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ASYMMETRY IN THE DECAY OF Σ HYPERONS

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ABSTRACT

A search has been made for an asymmetry in the decay of $\Sigma^{\pm}$ hyperons. The $\Sigma^{\pm}$ were produced in the reactions $\pi^{\pm} + p \rightarrow \Sigma^{\pm} + K^{+}$. Detection and identification of the K^{+} mesons by a counter technique selects the above reactions and establishes the plane of production. Additional counters, which detect the pions from the Σ-hyperon decay in coincidence with the K^{+} mesons, measure the symmetry with respect to the plane of production. The results yield the parameter $\alpha\bar{p}$, where α measures the strength of parity nonconservation and $\bar{p}$ is the average polarization of the Σ hyperon. The data give: for Σ^{-} produced by 1.0-Bev π^{-}, $\alpha^{-}\bar{p} = +0.02 \pm 0.05$; for Σ^{-} from 1.1-Bev π^{-}, $\alpha^{-}\bar{p} = -0.06 \pm 0.05$; for Σ^{+} from 1.0-Bev π^{+}, the decay mode $\Sigma^{+} \rightarrow \pi^{+} + n$ gives $\alpha^{+}\bar{p} = +0.02 \pm 0.07$ and the mode $\Sigma^{+} \rightarrow \pi^{0} + p$ gives $\alpha^{0}\bar{p} = +0.70 \pm 0.30$. The value of $\alpha^{0}\bar{p}$ for $\Sigma^{+} \rightarrow \pi^{0} + p$ strongly indicates that parity is not conserved. For the Σ^{+}, $|\bar{p}| \geqslant 0.70 \pm 0.30$; thus we can conclude $|\alpha^{+}| \lesssim 0.03 \pm 0.11$. The results therefore indicate that the asymmetry parameter α depends upon the isotopic spin states in the final pion-nucleon system. The dependence on the isotopic spin is compatible with the $\Delta I = \pm \frac{1}{2}$ rule.

ASYMMETRY IN THE DECAY OF Σ HYPERONS*

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I. INTRODUCTION

In the last two years, following the famous paper of Lee and Yang,[1] experiments have shown that most of the elementary particles that decay through weak interactions, violate the principle of the conservation of parity. Not only is parity conservation violated in nearly the maximum possible degree, but also the principle of invariance under charge conjugation is violated. Up to date, the decays of only the Σ hyperons (and the exceedingly rare Ξ hyperons) have not been demonstrated to violate these principles.

Several authors have reported attempts to find asymmetries in the decay of Σ^- hyperons produced by high-energy π^- mesons in bubble chambers. No statistically significant asymmetry has been found.[2] The number of Σ^+ hyperons observed in bubble chambers is too small for a significant observation. Both Σ^- and Σ^+ mesons have been produced by K^- mesons near or at the end of their range in nuclear emulsion. Early results indicated a possible asymmetry,[3] but the latest compilation of data gives an asymmetry not significantly different from zero.[4] The counter experiment reported here

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has been performed to improve the accuracy for Σ^- produced by 1.0- and 1.1-Bev negative pions, and to search for asymmetries in the two pionic decay modes of the Σ^+ hyperons produced by 1.0-Bev π^+ mesons.

The reactions

$$\pi^- + p \rightarrow \Sigma^- + K^+, \tag{1}$$

$$\pi^+ + p \rightarrow \Sigma^+ + K^+ \tag{2}$$

have been used to produce the hyperons. The beam energies were insufficient to produce additional pions or K^- mesons. The associated production phenomena are sufficiently well established empirically[5] to assure that, when a K^+ meson was produced by pions of known charge and momentum incident on a hydrogen target, a Σ hyperon of known charge, energy, and direction was produced simultaneously. The present experimental evidence indicates that parity is conserved in strong production reactions, and we will assume that this is the case here.[6] Therefore, if the Σ hyperon is polarized in production, the axis of polarization is in the direction of $\pm (\bar{p}_{\pi\ in} \times \bar{p}_{\Sigma})$.

