Leptonic Decays of Charged Σ Hyperons and the ΔS = ΔQ Selection Rule*

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Leptonic decays of Σ^+ and Σ^- hyperons have been searched for in a sample of about 500 000 $\Sigma^\pm$ decays. This report is based on the observation of 130 $\Sigma^\pm$ leptonic decays of various types. The principal results are: (a) no evidence for $\Delta S=-\Delta Q$ Σ^+ leptonic decays, with the upper limit (with 90% confidence) for the ratio of $\Delta Q=-\Delta S$ to $\Delta Q=+\Delta S$ transitions equal to 0.12; (b) $(\Sigma^-\to\Lambda+e^-+\nu)/(\Sigma^-\to n+\pi^-)=(0.75\pm0.28)\times10^{-4}$; (c) $(\Sigma^-\to n+e^-+\nu)/(\Sigma^-\to n+\pi^-)=1.4\pm0.3\times10^{-3}$; and (d) $(\Sigma^-\to n+\mu^-+\nu)/(\Sigma^-\to n+\pi^-)=0.66\pm0.14\times10^{-3}$. The data are consistent with $(\mu\nu)$, $(e\nu)$ universality for $\Sigma^-\to n+l^-+\nu$ decays and with the $\Delta I=1$ rule for $\Sigma^\pm\to\Lambda+e^\pm+\nu$ decays. A comparison is made between experiment and Cabibbo's theory of weak interactions. Acceptable agreement is found for Cabibbo's angle θ close to 0.26 and with the axial-vector (F/D) ratio approximately equal to $\frac{1}{2}$ or 2.

I. INTRODUCTION

THE concepts of a universal Fermi interaction[1] (UFI), with $(V\text{-}A)$ currents, whose vector part is conserved[2] (CVC), has had considerable success in describing the weak interactions of nonstrange particles.[3] The simple extension by Feynman and Gell-Mann[1] of these ideas to strangeness-changing decays leads to predictions of leptonic decay rates of Λ and Σ^- hyperons that are an order of magnitude larger than the experimental data indicate.[4]

Besides the need for much better statistics on $\Sigma^-\to n$ leptonic decays, two problems vital to an understanding of the weak four-fermion interaction exist: (1) To what extent does the selection rule, $\Delta S=+\Delta Q$, hold in strangeness changing hyperon decays? (2) Do the $\Delta S=0$ leptonic decays of Σ hyperons have a rate comparable to that predicted by UFI, or are they also suppressed by an order of magnitude? In this paper we provide partial answers to these questions.

We report here on a search for leptonic decays of the following six types:

$$\left.\begin{array}{l}\Sigma^-\to n+e^-+\bar\nu_e \quad (1a)\\ \Sigma^-\to n+\mu^-+\bar\nu_\mu \quad (1b)\end{array}\right\}\quad \Delta S/\Delta Q=+1,$$

$$\left.\begin{array}{l}\Sigma^-\to \Lambda+e^-+\bar\nu_e \quad (1c)\\ \Sigma^+\to \Lambda+e^++\nu_e \quad (1d)\end{array}\right\}\quad \Delta S=0,$$

$$\left.\begin{array}{l}\Sigma^+\to n+e^++\nu_e \quad (1e)\\ \Sigma^+\to n+\mu^++\nu_\mu \quad (1f)\end{array}\right\}\quad \Delta S/\Delta Q=-1,$$

from a sample of $\gtrsim$400 000 $\Sigma^\pm$ hyperons. When this experiment was begun, there were two or three examples of $\Sigma^-\to n+e^-+\nu$,[4] one example of $\Sigma^-\to\Lambda+e^-+\nu$ [5] and one reported example of an event that had as its most likely interpretation the decay $\Sigma^+\to n+\mu^++\nu$.[6] This report is based on the observation of 130 $\Sigma^\pm$ leptonic decays. The Σ hyperons were produced by K^- mesons, from the CERN proton synchrotron, coming to rest in the Saclay 81-cm hydrogen bubble chamber.

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[1] R. P. Feynman and M. Gell-Mann, Phys. Rev. **109**, 193 (1958); R. Marshak and G. Sudarshan, *ibid.* **109**, 1860 (1958).
[2] Gershtein and Zeldovitch, Zh. Eksperim. i Teor. Fiz. **35**, 821 (1958) [English transl.: Soviet Phys.—JETP **8**, 570 (1959)]; and Feynman and Gell-Mann, Ref. 1.
[3] See, for example, the review article of G. Feinberg and L. Lederman, Ann. Rev. Nucl. Sci. **13**, 431 (1963); and Y. K. Lee, L. W. Mo, and C. S. Wu, Phys. Rev. Letters **10**, 253 (1963).
[4] W. E. Humphrey, J. Kirz, A. H. Rosenfeld, and J. Leitner, *Proceedings of the International High Energy Physics Conference*, edited by J. Prentki (CERN, Geneva, 1962), p. 442.
[5] L. Grimellini, T. Kikuchi, L. Lendinara, L. Monari, and M. M. Block, *Proceedings of the International High Energy Physics Conference*, edited by J. Prentki (CERN, Geneva, 1962), p. 457.
[6] A. Barbara-Galtieri, W. H. Barkas, H. H. Heckman, J. W. Patrick, and F. H. Smith, Phys. Rev. Letters **9**, 26 (1962).

TABLE I. Beam parameters and particle fluxes in 800 MeV/c separated K^- beam at CERN proton synchrotron.

(a) Beam parameters

Parameter	1st Stage	2nd Stage
Length	13.3 m	9.6 m (22.9 m over-all)
Solid angle	0.6×10^{-3} sr	0.6×10^{-3} sr
Separator gap	10 cm	10 cm
Separator plate length	3 m	3 m
Separator voltage	460 kV	460 kV
Horizontal magnification	4.9	0.19 (0.9 over-all)
Vertical magnification	0.54	1.33 (0.72 over-all)
K-π separation	8 mm	9 mm
Momentum dispersion[a]	10 cm/1%($\Delta p/p$)	0.4 cm/1%($\Delta p/p$)

(b) Particle fluxes

Particle	Flux at 23 m from target, per 10^{11} circulating protons
π^+	0.51×10^5
K^+	81
K^-	30
$\bar{p}$	7
p	0.36×10^5

[a] The momentum band accepted was $\Delta p=15$ MeV/c.

Preliminary reports of this experiment were presented at the Brookhaven Conference on Weak Interactions (September 1963) and the Sienna Conference on Elementary Particles (October 1963). An experiment by the Columbia-Rutgers-Princeton[7] group, similar to this one has also been reported at these two conferences.

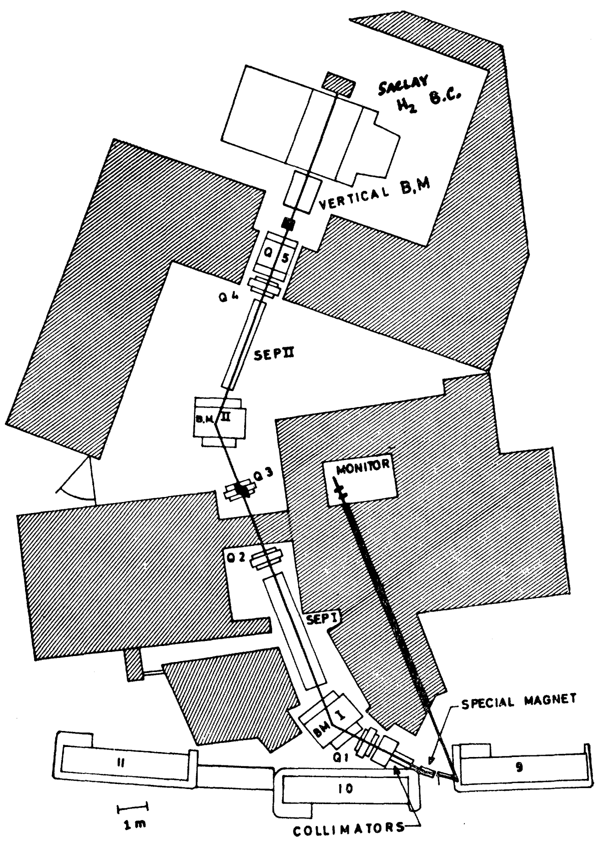


FIG. 1. Physical layout of the 800 MeV/c separated K^- beam and the Saclay 81-cm hydrogen bubble chamber at the CERN proton synchroton accelerator.

In Sec. II, the experimental method is described. Sections III and IV present the experimental data on $\Sigma^\pm \to \Lambda + e^\pm + \nu$ decays and $\Sigma^- \to n + (e^-,\mu^-) + \nu$ decays, respectively. Section V contains our data on $\Sigma^+ \to e^+$ +neutrals and $\Sigma^+ \to \mu^+$ or π^++neutrals, and the evidence against $\Delta S = -\Delta Q$ transitions. In Sec. VI the conclusions are summarized and discussed.

II. EXPERIMENTAL METHOD

Negative K mesons coming to rest in liquid hydrogen produce hyperons via the reactions

$$K^- + p \to \Sigma^- + \pi^+ \quad (0.45) \qquad (2a)$$

$$\to \Sigma^+ + \pi^- \quad (0.21) \qquad (2b)$$

$$\to \Sigma^0 + \pi^0 \quad (0.28) \qquad (2c)$$

$$\to \Lambda + \pi^0 \quad (0.06)\,. \qquad (2d)$$

The numbers to the right of each reaction denote the fractional yield as determined by Humphrey and Ross.[8] These reactions are seen to yield a copious supply of $\Sigma^\pm$ hyperons in clear, unambiguous topological configurations.

