[6] The product of the
two functions is shown by the solid curve. The shaded
"tails" of the combined result represent 32% of the
whole area, just as the area beyond one standard
deviation is 32% of the area under a gaussian distribution.

VI. Phenomenology of Σ Production and Decay

The phenomenological analysis into relative amplitude and phases of I-spin matrix elements of Σ production from K^- capture, contained in Ref. 1, is based upon the assumption of capture from a single angular momentum state. If, as is likely, the capture takes place from several angular momentum states, then the analysis is more difficult and the production ratios of $\Sigma^{\pm}$, Σ^0 are inadequate to establish the contributions from various I-spin and angular-momentum channels.

In Ref. 1 we showed that if parity is conserved in Σ decay, then the experimental ratio of the three rates $R(\Sigma^-|~n\pi^-)$, $R(\Sigma^+|~n\pi^+)$, $R(\Sigma^+|~p\pi^0)$ is incompatible with the proposed selection rule $|\Delta I| = 1/2$. If parity is not conserved the $|\Delta I| = 1/2$ rule imposes extremely loose restrictions on the three rates, which are indeed satisfied.

VII. K^- Interactions in Flight

Interactions of K^- in flight are of interest for several reasons. The energy dependence and angular distribution of the cross sections indicate the magnitude of the contributions from various partial waves. Furthermore, for those collisions producing hyperons, the hyperons may be polarized normal to the plane of interaction. Then if the hyperon decay violates parity conservation an asymmetry of the decay products with respect to the direction of polarization will in general result.

Table I contains a column listing the number of K^- - p reactions that take place in flight. In-flight production of charged hyperons is easily established, whereas for neutral hyperons it is in general difficult. This is because the noncolinearity of two charged outgoing particles shows the event to be in-flight $\Sigma^{\pm}$ production, but for neutral hyperons only when the $\wedge$ energy exceeds 28.7 Mev by more than the uncertainty in the energy measurements can the event be certified in-flight. Likewise the charge-exchange scattering of K^- in flight may be confused with the same reaction taking place at rest as long as the mass uncertainty of the $\overline{K}^0$ remains large. No further K_1^0 have been observed since Ref. 1, and we tentatively identify at least two of the K_1^0 as arising from K^- interactions in flight.

Figure 7 shows the cross sections observed for charged-hyperon production (black circles) and for K^- elastic scattering (open circles) as a function of K^- laboratory momentum. Cross sections below 50 Mev/c (2.5 Mev) are not given because of the possibility of systemic loss of low-energy events. Those points in Fig. 7 for which no errors are given represent fewer than two events. There seems to be no statistically significant evidence for an energy dependence to the cross sections, therefore we average over 50 to 200 Mev/c to obtain

$$\sigma_{\Sigma^+ + \Sigma^-} = 92 \pm 31 \text{ mb}$$

and

$$\sigma_{K^- \text{ elastic}} = 43 \pm 22 \text{ mb.}$$
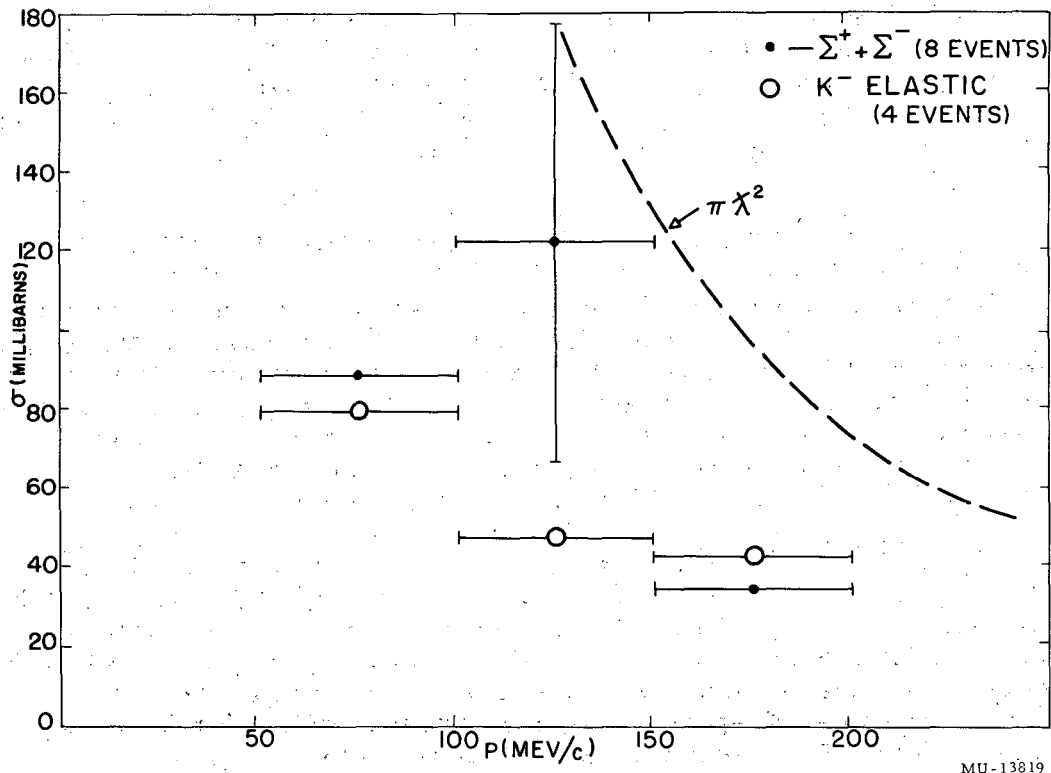
Fig. 7. Cross section for Σ^- interaction as a function of
     laboratory momentum. The cross sections for $\Sigma^+ + \Sigma^-$
     production are indicated by the black circles and for
     elastic scattering by the open circles. Those points
     for which no errors are given represent fewer than
     two events.