The hyperons are known to decay by the following three modes:

$$\Sigma^- \rightarrow \pi^- + n, \tag{3}$$

$$\Sigma^+ \rightarrow \pi^+ + n, \tag{4}$$

$$\Sigma^+ \rightarrow \pi^0 + p. \tag{5}$$

If the hyperon is polarized and parity is not conserved in the decay process, the number of decay pions (or nucleons) may be asymmetric with respect to the plane of production. Let R be the projection of the momentum of the decay pion on the direction $\bar{p}_{\pi\ in} \times \bar{p}_{\Sigma}$. The distribution function for R at an angle θ of production in the center-of-mass system is given by[7]

$$W(\theta, \xi) = I(\theta)\ d\Omega \times \tfrac{1}{2}\ [\ 1 + \alpha p\ (\theta)\ \xi]\ d\xi, \tag{6}$$

where

ξ = R/(maximum value of R),

$I(\theta)\, d\Omega$ = differential cross section for the production reaction,

$p(\theta)$ = polarization of the Σ hyperon.

The existence of a nonvanishing α is an unambiguous proof of parity non-conservation in the decay process. On the other hand, since the asymmetry is proportional to the product $\alpha p(\theta)$, the observation of a symmetric decay process may be due to the vanishing of either α or $p(\theta)$ and does not establish parity conservation.

Assuming that the spin of the Σ is $\frac{1}{2}$, the final state of the pion-nucleon system may be a mixture of s and p states, with amplitudes, say, a and b respectively. If time-reversal invariance is assumed, the asymmetry parameter is given by

$$\alpha = -2\, ab \cos(\delta_a - \delta_b) / [\, |a|^2 + |b|^2 \,], \tag{7}$$

where δ_a and δ_b are respectively the s- and p-state phase shifts in pion-nucleon scattering at about 189 Mev/c in the center-of-mass system.

The final state of the pion-proton system for the decay in Eq. (3) is a pure isotopic spin I = 3/2 state, while (4) and (5) are mixtures of I = 3/2 and I = 1/2 states. Under certain circumstances, therefore, a measurement of asymmetries for the three decay modes (3), (4), and (5) will give information about the isotopic-spin dependence of the decay process. This point is considered in detail in Section V.

II. APPARATUS

The pion beam was produced by 5.4-Bev protons striking a Ta target in a magnetic-field-free section of the Bevatron. Pions produced within a small solid angle at 30° from the forward direction of the proton beam were focused on a liquid hydrogen target. The arrangement of deflection magnets and strong-focusing lenses is shown in Fig. 1. The optical properties of the beam were as follows: the first lens was adjusted to focus an image of the target at the center of the second quadrupole lens. The second lens, operating as a "field" lens, was adjusted to focus an image of the exit aperture of the first lens on the hydrogen target. The angles through which the beam was turned by the two deflecting magnets, and their spacing along the beam, were chosen so that the images for all acceptable momenta were spatially recombined at the target. The width of the accepted momentum band was approximately $\pm 0.04\ p_o$, where p_o is the mean momentum. The value of the mean momentum p_o was established to $\pm 1\%$ by the floating-wire technique.

Vertical and horizontal intensity distributions at the target, obtained by the use of a small probe counter, are shown in Fig. 2. Within the error, the image was spatially symmetric. Additional measurements were made of the horizontal intensity distribution for the highest and lowest momentum components of the beam. They established that the images for each momentum were properly combined to give a symmetric image, centered at the same spatial point, for each momentum component of the beam.

The sign of the charge of the pions selected could be reversed by reversing the directions of the currents in all the magnets. Under average operating conditions the intensity of the π^- beam was about $10^6\ \mathrm{min}^{-1}$;

and of the π^+ beam, 1.5×10^6 min^{-1}. The positive beam contained protons of the same momentum as the pions. The ratio of protons to π^+ was ~4.

The arrangement of the liquid hydrogen target and counters is shown in Fig. 3. The target has been described.[8] The hydrogen container was approximately 12 in. long and 6 in. in diameter; the beam entered and exited through thin windows. All K^+ passed through ~0.040-inch Al windows.