A. Beam

An 800 MeV/c separated K meson beam[9] was designed and built at the CERN proton synchrotron. Before entering the Saclay 81-cm hydrogen bubble chamber, the K^- mesons were slowed down to a mo-

[7] U. Nauenberg, P. Schmidt, J. Steinberger, S. Marateck, R. Plano, H. Blumenfeld, and L. Seidlitz, Phys. Rev. Letters **12**, 679 (1964).

[8] W. E. Humphrey and R. R. Ross, Phys. Rev. **127**, 1305 (1962).

[9] B. Aubert, H. Courant, H. Filthuth, A. Segar, and W. Willis, Nucl. Inst. Methods **20**, 51 (1963).

mentum of 250 MeV/c by placing 20 cm of copper in front of the chamber. The beam layout and the chamber are shown in Fig. 1. One to two K^- mesons per 10^{10} circulating protons in the proton synchrotron came to rest inside the visible region of the chamber. Table I gives the characteristic parameters of the beam. During the exposure about 3×10^5 photographs were obtained containing about 10^6 K^- meson reactions at rest.

B. Method of Scanning and Measuring

The problem of distinguishing the rare Σ leptonic decays from the overwhelming number of $\Sigma^\pm\to n+\pi^\pm$ decays is illustrated in Fig. 2. It shows the theoretically expected electron momentum spectra from the decays $\Sigma^-\to(\Lambda \text{ or } n)+e^-+\nu$ and the π^- meson momentum distribution from $\Sigma^-\to n+\pi^-$ decay, in the laboratory system for a Σ^- of momentum 150 MeV/c (the mean momentum of Σ^- hyperons along their flight path). The Σ^+ hyperons present a similar situation shifted slightly by the small (Σ^+,Σ^-) mass difference.

To eliminate the bulk of $\Sigma^\pm\to\pi^\pm+n$ decays rapidly, we adopted the following procedure: The film was scanned twice in two views, with the third view available, for at-rest $K^-+p\to\Sigma^\pm+\pi^\mp$ events (colinear $\Sigma^\pm$ and $\pi^\mp$ at production). The decay secondary from the Σ decay was measured with curvature templates, and its dip angle was estimated. All events with curvature corresponding to a laboratory momentum $\lesssim120$ MeV/c and a dip angle $\lesssim60°$ were measured with standard digitized measuring machines. The dip criterion was not applied if the decay secondary stopped in the chamber or if it was a low-energy spiraling electron. A careful search was made for Λ's associated with $\Sigma^\pm\to e^\pm$ decays. In addition, decay secondaries with momenta >120 MeV/c were recorded if their length, curvature, and bubble density allowed them to be identified as electrons rather than pions. This method of scanning yields a high efficiency for finding secondaries of momenta $\lesssim80$ MeV/c and a rapidly decreasing efficiency as the momentum increases.

The reconstruction and fitting program gave data on the secondary assuming in turn that it was a pion, a muon or an electron. The kinematic fitting was carried out in two parts. First, the (K^-,p) production vertex was tested and retained in our sample if this vertex was consistent with a zero energy K^- reaction. Secondly, the fitted $\Sigma^\pm$ from production was combined with the measurements of the decay track, assuming it to be a $\pi^\pm$ to test the $\Sigma^\pm\to\pi^\pm+n$ hypothesis. Any event which fit the π decay with confidence greater than 0.01% was rejected as a possible leptonic decay. In addition, it was required that the Σ^+ and Σ^- have a length >1 mm and that the Σ^- have a residual range at the point of decay >1 mm.

The remaining candidates were then re-examined by physicists. From an estimate of the bubble density of each secondary track, it was always possible to distinguish electrons from pions or muons, but not to distinguish between the latter two unless the secondary came to rest. Special attention was given to the possible muons to eliminate the $\pi-\mu$ decay background from the chain $\Sigma^\pm\to\pi^\pm+n$, $\pi^\pm\to\mu^\pm+\nu$ in flight. Events were eliminated if the secondary track had a visible kink. Even if no kink was seen, if its momentum and angle in the laboratory with respect to the sigma directions was such that it could have arisen kinematically from the $\Sigma^\pm\to\pi^\pm\to\mu^\pm$ chain, the events were discarded from the sample discussed below.

C. Monitor

The number of $\Sigma^\pm\to n\pi^\pm$ decays needed to determine the branching ratios $R=\Sigma^\pm\to\text{leptons}/\Sigma^\pm\to n\pi^\pm$ is obtained as follows: The number of $\Sigma^0\to\Lambda e^+e^-$ events from (K^-,p) at-rest reactions in this film is known from a previous experiment, determining the relative $\Sigma^0-\Lambda$ parity.[10] There are 653 measured and processed $\Sigma^0\to\Lambda e^+e^-$ events in 270 110 pictures. The actual number of events of this type from stopping K^--meson interactions is obtained by multiplying the measured number of events with a correction factor of 1.30. This correction takes into account the scanning efficiency $(97\pm1\%)$ which was determined from a double scanning; the decay probability of $\Lambda\to p+\pi^-$ inside the fiducial volume; the loss of Λe^+e^- events with low-energy electrons or positrons and the fraction of unmeasurable events. With the branching ratios $(\Sigma^0\to\Lambda+\gamma)/$

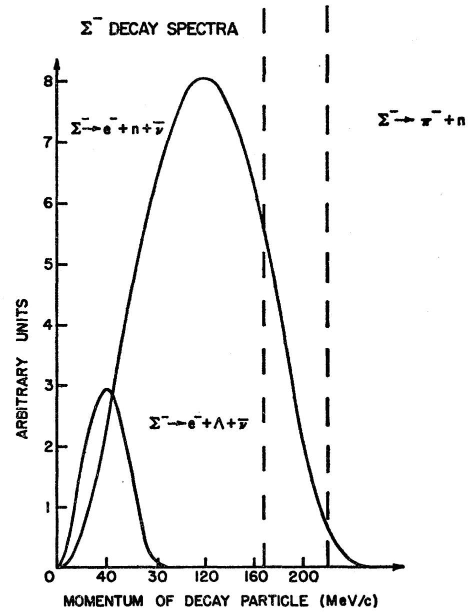


FIG. 2. Theoretical laboratory momentum distributions of electrons and pions from the decays $\Sigma^-\to n+e^-+\nu$, $\Sigma^-\to\Lambda+e^-+\nu$ and $\Sigma^-\to n+\pi^-$ for $p_{\Sigma^-}=150$ MeV/c.

[10] H. Courant, H. Filthuth, P. Franzini, R. G. Glasser *et al.*, Phys. Rev. Letters **10**, 409 (1963).

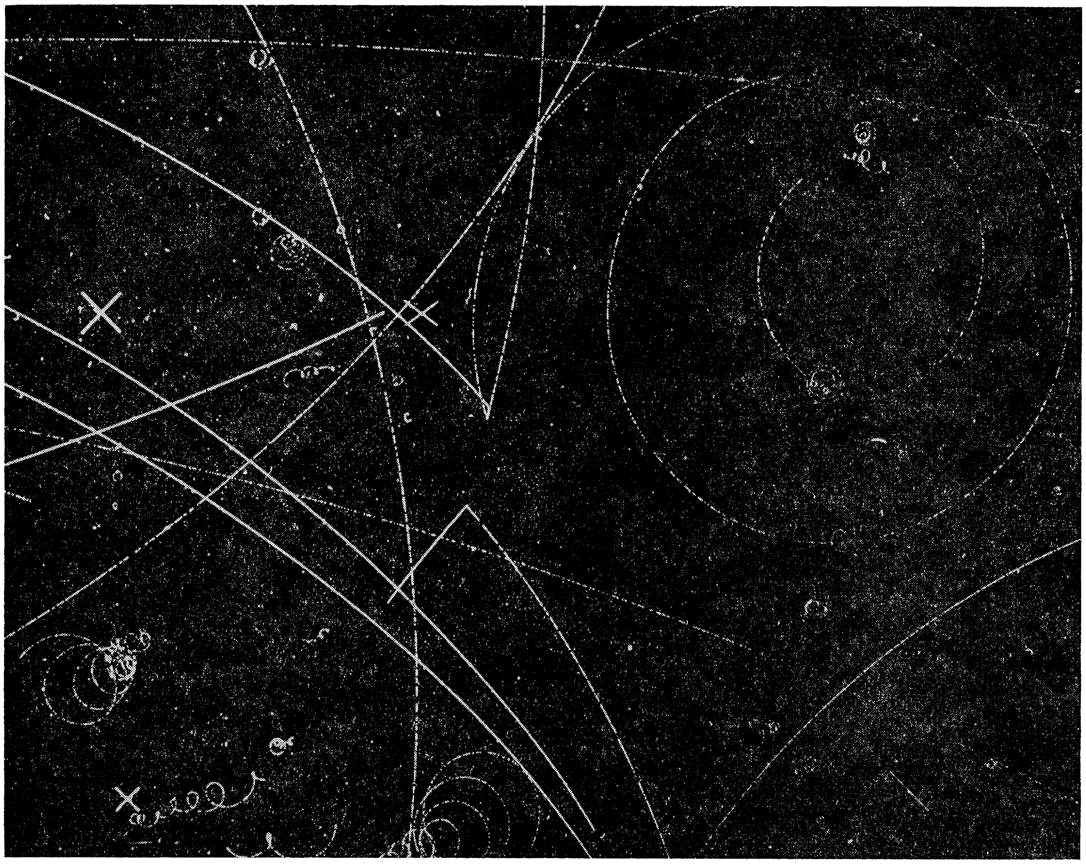


FIG. 3. Picture of a $\Delta S=0$ leptonic decay of the type $\Sigma^- \to \Lambda+e^-+\nu$, $\Lambda \to p+\pi^-$. The Σ^- hyperon is produced by a K^- at rest via the reaction $K^-+p \to \Sigma^-+\pi^+$.