The latter is in agreement with a recent emulsion compilation,[7] while the former is clearly not in agreement. Over a momentum interval 100 Mev/c to 175 Mev/c emulsions yield a cross section of 18±10 mb for $\Sigma^+ + \Sigma^-$ production on free protons.

The quantity $\pi \lambda^2$ is also shown on Fig. 7. This represents the maximum S-wave reaction cross section (production of $\Sigma^{\pm, 0}$, Λ, and $\overline{K}^0$). If the reaction cross section were this large then the elastic-scattering cross section would also be $\pi \lambda^2$. The experimental data clearly fall within the limits of these restrictions. Since the hyperon production reaction is quite exothermic, the outgoing momentum does not vary appreciably over the limited momentum region considered here, so that the hyperon-production cross section should have a dependence on the incoming momentum shown in the second column of Table II. The third column of Table II gives momentum dependence for elastic scattering.

Table II

Momentum (p) dependence of reaction and elastic cross sections

State	Reaction cross section	Elastic cross section
S	$\dfrac{1}{p}$	Constant
P	p	p^4

Additional data should permit us to determine the amount of S and P wave through this momentum dependence. One should note that, knowing the strength of the P-wave interaction, one can then predict the ratio of K^-p capture from the Bohr orbit P state to that from the S state. If at 150 Mev/c the total K^--p cross section exceeds about 5 mb, then P-state capture from the Bohr orbit should predominate.

The angular distributions both for elastic scattering and for $\Sigma^+ + \Sigma^-$ production show no statistically significant deviations from isotropy. This is in agreement with the emulsion compilation.

In order for the hyperons to be polarized in K^- interactions, there must be interference between several incoming channels: i.e., one must go to sufficiently high momenta for P waves to contribute to the reaction. In computing asymmetries we have therefore discarded those events occurring at a laboratory momentum of less than 100 Mev/c. Assuming that the radius of interaction is $r \approx \lambda_\pi$, this exclusion is equivalent to including only those events with $kr > 1/2$.

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[7] A compilation of all available emulsion data by M. Ceccarelli for the Seventh Annual Rochester Conference on High-Energy Physics (to be published, 1957).

The differential cross section and polarization for a spin-1/2 particle as a function of the center-of-mass angle can be written as

$$\sigma(\theta) = \left| a + b \cos \theta \right|^2 + \left| c \right|^2 \sin^2 \theta, \tag{2}$$

$$\sigma(\theta) P(\theta) = 2 \text{Im} \left[(a^* + b^* \cos \theta) c \sin \theta \right]. \tag{3}$$

The S-P interference term produces a polarization proportional to $\sin \theta$, while the polarization from P-P interference goes as $\sin \theta \cos \theta$. At low momenta one would expect the S-P interference to dominate so that $p \approx p_0 \sin \theta$.

If parity is not conserved in the decay process then the two possible orbital angular-momentum states of the decay products interfere so as to yield an asymmetric angular distribution about the polarization direction. The decay angular distribution can be written as

$$I(\phi) = 1 + \alpha P \cos \phi$$

$$= 1 + e \cos \phi.$$

Under the above assumption of predominant S-P interference, this can be written as

$$I(\phi) = 1 + e_0 \sin \theta \cos \phi, \tag{4}$$

where α is the asymmetry coefficient of the hyperon decay and ϕ is the angle between the normal to the production plane $(\underline{n} = \underline{p}_k \times \underline{p})$ and the direction of the decay pion; α, P, and e must lie between -1 and +1. Defining "up" to be in the direction of the normal, we find for Σ^- decays seven pions going down and two up, while for Σ^+ decays we find three pions going down and none up. The number of events is obviously too small to permit any firm conclusion. However, a likelihood-function calculation for both the Σ^- and the Σ^+ distribution indicates that in each case e_0 has three times the likelihood of being -1 (where the likelihood function is maximum) than of being zero.

VII. Acknowledgments