The telescopes which selected the K^+ mesons were placed at laboratory-system angles of $\pm 31^\circ$ with respect to the pion beam ($105 \pm 20^\circ$ center-of-mass angles). Each telescope accepted K^+-mesons produced within a cone of half angle 6°. Approximately one-half the K^+ mesons produced within this cone passed through the counters S1, S2, S3, and A and stopped in counter C. All the K^+ mesons that stopped in C ionized more than twice minimum in S2 and S3 and more than 1.5 times minimum in S1. Their relative velocity $\beta = v/c$ was less than 0.68. To select these K^+ mesons preferentially, counters S1, S2, and S3, which were $7 \times 7 \times \frac{1}{2}$-in. plastic scintillators, were each equipped with discriminators which were calibrated and adjusted to detect particles ionizing at least as heavily as K mesons. Counter A, a 2-in.-thick water-filled Cherenkov counter, produced pulses for particles with $\beta > 1/n = 0.75$. Thus no A pulse resulted from the passage of a stopping K^+ meson. The discriminated pulses of S1, S2, and S3 were placed in coincidence ($\tau \cong 20$ mμsec), with A in anticoincidence. The output of these coincidences we will call G_u and G_d, the "gate pulses" for the "up" and "down" K-meson telescopes respectively. This coincidence requirement rejected fast, minimum-ionizing particles by a factor of ~2000, while accepting slow particles of K-meson velocities with full efficiency.

The counters C were 8-in. cubic water-filled Cherenkov counters. Practically all the particles that produced a gate pulse had velocities too low to produce pulses in C. After stopping, however, ~90% of the K^+ mesons produced fast decay particles which could give pulses from C. Stopping protons, of course, produced no such pulse.[9] The gate pulse was placed in coincidence with C with $\tau \cong 10^{-7}$ sec. If the G coincidences select only K^+ mesons, the time relation of the C pulses to, say, S1 should show the characteristic K^+-meson lifetime with a mean life of $(1.224 \pm 0.013) \times 10^{-8}$ sec.[10]

The pulses from G in coincidence with pulses from C were used to trigger a fast oscilloscope (Tektronix 517), and undiscriminated pulses from S1, S3, and C were displayed and photographed. Measurements on the film were then made to obtain the time distribution of the C pulses. As is described in more detail in Section IV, about 80% of these coincidences can be ascribed to K^+ mesons stopped in C.

As we have remarked earlier, whenever a K^+ was recorded, a Σ hyperon was produced. To be specific, with an incoming π^-, we had a Σ^-. Because of its very short lifetime, it decayed, with a mean free path of only 3.6 cm, into $\pi^- + n$. The counters L and R, placed symmetrically to the left and right of the production plane and roughly parallel to it (see Fig. 3), detected the decay π^-. The counters L and R were 2×18×18-in. plastic scintillators which were equipped with discriminators. In order to reduce background rates, a pulse was required which was equal to one-half that produced by a minimum-ionizing particle crossing through the 2-in. dimension.

The pulses from counters L and R in coincidence with G_u and G_d were displayed on the oscilloscope trace along with their associated S1,

S3, and C pulses. Thus, whenever a K^+-meson pulse was identified on the film, we could also determine whether an L or R pulse was time-coincident, with a resolution of ±4 mμsec. Such a pulse was found in 32 ± 1 % of the cases, a value close to that calculated from purely geometrical considerations.

A simplified schematic diagram of the electronics is given in Fig. 4. In order that each pulse on a given trace be assigned to the correct counter, we have made use of a multichannel coincidence mixer.[8] Each channel in the mixer was a simple twofold diode coincidence circuit. The gate pulse was fed in common to one diode of each of these twofold circuits, while the various pulses to be observed were connected to the other diode of their respective twofold circuit. The output of each channel was connected into a transmission line at intervals approximately equal to the resolution time of the coincidence. The amplified output of the line went to the deflection plates of the oscilloscope. In this way, the pulse from one particular counter, and no other, appeared within a known interval along the sweep. The mixer had two separate sets of channels, one for the "up" ≡ U telescope and one for the "down" ≡ D telescope. Pulses in coincidence with the U and the D telescopes were arranged to give opposite deflections of the oscilloscope trace. A distinction was clearly essential since if, for example, a predominantly leftward intensity occurred for pulses associated with the U telescope as a result of parity nonconservation, a predominantly rightward intensity would be expected for D.