$(\Sigma^0 \to \Lambda e^+e^-)=183$ [10] and (all Λ)/$(\Lambda \to p\pi^-)=1.56$,[11] one deduces that the number of reactions of the type (K^-,p) at rest $\to \Sigma^0\pi^0$ in these 270 110 pictures is 241 500 with an uncertainty of $\pm 5\%$. Using the data of Humphrey and Ross[8] listed in Eq. (2), for the relative production rates of different charge channels from (K^-,p) captures, one obtains the numbers in Table II. These are the basic numbers which will be used in the following computations of leptonic decay rates of the Σ hyperons. Combining the errors (2–5%) in the hyperon production ratios of Eq. (2) with our uncertainty ($\pm 5\%$) in the number of $\Sigma^0\pi^0$ events, one obtains an uncertainty in the number of $\Sigma^\pm \to \pi^\pm+n$ decays of $\pm 7\%$.

TABLE II. Number of $\Sigma\pi$ events from (K^-,p) at rest.

Event type	No. $(\Sigma^0\pi^0)$	No. $(\Sigma^-\pi^+)$	No. $(\Sigma^+\pi^-, \Sigma^+ \to n+\pi^+)$
No. of events in 270 110 pictures	241 500	388 000	90 600
No. per picture	0.894	1.432	0.334

[11] W. H. Barkas and A. H. Rosenfeld, University of California Radiation Laboratory Report UCRL-8030 Rev. (unpublished).

III. $\Delta S=0$ TRANSITIONS: $\Sigma^\pm \to \Lambda+e^\pm+\nu$

In 266 110 photographs, we have observed eleven $\Sigma^- \to \Lambda e^-\nu$ and one $\Sigma^+ \to \Lambda e^+\nu$ event with visible $\Lambda \to p+\pi^-$ decays that come from the $\Sigma^\pm$ decay points. The electrons are identified as such by bubble density and the events all satisfy the kinematic constraints imposed by energy and momentum conservation. An example of such an event is shown in Fig. 3. Table III

TABLE III. List of $\Sigma^- \to \Lambda+e^-\nu$ from (K^-,p) reactions at rest. p_Λ^* and p_e^* are the momenta of the Λ and the e^- in the Σ^- rest frame. $(\hat{p}_\pi^*\cdot\hat{p}_\Lambda^*)$ is the cosine of the angle between the π^- direction in the Λ rest frame and the Λ direction in the Σ^- rest frame.

Frame	Length Σ^- (cm)	p_Λ^* (MeV/c)	p_e^* (MeV/c)	$(\hat{p}_\pi^*\cdot\hat{p}_\Lambda^*)$
1361 334	0.72	39.7± 7.9	57.0±3.0	+0.059
1413 508	0.38	64.2± 1.9	65.3±3.5	−0.219
1578 386	0.56	77.5± 0.3	39.3±2.7	−0.014
1588 986	0.31	44.5±15.5	34.0±2.0	+0.308
1744 878	0.75	66.5± 2.4	29.6±3.1	−0.536
1420 343	0.80	77.4± 1.5	63.4±7.8	+0.152
1489 057	0.55	36.1± 3.0	29.8±0.6	−0.038
1516 815	0.52	78.0± 2.6	23.9±2.2	−0.469
1476 147	0.16	67.2± 4.8	63.0±2.5	+0.554
1769 412	0.92	50.9± 8.1	31.5±1.0	+0.199
1804 109	0.12	60.1± 2.8	52.0±1.4	−0.721

summarizes the pertinent measured quantities for these rare events. The table contains only events that satisfy these three additional criteria:

(1) The $\Sigma^{\pm}$ arises from an at-rest (K^{-},p) reaction.
(2) Length of $\Sigma^{-} \geq 1$ mm.
(3) Length of $\Sigma^{-} \leq 9.5$ mm.

The first condition is necessary in order to allow us to use the number of $\Sigma^{\pm}\pi^{\mp}$ events listed in Table II to determine the branching ratio of these $\Delta S=0$ leptonic decays. The second condition is necessary to make condition (1) meaningful, and also to eliminate background events of type

$$\begin{array}{l} K^{-}+p \to \Sigma^{0}+\pi^{0} \\ \qquad\quad \downarrow \qquad \searrow \\ \quad \Lambda^{0}+\gamma \qquad e^{-}+e^{+}+\gamma \end{array},$$

where the e^{-} or e^{+} has a momentum≈ 180 MeV/c (similar to a π^{-} or π^{+} from the at-rest $K^{-}+p\to\Sigma^{\pm}+\pi^{\mp}$ reaction) and the other electron plus the Λ fits the kinematics of a zero length $\Sigma^{\pm}$ decaying into a $\Lambda+e^{\pm}+\nu$. The third condition is used to eliminate background from the chain $\Sigma^{-}+p\to\Sigma^{0}+n$ (Σ^{-} at rest), $\Sigma^{0}\to e^{-}+e^{+}+\Lambda$, where the e^{+} has too low an energy to be seen or $\Sigma^{0}\to\Lambda+\gamma$, $\gamma+e^{-}\to\gamma+e^{-}$ at a distance less than one or two mm. A calculation predicts that about 1 or 2 such background events should occur from *stopping* Σ^{-} in this experiment. The upper Σ^{-} length criterion (3) eliminates all stopping Σ^{-} (range 10.5 mm) and hence removes this source of background. (In-flight $\Sigma^{-}+p\to\Sigma^{0}+n$ events are lower in frequency by a factor of ~ 100.)

To derive the branching ratios for $\Sigma^{\pm}\to\Lambda+e^{\pm}+\nu$ decays, we have to compute the effective number of $\Sigma^{\pm}\to n+\pi^{\pm}$ decays in our sample. The number of at-rest produced Σ^{-} hyperons has to be reduced by 14.2% for the number that decay in the first mm of path length and by 18.4% for the number of Σ^{-} with residual range at decay or capture of less than 1 mm. We get 256 000 effective $\Sigma^{-}\to n+\pi^{-}$ decays. In an analogous way, correcting for the 24% Σ^{+}'s that decay in the first mm, we get 67 600 $\Sigma^{+}\to n+\pi^{+}$ decays. For the $\Delta S=0$ leptonic decay branching ratios we find

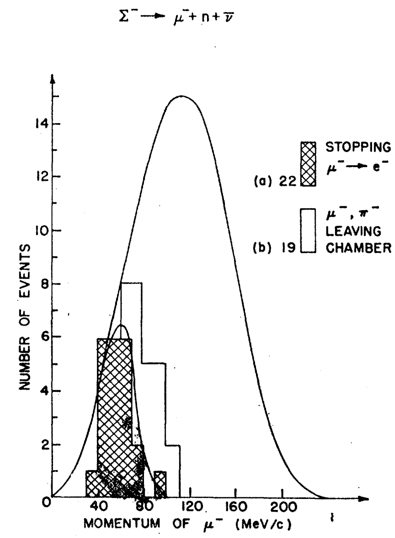


FIG. 5. Observed momentum distribution of μ^{-} (and π^{-}) secondaries from the decays $\Sigma^{-}\to n+\mu^{-}+\nu$ (and $\Sigma^{-}\to n+\pi^{-}+\gamma$) satisfying the criteria described in Sec. II. The crosshatched events are definite μ^{-} that stop and decay in the chamber. The upper smooth curve represents the expected theoretical laboratory momentum spectrum for μ^{-} mesons from $\Sigma^{-}\to n+\mu^{-}+\nu$ ($p_{\Sigma^{-}}=150$ MeV/c). The lower smooth curve gives the results of folding this spectrum with the probability that a μ^{-} stop in the chamber. The fraction of μ^{-} that are expected to stop in the chamber is 15%.

$$R_{\Lambda}{}^{-}\equiv\frac{(\Sigma^{-}\to\Lambda e^{-}\nu)}{(\Sigma^{-}\to n\pi^{-})}=\frac{11\ (1.56)}{(0.9)(256\,000)}=(0.75\pm0.28)\times10^{-4}, \quad (3a)$$

$$R_{\Lambda}{}^{+}\equiv\frac{(\Sigma^{+}\to\Lambda e^{+}\nu)}{(\Sigma^{+}\to n\pi^{+})}=\frac{1\ (1.56)}{(0.9)(67\,600)}\approx0.3\times10^{-4}. \quad (3b)$$

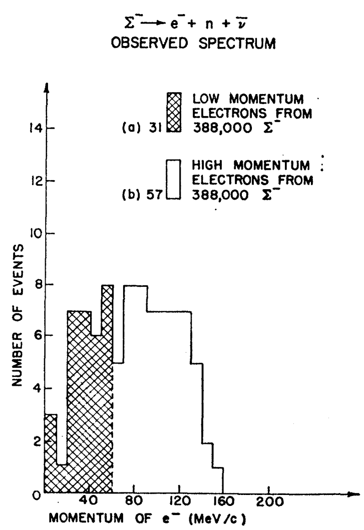
The factor 0.9 is the best estimate of our scanning efficiency, within an uncertainty of ±0.05. The error on $R_{\Lambda}{}^{-}$ includes the statistical error of 11 events and the uncertainties of $\pm5\%$ for scanning efficiency and $\pm7\%$ for the monitor rate.