In addition to the counters already described, a beam anticoincidence counter in the approximate form of an annulus (see Fig. 3) was placed directly in front of the target. Events associated with stray particles were rejected by an anticoincidence with G_u and G_d.

When the magnetic system was set to select π^+ mesons, the large number of protons in the beam created additional background. It was therefore desirable to select out of this beam only the pions in coincidence with G. For this purpose, a 2-in.-thick water-filled Cherenkov counter was placed in the beam just ahead of the second quadrupole lens. This counter responded well to the π^+ mesons, but with very low efficiency to protons of this momentum. With the pulse from this counter in coincidence with G, most of the proton-created background was eliminated.

III. EXPERIMENTAL PROCEDURES

An integration over the variable ξ of Eq. (6) gives the parameter $\alpha\bar{p}$ in terms of the measured counting rates and the geometry of the apparatus, that is

$$\alpha\bar{p} = a\,(LU-RU)/(LU+RU) = -\,a(LD-RD)/(LD+RD), \qquad (8)$$

where LU is the counting rate of counter L in coincidence with the U K-meson telescope, and so on in an obvious notation. Here "a" is a geometrical factor numerically evaluated for our geometry, and is equal to 1.30 ± 0.05.

Even though we carefully checked the symmetry of the beam in position and energy, and positioned the counters with care, it is important to have other direct tests for the symmetry of the apparatus. A parity-nonconserving asymmetry should appear in an opposite sense for the U and D K-meson telescopes, and we have thus two independent measurements of $\alpha\bar{p}$. On the other hand, geometrical uncertainties due to the location or symmetry of the beam, positioning of counters L and R, and efficiencies of counters L and R all produce asymmetries with the same sense for the U and D telescopes. Thus, they cancel out in the average of

$\alpha\bar{p}$ for the U and D telescopes. In our arrangement, owing to inefficiencies in the K telescopes, it was difficult to make their absolute counting rates equal. It is to be noted that this difference, which was ~20 % in some cases, does not appreciably alter the result of averaging. Whereas the efficiencies of counters L and R cancel in the average, the electronic coincidence circuits branched in such a way that a different circuit efficiency could result in an apparent asymmetry which would not cancel in the average. Although checks of the pulse height on the film and the counting rates indicate that this efficiency was very close to 1, we also periodically reversed the counters at the inputs to the electronic circuitry. In each case, about one-half the counts were taken with L and R reversed so that any circuit asymmetry should balance out to first order. The only geometrical uncertainty which fails to cancel out in these averages is that the line joining the midpoints of counters L and R might not have been exactly perpendicular to the plane containing the K telescopes U and D. It can be shown that the measured values of $\alpha\bar{p}$ are not particularly sensitive to this misalignment.

A more direct test of the over-all symmetry of the apparatus was made in the following way. With the discriminators of S1, S2, and S3 set to accept minimum-ionizing particles and with the A anticoincidence removed, the counting rates LU, RU, LD & RD increased by a factor of ~500, owing to inelastic pion-proton collisions. The geometrical arrangement of counters was such that elastic scattering could not produce this coincidence. Since the beam was predominantly composed of pions, which have spin zero, and the target was unpolarized, a pseudoscalar quantity cannot be constructed for the production process. Thus, except for weak decays and possible higher-order processes, we expect zero asymmetry for these counting rates. At the beginning and end of each run, we recorded on the film a suitable number of these pion-production coincidences.

In analogy to Eq. (8), we define for pion production the quantity

$$\epsilon = a(LU-RU)/(LU+RU) = -a(LD-RD)/(LD+RD). \qquad (9)$$

The average value of ϵ shows, within the statistical errors, no intrinsic asymmetry for the apparatus. Numerical results are given in the next section.