IV. $\Delta Q=+\Delta S$ TRANSITIONS: $\Sigma^{-}\to n+(e^{-},\mu^{-})+\nu$

A. $\Sigma^{-}\to ne^{-}\nu$

In 266 110 pictures, we have observed 88 $\Sigma^{-}\to e^{-}$ decays satisfying the criteria described in Sec. II; namely, 1.0 mm$\leq l_{\Sigma^{-}}\leq$9.5 mm, dip $e^{-}\leq60°$. Figure 4 shows the observed electron spectrum satisfying these criteria. In addition to the electrons with $p_e<120$ MeV/c found systematically, a few obvious $\Sigma^{-}\to e^{-}$ decays found with $p_e>120$ MeV/c are included. The detection efficiency for electrons is a function of the

FIG. 4. Momentum distribution of observed electrons from the decay $\Sigma^{-}\to n+e^{-}+\nu$, satisfying the criteria described in Sec. II. Only low momentum electrons (crosshatched) are used to determine the branching ratio $(\Sigma^{-}\to n+e^{-}+\nu)/(\text{all }\Sigma^{-})$.



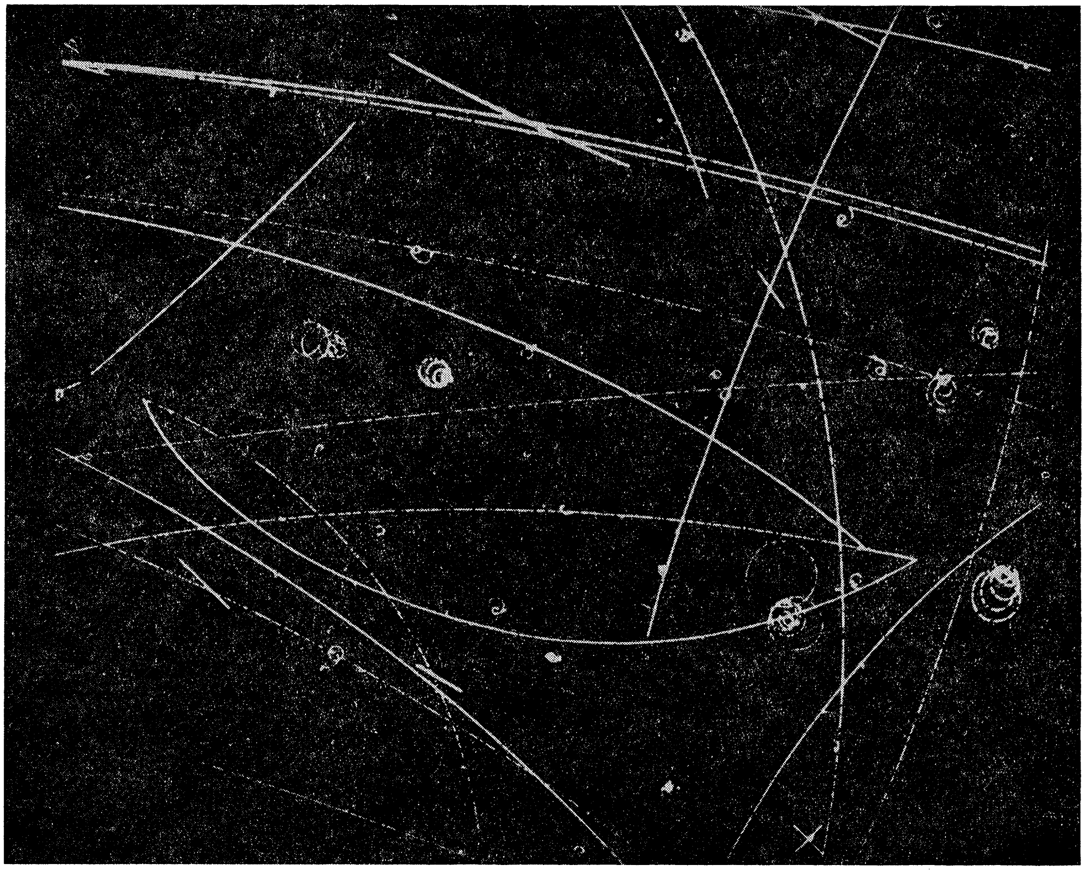


FIG. 6. Picture of a $\Sigma^- \to n+\mu^-+\nu$ decay event, where the μ^- stops in the chamber and decays into an electron and two neutrinos. The Σ^- is produced by a K^- at rest via the reaction $K^-+p\to\Sigma^-+\pi^+$.

electron momentum. We estimate that the detection efficiency for electrons with $p_e<60$ MeV/c is 90±5%. For higher momentum electrons the detection efficiency decreases and falls to ~50% at $p_e\cong 100$ MeV/c. Therefore, we only include the 31 $\Sigma^-\to e^-$ decays with $p_e\leq 60$ MeV/c in the computation of the $\Sigma^-\to ne^-\nu$ decay rate. The 31 observed $\Sigma^-\to e^-$ events must be corrected for the contamination due to $\Sigma^-\to\Lambda e^-\nu$ where the Λ is not seen. The best estimate, using the data of Sec. III, is that 5 events must be subtracted from the 31 events to correct for this background. The best estimate of the total number of $\Sigma^-\to n+e^-+\nu$ decays in this sample of film, obtained by integrating p_e over the entire spectrum,[12] is

$$\#(\Sigma^-\to ne^-\nu)=(31/0.87-5)/0.90\times 0.094=362.$$

The factor 0.87 in the above equation is the correction for the $\leq 60°$ dip criterion. The factor 0.094 is the fraction of the total electron spectrum below 60 MeV/c as calculated from phase space, transformed to the laboratory system.

[12] The spectrum used was simply nonrelativistic three-body phase space.

The $\Sigma^-\to ne^-\nu$ branching ratio is therefore

$$R_{e^-}=\frac{(\Sigma^-\to ne^-\nu)}{(\Sigma^-\to n\pi^-)}=\frac{362}{256\,000}=(1.4\pm 0.3)\times 10^{-3}. \quad (4)$$

The error given combines the uncertainties due to statistics, scanning efficiency and the determination of the denominator. As a further check, we have evaluated R_{e^-} using different portions of the observed electron spectrum. For $p_e\leq 50$ MeV/c and for $p_e\leq 70$ MeV/c, the calculated values of R_{e^-} agree with the above result within the errors.

B. $\Sigma^-\to n\mu^-\nu$

In 242 110 photographs, 45 Σ^- decays were found according to the scanning and measuring criteria of Sec. II, where the secondary was not an electron. The reconstruction and fitting program excluded the possibility that these events were $\Sigma^-\to n\pi^-$ with the π^- decaying into a μ^- at the Σ^- decay point. Four of 45 cases were identified as Σ^- radiative decays. Two of these four events had the signature of a stopping π^- and the other two were identified by π-μ decays in flight, with a subsequent μ-e decay. In Appendix A the radiative decays $\Sigma^- \to n\pi^-\gamma$ are discussed in greater detail.

Figure 5 is a display of the momentum distribution of the remaining 41 events. For 22 of these events the Σ^- decay secondary is a μ^- which stops in the chamber. An event of this type is shown in Fig. 6. These events are displayed as crosshatched in Fig. 5. The upper smooth curve represents the theoretical momentum spectrum for μ^- mesons from $\Sigma^- \to n\mu^-\nu$. The lower smooth curve represents the calculated probability of obtaining stopping μ^- events in the Saclay 81-cm chamber multiplied by the phase space distribution[13] transformed to the laboratory system (using an average Σ^- momentum of 150 MeV/c). This leads to the result that the fraction of μ^- mesons that are expected to stop inside the chamber is 15% of the total integrated spectrum. The scanning efficiency for these stopping μ^- events is very high ($\sim$95%).

Using the events with stopping μ^-, we determine the branching ratio for $\Sigma^- \to n\mu^-\nu$ decays to be

$$R_{\mu^-} = \frac{(\Sigma^- \to n\mu^-\nu)}{(\Sigma^- \to n\pi^-)} = \frac{22}{0.15\times 0.95\times 0.674\times 347\,000} = (0.66\pm 0.15)\times 10^{-3}. \quad (5)$$

The remaining 19 of the 41 events are a mixture of $\Sigma^- \to n\mu^-\nu$ and $\Sigma^- \to n\pi^-\gamma$. The momentum distribution of these events is also displayed in Fig. 5.

V. $\Delta Q = -\Delta S$ TRANSITIONS: $\Sigma^+ \to n + (e^+, \mu^+) + \nu$

We have searched for positive sigma leptonic decays applying the same selection criteria as for the negative events which we have discussed so far. Negative K mesons captured at rest in hydrogen produce only half as many Σ^+ as Σ^- hyperons and one half of the Σ^+ decay into a neutron and a positive π meson. The transition probabilities for $\Sigma^+ \to n\pi^+$ equals that for $\Sigma^- \to n\pi^-$. Therefore, the same leptonic decay rates for Σ^+ as for Σ^- would yield one fourth as many Σ^+ leptonic decays as Σ^- leptonic decays in our scan.

A. $\Sigma^+ \to e^+$+Neutrals

The 266 110 pictures contain 89 000 $\Sigma^+ \to n\pi^+$ decays from (K^-p) interactions at rest, of which 67 600 satisfy the criteria of Sec. II. In this sample we have found 3 events of the type $\Sigma^+ \to e^+$+neutrals. In these 3 cases, the positrons have momenta 33.3, 36.1, and 43.1 MeV/c, respectively. Due to the ambiguity between $\Sigma^+ \to ne^+\nu$ decays and $\Sigma^+ \to \Lambda e^+\nu$, $\Lambda \to n\pi^0$ decays for positron momentum below 77 MeV/c, these 3 events cannot be taken as a demonstration of the existence of $\Delta Q = -\Delta S$ transitions in Σ^+ decays. Taking the rate for $\Sigma^- \to \Lambda e^-\nu$ decays from Eq. (3a), we expect about three $\Sigma^+ \to \Lambda e^+\nu$ decays (2 with $\Lambda \to p\pi^-$ and 1 with $\Lambda \to n\pi^0$). We actually observed one $\Sigma^+ \to \Lambda e^+\nu$, $\Lambda \to p\pi^-$ and the three e^+ events described above. Since we have found no Σ^+ events with high-momentum positrons, these three events are most likely $\Delta S = 0$, $\Sigma^+ \to \Lambda$ decays.

B. $\Sigma^+ \to \mu^+$+Neutrals

We have found four Σ^+ events which have secondaries satisfying our measuring and analysis criteria, where the secondary particle is not a positron. Two of these four secondaries are π^+ mesons, which stop in the chamber and undergo $\pi^+ \to \mu^+ \to e^+$ decay. The third and the fourth events are ones in which the secondary, with an initial momentum of (90.0±2.7) and (84±6) MeV/c, leave the chamber after traveling 24 and 10.7 cm, respectively. Measurements of bubble density and variation of momenta with range of these tracks are consistent with either a π^+ or μ^+ assignment. For the third event a detailed study of a tiny delta ray (length 2 mm, kinetic energy 148 keV) on this track was made to attempt to distinguish between the π^+ and μ^+ assignments. The kinematical analysis of this δ ray slightly favors the hypothesis that the secondary is a π^+ meson rather than a μ^+ meson but is not at all definitive. Since we have seen no stopping μ^+ event, the most probable interpretation of these events is that they are radiative decays of the type $\Sigma^+ \to n + \pi^+ + \gamma$. The radiative decays are discussed further in Appendix A.

C. Relative Strength of $\Delta Q = \Delta S$ and $\Delta Q = -\Delta S$ Transitions

Assuming that we can neglect $\Sigma^\pm \to \Lambda e^\pm\nu$ decays for $p_e > 70$ MeV/c ($\sim$2% of $\Sigma \to \Lambda e\nu$ decays have $p_e \geq 70$ MeV/c, so that the expected number of $\Delta S = 0$ $\Sigma \to e$ decays in this momentum region is $\frac{1}{10}$ of an event in our film), we have 52 unambiguous $\Sigma^- \to ne^-\nu$ events versus *zero* $\Sigma^+ \to ne^+\nu$ events as described in Sec. III. The effective number of $\Sigma^- \to n\pi^-$ and $\Sigma^+ \to n\pi^+$ decays in this sample are 256 000 and 67 600, respectively. Since $w(\Sigma^+ \to n\pi^+) = w(\Sigma^- \to n\pi^-)$, where w is a transition rate, the time of observation of Σ^- and Σ^+ hyperons is in the ratio 256/67.6 = 3.8. Hence we find

$$\rho(e) \equiv \frac{\text{rate of } (\Sigma^+ \to ne^+\nu)}{\text{rate of } (\Sigma^- \to ne^-\nu)} = \left(\frac{0}{52}\right) 3.8 = \frac{0}{13.7}. \quad (6)$$

To compare $\Delta Q = \pm\Delta S$ transitions in the $\Sigma \to n\mu\nu$ decay mode, we restrict ourselves to events in which

[13] See, e.g., D. R. Harrington, Phys. Rev. **120**, 1482 (1960) for a discussion of the μ momentum distribution. We used a momentum distribution that corresponds to setting the vector and axial-vector coupling constants equal to each other, ignoring all magnetic or induced pseudoscalar terms. This is essentially the same as phase space. The differences in the μ^- spectrum for different strengths of coupling are negligibly small when compared with the statistical accuracy of this experiment. The probability of a μ^- stopping in the chamber was calculated by taking a sample of K^- stopping points (these K^- gave rise to $e^- + e^+ + \Lambda$ events) and evaluating the potential range of μ^- mesons versus momentum for a large selection of initial directions. The results of these calculations were combined to give the probability of a μ^- stopping in the chamber as a function of its initial momentum.

TABLE IV. Summary of branching ratios of $\Sigma^{\pm}$ leptonic decays.

Decay	UFI prediction	$R=\frac{\Sigma^{\pm}\to\text{lepton}}{\Sigma^{\pm}\to\pi^{\pm}}$	No. of events used
$\Sigma^{-}\to e^{-}+n+\bar{\nu}$	580×10^{-4}	$(14\pm3)\times10^{-4}$	31 ($p_e\leq60$ MeV/c)
$\Sigma^{-}\to\mu^{-}+n+\bar{\nu}$	260×10^{-4}	$(6.6\pm1.4)\times10^{-4}$	22 (μ^{-} stop)
$\Sigma^{+}\to e^{+}+n+\nu$	0	$<2.3\times10^{-4}$	0
$\Sigma^{+}\to\mu^{+}+n+\nu$	0	$<2.6\times10^{-4}$	0
$\Sigma^{-}\to\Lambda+e^{-}+\bar{\nu}$	1.8×10^{-4}	$(0.75\pm0.28)\times10^{-4}$	11 ($\Lambda\to p\pi^{-}$)
$\Sigma^{+}\to\Lambda+e^{+}+\nu$	1.1×10^{-4}	$(0.66\pm0.35)\times10^{-4}$	1 ($\Lambda\to p\pi^{-}$), 3 (Λ not observed)

the identification of the secondary as a μ meson is certain. This is only possible if the μ meson comes to rest inside the bubble chamber and decays into an electron. We have found 22 $\Sigma^{-}\to n\mu^{-}\nu$ events, the μ^{-}-meson stopping and undergoing $\mu^{-}\to e^{-}$ decays, and *zero* Σ^{+} decays of this type. Consequently, the ratio $\rho(\mu)$ of the $\Sigma^{+}\to n\mu^{+}\nu$ decay rate to the $\Sigma^{-}\to n\mu^{-}\nu$ decay rate is

$$\rho(\mu)=\frac{0}{22}\times3.8=\frac{0}{5.8}. \tag{7}$$

We have no definite indications of any $\Delta Q=-\Delta S$ transitions. Assuming $\rho(e)=\rho(\mu)$, the upper limit with 90% confidence for the ratio of $\Delta Q=-\Delta S$ to $\Delta Q=+\Delta S$ transitions is

$$\rho=\frac{\text{rate of }\Delta Q=-\Delta S\text{ transitions}}{\text{rate of }\Delta Q=+\Delta S\text{ transitions}}<\frac{2.3}{19.5}=0.12, \tag{8}$$

where 19.5 is the sum 13.7+5.8 from Eqs. (6) and (7) and the factor 2.3 is obtained by using a Poisson probability distribution for the number of $\Delta S=-\Delta Q$ events expected.

VI. CONCLUSIONS AND DISCUSSION

The first result to be emphasized is the small upper limit set for $\Delta S=-\Delta Q$ transitions in Σ^{+} decay, in decays to both electrons and muons. The upper limit in the $\Delta S=-\Delta Q$ rate relative to $\Delta S=+\Delta Q$ rate, combining electron and muon decays, is 0.12, at the 90% confidence limit. The Columbia-Rutgers-Princeton collaboration independently obtains a similar upper limit of 0.15.[7] It is quite certain that these decays are at least considerably suppressed in rate, and perhaps absent altogether.

This result is important in several contexts. First, the occurrence of $\Delta S=-\Delta Q$ transitions would imply that if intermediate bosons mediate the weak interactions, several different types would have to exist[14] in order to avoid the possibility of $\Delta S=2$ transitions, which are experimentally known to be forbidden.[15]

[14] R. E. Behrends and A. Sirlin, Phys. Rev. Letters 8, 221 (1962).

[15] M. Ferro-Luzzi, M. H. Alston, A. H. Rosenfeld, and S. G. Wojcicki, Phys. Rev. **130**, 1568 (1963); L. Okun and B. Pontecorvo, Zh. Eksperim. i Teor. Fiz. **32**, 1587 (1957) [English transl.: Soviet Phys.—JETP **5**, 1297 (1957)].

Second, it has been suggested[16] that the current of strongly interacting particles in the strangeness-changing weak interaction carries only $\Delta I=\frac{1}{2}$. This is known as the $\Delta I=\frac{1}{2}$ current rule. Existence of transitions with $\Delta S=-\Delta Q$ would require the presence of $\Delta I=\frac{3}{2}$ currents, with the third component $\Delta I_3=\frac{3}{2}$. (Currents with $\Delta I=\frac{3}{2}$ and third component one-half, do not contribute to hyperon decay, but do affect K decay.) The $\Delta I=\frac{1}{2}$ current rule is a necessary condition for the idea[17] that the weak current of strongly interacting particles transforms like some members of an octet in the SU_3 group. A specific and apparently successful theory of this type will be considered below.

Early experiments[18] on K^0 leptonic decay seemed to indicate a large $\Delta S=-\Delta Q$ transition rate, but this conclusion has not been supported by more recent experiments.[19] It is to be noted that the K_{l3} decay interaction is, with the usual parity conventions, vector, while Σ decay is a mixture of axial vector and vector, with a weighting factor of three favoring axial vector. Since it is conceivable that the violation might be limited to one reaction, or one type of interaction, the conclusion that the $\Delta Q=-\Delta S$ currents are very small is considerably strengthened by the results of this experiment. An even smaller upper limit for the ratio $(\Delta S=-\Delta Q)$ to $(\Delta S=+\Delta Q)$ transitions in axial-vector couplings has been obtained from the recent investigations of Ke_4 decay.[20]

The rates for the decay modes we have observed are summarized in Table IV. The rate for $\Sigma^{-}\to n+e+\nu$ has long been known to be less than that predicted by the universal Fermi interaction (UFI).[4] The branching

[16] M. Gell-Mann and A. H. Rosenfeld, *Annual Review of Science*, (Annual Reviews Inc., Stanford, 1957), Vol. 7; S. Okubo, R. E. Marshak, E. C. G. Sudarshan, W. B. Teutsch, and S. Weinberg, Phys. Rev. **112**, 665 (1958); and L. B. Okun, Proceedings of the Conference on Mesons and Recently Discovered Particles, Padua, Venice, 1958 (to be published).