With an incoming π^- beam, we looked for a Σ^--hyperon decay asymmetry for two kinetic energies of the incoming beam, 1.0 and 1.1 Bev. At any one energy, $\alpha\bar{p}$ can be small or zero owing to a small or zero $\bar{p}$. At a second, sufficiently different energy, there is no a priori reason to suppose that the same small value of $\bar{p}$ should persist. For this reason it seemed appropriate to use two values of the incoming pion-beam energy. At 1.1 Bev, most of the K^+ mesons produced at 31° were too energetic to stop in Counter C. A 7-inch carbon absorber, placed in front of the K telescope, reduced the K-meson energy so that a reasonable fraction of these K mesons stopped in Counter C.

With π^+ mesons of 1.0 Bev, the Σ^+ hyperons produced may decay by either of the two modes (4) or (5). The decays from which a π^+ meson struck the L or R counter were recorded with full efficiency. However, only a small fraction of the π^0 mesons, which decayed very rapidly into two γ rays, was recorded. These decays were recorded only if one or both of the γ rays were directed toward L or R and also were converted in the counter or the walls of the target. This fraction of the π^0-meson decay mode has been numerically computed as $20 \pm 5\%$. On the other hand, when a $\frac{1}{4}$-in. Pb radiator was placed in front of counters L and R, most of the π^0-meson decays were detected, while the π^+ mesons were only slightly attenuated. With the Pb in position, $80 \pm 10\%$ of these π^0 mesons were recorded.

We have made experimental runs with and without Pb radiator. From these data, using the conversion probabilities and the known branching ratio of the two modes,[11]

$$[\Sigma^+ \rightarrow \pi^0 + p]/[(\Sigma^+ \rightarrow \pi^0 + p) + (\Sigma^+ \rightarrow \pi^+ + n)] = 0.49 \pm 0.03,$$

the asymmetry for the two decay modes can be calculated. Since the counters L or R detected the conversion of the γ rays, and not the π^0 mesons directly, the distribution function of Eq. (6) was modified. It has been shown that, when a single γ ray is detected, the coefficient $\alpha\bar{p}$ must be multiplied by a factor which depends only upon the energy and momentum of the π^0 meson.[12] In our case, the value of this factor was 0.68.

The ratio of the K^+-meson rate with hydrogen in the target to that with no hydrogen was approximately 10. The rate with no hydrogen can be accounted for by assuming that the source of interactions was the material in the walls of the empty hydrogen container. There is no a priori reason to suppose that the polarization of the Σ hyperons produced in the heavy nuclei of the container was equal to that in π-p collisions. However, for lack of information on this point, we have assumed that these polarizations were equal. For the cases in which we find a very small value of $\alpha\bar{p}$, this assumption is of little consequence; for the case in which we find a nonzero value, it introduces an uncertainty of about 10%. This error is much smaller than the statistical uncertainty and has been neglected.

In addition to the time-distribution curves, presented in the next section to show that the K telescopes indeed select K mesons, we have also measured the number of K-meson counts when the energy of the pion beam was reduced to 800 Mev, which is below the threshold. The result was that the number of counts obtained in which C was delayed by more than 5 mμsec was equal to that expected for background chance coincidences only.

We have remarked earlier that the kinematics of the reactions allowed, for the most part, only the pions to reach counters L and R. However, in $12 \pm 5\%$ of the cases in which a pion was detected, the nucleon struck the opposite counter as well. Also, in 7% of the cases in which one of the γ rays from the π^0 meson struck one of the counters, the other γ ray struck the opposite counter. These events led to a small fraction of cases in which both Counters L and R gave simultaneous pulses; the ratio of these to cases in which only one counter gave a pulse was: for Σ^-, 0.032 ± 0.007; for Σ^+ with no Pb, 0.06 ± 0.01; and for Σ^+ with Pb, 0.8 ± 0.2. The events in which L and R gave simultaneous pulses allow us to make an empirical correction for the number of events in which the nucleon alone was counted. Such events, of course, gave an asymmetry of sign opposite to that of the pions. A relatively small correction has to be made to the value of $\alpha_{\bar{p}}$ for $\Sigma^+ \rightarrow \pi^+ + n$ for this effect. For the other decays, the correction was negligible.