[17] M. Gell-Mann, California Institute of Technology Synchrotron Laboratory CTSL-20, 1961 (unpublished).

[18] R. P. Ely, W. M. Powell, H. White, M. Baldo-Ceolin *et al.*, Phys. Rev. Letters **8**, 132 (1962).

[19] B. Aubert, L. Behr, J. P. Lowys, P. Mittner, and C. Pascaud, Phys. Letters **10**, 215 (1964); and L. Kirsch, R. Plano, J. Steinberger, and P. Franzini, Phys. Rev. Letters **13**, 35 (1964).

[20] R. W. Birge, R. P. Ely, G. Gidal, G. E. Kalmus, A. Kernan, W. M. Powell, A. Camerini, W. F. Fry, J. Gaidos, R. H. March, and S. Natali, Phys. Rev. Letters **11**, 35 (1963); and V. Bisi, G. Borreani, R. Cester, A. Debenedetti, M. I. Ferreo *et al.*, *ibid.* **10**, 498 (1963).

TABLE V. Data used to test Cabibbo's theory of leptonic decays.

Quantity	Value	Source
1. $\dfrac{(\Lambda\to p+e^-+\nu)}{(\text{all }\Lambda)}$	$(1.0\pm0.1)\times10^{-3}$	Ref. 22, weighted average
2. $\dfrac{(\Sigma^-\to n+e^-+\nu)}{(\Sigma^-\to n+\pi^-)}$	$(1.39\pm0.2)\times10^{-3}$	Table IV and Ref. 7
3. $\dfrac{(\Sigma^-\to \Lambda+e^-+\nu)}{(\Sigma^-\to n+\pi^-)}$	$(0.75\pm0.28)\times10^{-4}$	Table IV
4. $\dfrac{(\Xi^-\to \Lambda^0+e^-+\nu)}{(\text{all }\Xi^-)}$	$(2.4\pm1.4)\times10^{-3}$	Ref. 27
5. $(G_V{}^{n\to p}/G_V{}^{\mu\to e})$	0.975 ± 0.010	Ref. 31
6. $(G_A/G_V)_{n\to p}$	$1.15\ \pm0.05$	Ref. a
7. $\dfrac{(K^+\to \mu^++\nu)}{(\text{all }K^+)}$	$0.60\ \pm0.04$	Ref. b
8. $\dfrac{(K^+\to \pi^0+e^++\nu)}{(\text{all }K^+)}$	0.050 ± 0.005	Ref. b

[a] C. Bhalla (private communication); reinterpretation of neutron and O^{14} lifetime experiments.
[b] Average of data from R. W. Birge, D. H. Perkins, J. E. Peterson, D. H. Stork, and M. H. Whitehead, Nuovo Cimento **4**, 834 (1956); G. Alexander, R. H. W. Johnston, and C. O'Ceallaigh, *ibid.* **6**, 478 (1957); and B. P. Roe, D. Sinclair, J. L. Brown, D. A. Glaser, J. A. Kadyk, and G. H. Trilling, Phys. Rev. Letters **7**, 346 (1961).

ratio $R_e^-=(1.4\pm0.3)\times10^{-3}$ obtained here is in excellent agreement with two other recent measurements that yielded[7] $R_e^-=1.37\pm0.34\times10^{-3}$ and $(1.0\pm0.5)\times10^{-3}$,[21] respectively. From the table it can be seen that, in fact, the $\Sigma^-\to e+n+\nu$ rate is about 1/40 of the UFI rate. The other baryon decay with $\Delta S=1$ which has been measured is $\Lambda\to p+e^-+\nu$. The average of several measurements of the branching ratio is $(\Lambda\to p+e^-+\nu)/(\Lambda\to n+\pi)=(1.0\pm0.1)\times10^{-3}$,[22] which is less than the UFI prediction by a factor of 1/14. It is always possible, of course, that the UFI is a correct description of the weak interactions and that the discrepancy in rate is due to the renormalization by the strong interactions.

On the other hand, our determination of the rate for $\Sigma^-\to\Lambda+e^-+\nu$ shows that it is of the same order of magnitude but half as large as the UFI prediction. For this decay, with $\Delta S=0$, the UFI theory can be understood to include the hypothesis of the conserved vector current (CVC), which requires $\Delta I=0$ for the vector interaction. Consequently, this decay interaction should be only axial vector. In this sense the UFI prediction for the branching ratio is 1.8×10^{-4}, which is about twice as large as our measured value.

If the axial-vector coupling is calculated on the basis of a Goldberger-Treiman relation, the result[23] is a predicted branching ratio of 0.85×10^{-4}, if $(g_{\Sigma\Lambda\pi}/g_{NN\pi})=1$. This certainly agrees with the measured value, $(0.75\pm0.28)\times10^{-4}$.

[21] C. T. Murphy, Phys. Rev. **134**, B188 (1964).
[22] V. G. Lind, T. O. Binford, M. L. Good, and D. Stern, Phys. Rev. **135**, B1483 (1964); R. P. Ely, G. Gidal, G. E. Kalmus, L. O. Oswald *et al.*, Phys. Rev. **131**, 868 (1963); and C. Baglin *et al.* (to be published).
[23] J. Dreitlein and H. Primakoff, Phys. Rev. **125**, 1671 (1961).

The hypothesis[24] that the interaction in $\Sigma^\pm\to\Lambda+e^\pm+\nu$ decay transforms as $\Delta I=1$ predicts[25] that

$$R_{\Sigma\Lambda}=\frac{\text{rate of }\Sigma^-\to\Lambda+e^-+\nu}{\text{rate of }\Sigma^+\to\Lambda+e^++\nu}=1.6\,.$$

This ratio differs from 1 only by the phase space ratio for the different Σ^- and Σ^+ masses.

The best determination of the Σ^+ rate from our data is obtained by using the three events with low-energy positrons, as well as the one event where the lambda is also visible (Table IV). Combining this rate with the $\Sigma^-\to\Lambda+e^-+\nu$ rate gives

$$R_{\Sigma\Lambda}=1.1_{-0.4}{}^{+1}$$

in agreement with the prediction, within the large statistical errors.

A test of the hypothesis of equal $(\mu\nu)$ and $(e\nu)$ couplings in hyperon decay can be made by comparing the decay rates of $\Sigma^-\to n+\mu^-+\nu$ and $\Sigma^-\to n+e^-+\nu$. Ignoring all interactions other than allowed vector and axial vector, μ, e universality predicts that $w(\Sigma^-\to n+\mu^-+\nu)/w(\Sigma^-\to n+e^-+\nu)=0.45$, essentially the ratio of phase space for the two decay modes. From Table IV, we see that our experimental result for this ratio is 0.47 ± 0.14, in excellent agreement with μ, e universality.

Finally, we wish to compare Cabibbo's theory[26] of leptonic decays with experiment. In brief, Cabibbo

[24] S. Weinberg, Phys. Rev. **112**, 1375 (1958).
[25] T. D. Lee and C. N. Yang, Phys. Rev. **119**, 1410 (1960).
[26] N. Cabibbo, Phys. Rev. Letters **10**, 531 (1963); see also M. Gell-Mann and M. Lévy, Nuovo Cimento **16**, 705 (1958).

TABLE VI. Least-square solutions to Cabibbo's theory of leptonic decays using the data of Table V as input.

	Sol. *A*		Sol. *B*	
No. of input data	(i) 8	(ii) 6	(i) 8	(ii) 6
No. of constraints	5	3	5	3
(χ^2) probability	(4.75) 45%	(3.51) 32%	(7.92) 17%	(7.04) 8%
θ	0.264	0.272	0.249	0.246
F	0.437	0.436	0.715	0.749
D	0.742	0.742	0.409	0.377
$(\Lambda\rightarrow p+e^-+\bar{\nu}/\text{all }\Lambda$	0.91×10^{-3}	0.96×10^{-3}	1.08×10^{-3}	1.10×10^{-3}
$(\Sigma^-\rightarrow n+e^-+\bar{\nu}/\text{all }\Sigma^-$	1.32×10^{-3}	1.38×10^{-3}	1.19×10^{-3}	1.28×10^{-3}
$(\Sigma^-\rightarrow \Lambda+e^-+\nu)/\text{all }\Sigma^-$	0.61×10^{-4}	0.59×10^{-4}	0.19×10^{-4}	0.16×10^{-4}
$(\Xi^-\rightarrow \Lambda+e^-+\bar{\nu})/\text{all }\Xi^-$	0.65×10^{-3}	0.66×10^{-3}	1.06×10^{-3}	1.06×10^{-3}
A/V for $\Sigma^-\rightarrow e^-+n+\bar{\nu}$	$+0.305$	$+0.292$	-0.306	-0.372

postulates that the strongly interacting charged currents, coupled to leptons, transform under SU_3 transformations like members of an octet. It follows that there are only two types of currents, $\Delta S=0$, $\Delta I=1$ and $\Delta S=+\Delta Q$, $\Delta I=\frac{1}{2}$. The currents are further assumed to be linear combinations of vectors and axial vectors with respect to space time. In the limit of exact SU_3 symmetry, all the vector currents are conserved. The original idea of a universal four-fermion interaction is modified by assuming that the sum of the squares of unrenormalized vector coupling constants for the $\Delta S=0$ and $\Delta S=+\Delta Q$ currents equals the square of the $\mu\rightarrow e+\nu+\bar{\nu}$ coupling constant. Hence one can define an angle θ such that $j_\mu^{(\Delta S=0)}\sim\cos\theta$ and $j_\mu^{(\Delta S=+\Delta Q)}\sim\sin\theta$. The axial-vector currents which are not conserved are assumed to be proportional to the same-angle factors, and to have the same renormalization factors for all hyperon decays as for the $n\rightarrow p$ beta decay. Cabibbo[26] has shown with preliminary hyperon leptonic decay data that with the assumptions outlined above, there exists an angle, $\theta\approx0.26$, that fits roughly, not only the baryon leptonic decays but also the $K^+\rightarrow\mu^++\nu$ and $K^+\rightarrow\pi^0+e^++\nu$ decays.

In what follows we carry out a least-square fit to all the pertinent data using Cabibbo's theory. We find two distinct acceptable fits to the data. (Cabibbo obtained only one solution because he singled out the $n\rightarrow p$ and $\Sigma^-\rightarrow\Lambda$ beta decays as input and then predicted the $\Delta S=+\Delta Q$ hyperons decay rates. This method does not allow the full variation of experimental values within their errors to play a role in the comparison with theory.)

As experimental input, we take the eight pieces of data listed in Table V.

The parameters that enter into the theory are the angle θ, defined above, and the strengths of the F and D reduced matrix elements of the axial-vector current. Two independent matrix elements arise since in SU_3 an 8×8 can combine to form two types of octets, which we call F and D in a notation suggested by that of Gell-Mann.[17] The CVC hypothesis implies that only F_V terms exist for the vector part. The equations that must be satisfied are the following:

$$(\Lambda^0\rightarrow p+e^-+\nu)/(\text{all }\Lambda)=0.37\times10^{-2}\sin^2\theta\,(\tfrac{3}{2})[1+2.98(F+\tfrac{1}{3}D)^2],\quad(9)$$

$$(\Sigma^-\rightarrow n+e^-+\nu)/(\text{all }\Sigma^-)=1.52\times10^{-2}\sin^2\theta\,(1)[1+2.95(D-F)^2],\quad(10)$$

$$(\Sigma^-\rightarrow \Lambda^0+e^-+\nu)/(\text{all }\Sigma^-)=0.60\times10^{-4}\cos^2\theta\,(\tfrac{2}{3})[3.00D^2],\quad(11)$$

$$(\Xi^-\rightarrow \Lambda^0+e^-+\nu)/(\text{all }\Xi^-)=5.7\times10^{-3}\sin^2\theta\,(\tfrac{3}{2})[1+2.98(F-\tfrac{1}{3}D)^2],\quad(12)$$

$$(G_V^{n\rightarrow p}/G_V^{\mu\rightarrow e})^2=\cos^2\theta,\quad(13)$$

$$(G_A/G_V)_{n\rightarrow p}=F+D.\quad(14)$$

In obtaining the numbers in Eqs. (9)–(12), we have adopted $G_V^{\mu\rightarrow e}=1.025\times10^{-5}/M_p^2$ as deduced from the μ lifetime, $\tau_\mu=2.200$ μsec,[3] and masses and lifetimes from Barkas and Rosenfeld[11] and Ticho.[27] For the transition rates for hyperon leptonic decays with arbitrary amounts of V and A coupling, we have used the formulas of Yamaguchi[28] and Ryan,[29] which agree numerically. These formulas have as a factor the SU_3 Clebsch-Gordan coefficients appropriate to each decay, which follow from the assumption of *octet* currents.[30] The formulas used by Cabibbo to relate the K^+ decay rates, (7) and (8) of Table *V*, to θ, are given in Ref. 26 and are not repeated here.

We have searched for the best values of the parameters θ, F, and D in the sense of the minimum value of the chi-squared function computed with (i) all eight pieces of data in Table V, and (ii) the first six omitting

[27] H. H. Bingham, Talk presented to Royal Society Discussion on Leptonic Interactions, February 1964 (unpublished); and H. Ticho, *Proceedings of the Sienna Conference on Elementary Particles, 1963*, edited by G. Bernadini and G. P. Puppi (Societa' Italiana di Fisica, Bologna, 1963).

[28] Y. Yamaguchi, CERN Technical Report No. 59-35, 1959, p. 342 (unpublished).

[29] C. Ryan (private communication).

[30] The appropriate SU_3 coefficients are written out explicitly in notes on a lecture by N. Cabibbo at the summer school in Erice, Italy, May 1963 (unpublished).

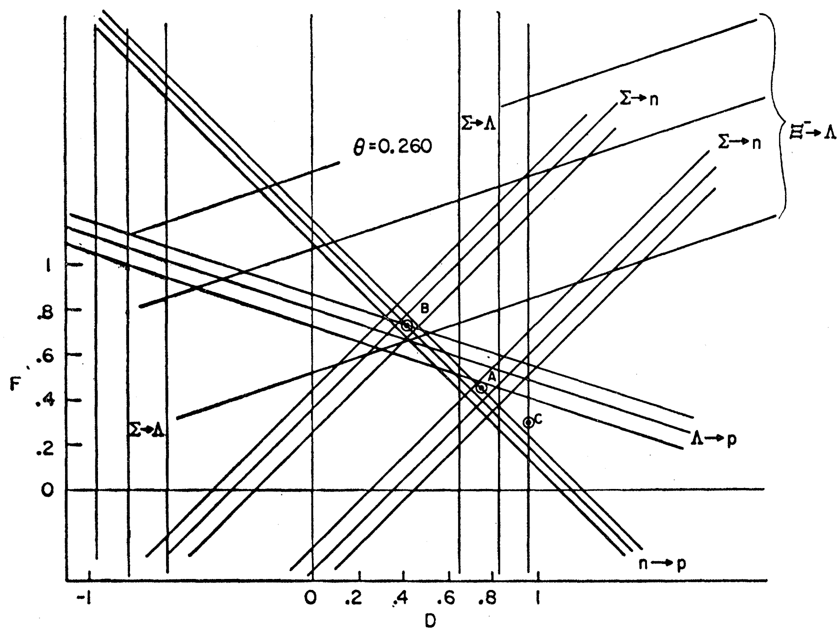


FIG. 7. Comparison of experimental data on baryon leptonic decays with Cabibbo's theory for $\theta=0.26$. The parameters F and D are the strengths of the two independent reduced matrix elements of the axial vector current. Table V and Eqs. (9)–(14) in the text list the experimental data and formulas used to construct this figure. The points A and B denote the best-fit solutions obtained by minimizing χ^2. Point C denotes the original solution of Cabibbo based on earlier data.

the K^+ decay data. The second alternative was tried since there have been some theoretical objections, particularly by Sakurai,[31] to the direct comparison of K^+ decays to π^+ decays because of the large mass splittings within the pseudoscalar meson octet. The general minimization program MINFUN of Humphrey was used.

The results are listed in Table VI, along with the probabilities of the chi-squared values for 5 and 3 degrees of freedom for the solutions (i) and (ii). The values of some of the experimental quantities deduced from these solutions are also given. The χ^2 probability values indicate two acceptable types of solutions called A and B. The addition of the K^+ data hardly changes the solutions and is in surprisingly good agreement with the hyperon data. Solution A is of the type originally obtained by Cabibbo.[26] It is characterized by large D, small F, small $\Xi^- \to \Lambda$ decay, large $\Sigma^- \to \Lambda$ decay and an $(A/V)\Sigma^- \to n$ ratio that is positive. In contrast, solution B has large F, small D, large $\Xi^- \to \Lambda$ decay, small $\Sigma^- \to \Lambda$ decay, and an $(A/V)\Sigma^- \to n$ ratio that is negative. Solution B is closer to the type of hyperon decay pattern suggested by Zweig[32] based on "aces." Solution A, on the other hand, has the character suggested by the generalized Goldberger-Treiman relations. Figure 7 illustrates the positions of these two solutions in the F, D space and also shows how each baryon leptonic decay experiment serves to impose conditions in this space, assuming $\theta=0.26$.

The Cabibbo angle θ is not sensitive to the type of solution, but is always within the limits $0.25<\theta<0.27$. The assumption of an *octet* current is to some extent born out by the relative magnitudes of the $\Lambda \to p$ and $\Sigma^- \to n$ beta decays.

Both solutions A and B have acceptable chi-squared probabilities, but as one can see from Fig. 7, the present experiments have sufficiently large errors that a fortuitous agreement with Cabibbo's theory cannot be excluded. However, further support for this theory is given by a calculation that we have carried out, minimizing chi-squared with independent angles θ and θ' for the vector and axial-vector currents, respectively, using only the baryon leptonic decay data. We find for solutions of both types A and B that the best values of θ and θ' are equal within a few percent to 0.26. The same result has been found already by Cabibbo[26] to be true for the K^+ decays, but for baryon decays there are fewer theoretical uncertainties due to mass splittings.

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APPENDIX A: RADIATIVE DECAYS OF THE TYPE $\Sigma^\pm \to \pi^\pm + n + \gamma$

In the course of scanning systematically for leptonic decays of $\Sigma^\pm$ hyperons, as described in Sec. II B,

[31] J. J. Sakurai, Phys. Rev. Letters 12, 79 (1964).
[32] G. Zweig, CERN (unpublished).

TABLE VII. Radiative decays of $\Sigma^{\pm}$ hyperons.