IV. RESULTS

The time distributions for the particles that produced pulses in the C counters in coincidence with G_u and G_d are given in Fig. 5 for each situation in which we have obtained measurements. The observed data have been corrected for an accidental background amounting to about 6% of the total counts. This correction has been estimated by using the information from C coincidences with negative time delays, and from counting rates obtained with the C counter delayed by 160 mμsec. The solid curves, shown in Fig. 5, are the result of folding the empirical resolution curve with a pure exponential of mean life equal to 1.22×10^{-8} sec.[10] These

curves are normalized in abscissa to the zero time known from the measurements for ϵ and in ordinate to give the best visual fit to the points with time delays greater than 6 mμsec.

Clearly, there was a background of coincidences near time zero which cannot be ascribed to K mesons. When the solid-line curve is subtracted from the observed values, the points shown as open squares are obtained. The excellent fit with the dashed resolution curve shows that this background was very probably due to protons or to fast pions which were accepted because the G coincidence did not perfectly bias out all fast particles. The determination of $\alpha\bar{p}$ appears to us to be most reliable if we consider only those coincidences in which C was delayed by more than about 5 mμsec. For the results reported here, this procedure was followed.

The chance coincidences which appeared with negative time decays for C were sometimes associated with an L or R pulse. The measured "asymmetry" for these chance coincidences is very small. In evaluating $\alpha\bar{p}$, therefore, we have treated the background as having zero asymmetry. For C time delays greater than ~30 mμsec, a large fraction of the rate was due to chance coincidences. For evaluating $\alpha\bar{p}$, we have therefore accepted only those counts with delays less than this value. Three per cent of the L or R pulses coincident with a K count were due to chance background. A correction was applied for this effect.

The mean life of the K^+ mesons accepted with delays between 6 and 30 mμsec has been evaluated in each case by means of a least-squares fit of the data. The values shown on Fig. 5 are in excellent agreement with the published values.[10] We believe therefore that, except for the chance background discussed above, the K^+ counts accepted for the asymmetry analysis contain less than 5% of particles not true K^+ mesons.

The experimental values of $\alpha\bar{p}$ and ϵ are given in Table I (the errors are statistical standard deviations). The values of $\alpha\bar{p}$ for Σ^- hyperons produced by pions in hydrogen bubble chambers are also given in Table I. We have given the values for Σ^+, with and without Pb, in order to indicate which part of the error in the asymmetry is statistical. The values deduced for $\alpha\bar{p}$ for the two decay modes include additional errors due to uncertainty in the branching ratio and in the conversion probability for the π^0 γ rays.

We conclude that for $\Sigma^- \rightarrow \pi^- + n$, at both energies, the value of $\alpha\bar{p}$ does not differ significantly from zero. Therefore, no conclusion with respect to parity nonconservation can be drawn.

On the other hand, from the asymmetries for Σ^+ hyperons with and without Pb, a violation of parity conservation is quite strongly indicated. The value for $\alpha\bar{p}$ obtained with Pb differs from zero by 3.3 standard deviations. The chance of observing a value as large as or larger than this in a single measurement, if the true value were zero, is roughly 1/1000. If the true asymmetry were zero for each of the eight series of measurements, the chance that one of them would show a value as large as this or larger is about 1/100.

The error quoted is purely statistical. From the four values of ϵ reported above, we conclude that the systematic error due to an intrinsic asymmetry in the apparatus is probably less than 0.03. For the Σ^+ hyperons, with Pb, the asymmetries obtained separately with the U and D telescopes show the expected reversal of sign (Eq. (8)); the values of $\alpha\bar{p}$ are $+0.21 \pm 0.09$ and $+0.19 \pm 0.08$, respectively. The internal consistency of the data indicates that the systematic errors are small compared with the statistical errors.