Frame No.	Length Σ	p_{π}(lab)MeV/c	Means of identification
1381 246	0.92 (Σ^-)	90 (π^-)	$\pi^- \rightarrow \mu^- \rightarrow e^-$, π^- decay in flight
1451 695	0.54 (Σ^-)	109 (π^-)	π^- stops
1533 604	0.20 (Σ^-)	92 (π^-)	π^- stops
1407 936	0.45 (Σ^+)	120 (π^+)	$\Sigma^+ \rightarrow n+\pi^++e^-+e^+$ π^+ leaves chamber
1503 408	0.37 (Σ^+)	75 (π^+)	π^+ stops
1533 266	0.26 (Σ^+)	76 (π^+)	π^+ stops
1504 933	0.14 (Σ^+)	89 (π^+ or μ^+)	π^+ or μ^+ events described in Sec. V B of text; both secondaries leave the chamber.
1535 107	0.48 (Σ^+)	84 (π^+ or μ^+)	

several examples of radiative decays, $\Sigma^{\pm} \rightarrow n+\pi^{\pm}+\gamma$, were found. These events are listed in Table VII. A radiative decay event is identified not by the observation of the γ ray (except for event No. 1503 408, which is of the class $\Sigma^+ \rightarrow n+\pi^++e^-+e^+$) but by the positive identification of the charged secondary as a pion with momentum too low to have come from the usual two-body $\Sigma^{\pm} \rightarrow \pi^{\pm}+n$ decays. Below 90 MeV/c, a pion has a good chance of stopping in the chamber. This provides an easy means of identification since the π^+ exhibits the $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay chain, while the π^- is captured with no visible tracks, whereas a μ^- would exhibit $\mu^- \rightarrow e^-$ decay.

Four stopping pion examples, two positive and two negative, were found and are included in Table VII. Event No. 1381 246 of the type $\Sigma^- \rightarrow n+\pi^-+\gamma$, where the π^- decays in flight into a μ^-, is an event wherein the π^- would have stopped in the chamber if it had not decayed. Finally, events No. 1535 107 are the positive events discussed in Sec. V B. These two events are either $\Sigma^+ \rightarrow n+\pi^++\gamma$ or $\Sigma^+ \rightarrow n+\mu^++\nu$. Since we have seen several other examples of Σ^+ radiative decay and no definite examples of $\Delta S=-\Delta Q$ leptonic decays, the betting odds favor the radiative pionic decay assignment for these events. The number of radiative decays observed is of the order of magnitude expected from inner bremsstrahlung.[33–36]

Note added in proof. A short summary of the results of this paper has been published in Phys. Rev. Letters **13**, 291 (1964). A similar comparison of the experimental data on leptonic decays with Cabibbo's theory has been made by N. Breme, B. Hellesen, and M. Roos, Phys. Letters **11**, 344 (1964). They discuss only solutions of type *A*. Our statistical analysis in Sec. VI implies that better data on the $\Sigma^- \rightarrow \Lambda+e^-+\nu$ branching ratio is needed to exclude solutions of type *B*. Finally an excellent discussion of hyperon leptonic decays, containing many points in common with Sec. VI, has been given by L. Wolfenstein, Phys. Rev. **135**, B1436 (1964).

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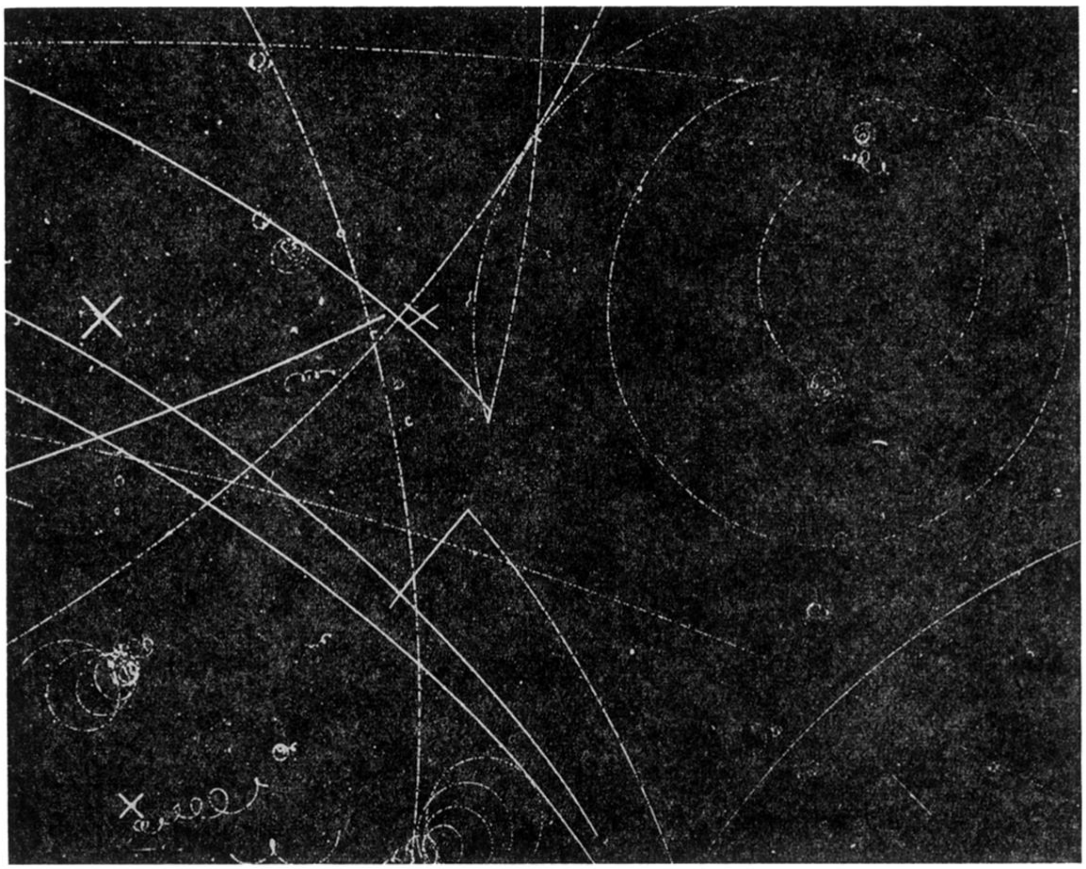

FIG. 3. Picture of a $\Delta S=0$ leptonic decay of the type $\Sigma^- \to \Lambda+e^-+\nu$, $\Lambda \to p+\pi^-$. The Σ^- hyperon is produced by a K^- at rest via the reaction $K^-+p \to \Sigma^-+\pi^+$.

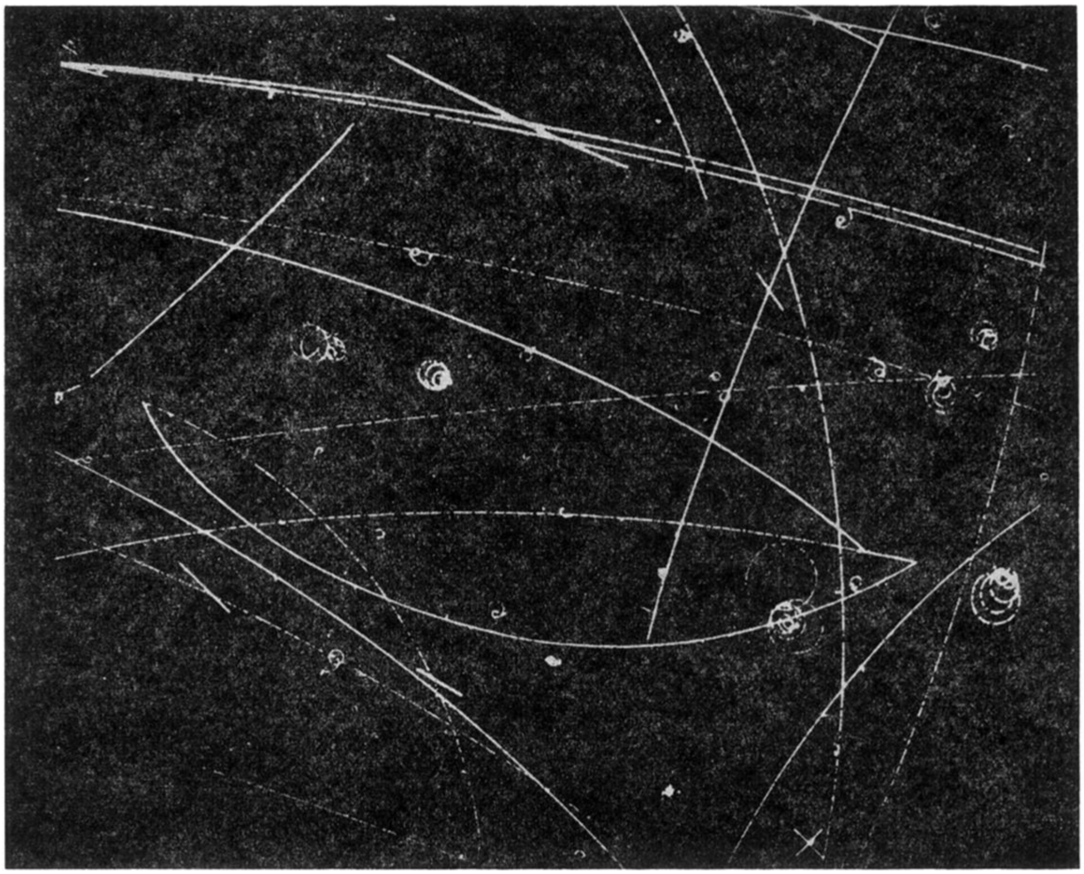

FIG. 6. Picture of a $\Sigma^- \rightarrow n+\mu^-+\nu$ decay event, where the μ^- stops in the chamber and decays into an electron and two neutrinos. The Σ^- is produced by a K^- at rest via the reaction $K^-+p \rightarrow \Sigma^-+\pi^+$.