Table I

Values of the asymmetry parameter $\alpha\bar{p}$ for Σ^+- and Σ^--hyperon decay. The asymmetry parameter ϵ for inelastic pion-proton collisions is a measure of the geometrical symmetry of the apparatus.

Process	Incoming pion kinetic energy (Bev)	$\alpha\bar{p}$	ϵ	$\alpha\bar{p}$ from bubble chamber observations[a]
$\Sigma^- \rightarrow \pi^- + n$	1.0	$+0.018 \pm 0.050$	-0.004 ± 0.036	0.11 ± 0.13
$\Sigma^- \rightarrow \pi^- + n$	1.1	-0.058 ± 0.050	$+0.008 \pm 0.021$	0.04 ± 0.13
$\Sigma^+ \rightarrow \pi^+ + n$, $\Sigma^+ \rightarrow \pi^0 + p$ without Pb radiator	1.0	$+0.039 \pm 0.050$	$+0.04 \pm 0.03$	
$\Sigma^+ \rightarrow \pi^+ + n$, $\Sigma^+ \rightarrow \pi^0 + p$ with Pb radiator	1.0	$+0.20 \pm 0.06$	$+0.004 \pm 0.043$	
$\Sigma^+ \rightarrow \pi^+ + n$	1.0	$+0.02 \pm 0.07$		
$\Sigma^+ \rightarrow \pi^0 + p$	1.0	$+0.70 \pm 0.30$		

[a]Proceedings of the 1958 Annual International Conference on High Energy Physics at CERN, p. 267, and Frank S. Crawford, Jr. (UCRL), private communication.

The value of $\alpha\bar{p}$ deduced for $\Sigma^+ \rightarrow \pi^+ + n$ does not differ significantly from zero, so that the observed asymmetry with Pb is ascribed to the mode $\Sigma^+ \rightarrow \pi^0 + p$.

V. CONCLUSIONS

The value $\alpha^0\bar{p} = 0.70 \pm 0.30$ strongly indicates the nonconservation of parity for this decay.[13] For $|\alpha^0\bar{p}| > 0.27$, invariance under charge conjugation is violated as well,[14] and our measurements indicate that this is probably the case.

Since $|\alpha^0| \leq 1$, then we have $|\bar{p}| \geq 0.70 \pm 0.30$ for the Σ^+ hyperons produced in this reaction. Since the Σ^+ hyperons are polarized, our measurement of $\alpha^+\bar{p}$ becomes especially significant. From the value $\alpha^+\bar{p} = +0.02 \pm 0.07$, we conclude that $|\alpha^+| \leq 0.03 \pm 0.11$.

We can draw no further conclusions from our results unless we make some hypothesis which connects the final-state s- and p-wave amplitudes of all the Σ-hyperon decays. One such hypothesis is that the change in isotopic spin in weak decays obeys the rule $\Delta I = \pm 1/2$. This possibility has been discussed by several authors.[15] The present experimental evidence from the branching ratio in Λ^0 and θ^0 decay appears to be in reasonable agreement with this assumption.[16] Following closely the discussion of Gell-Mann and Rosenfeld,[17] we assume that the $\Delta I = \pm 1/2$ rule holds, that the decay is invariant under time reversal, and that the spin of the Σ is 1/2.[15] The number of amplitudes then required to describe all the Σ-hyperon decays is reduced from six to four; the s- and p-state amplitudes for decays to final states with $I = 1/2$ and $I = 3/2$. The three known decay rates W^+, W^-, and W^0, together with our value of

$|\alpha^+| \leqslant 0.03 \pm 0.11$, are sufficient to determine the four constants. The absolute values of α^- and α^0 can then be computed and compared with the measurements. Gell-Mann and Rosenfeld have shown that, within about 10%, the decay rates allow us to write the α's in terms of a common angle ν_-, thus:

$$\alpha^+ = -\sin 2\nu_- ;\ \alpha^- = \sin 2\nu_- ;\ \alpha^0 = \pm \cos 2\nu_- ;$$

then:

$$\alpha^+ = -\alpha^- \leqslant \pm (0.03 \pm 0.11),$$

$$\alpha^0 = \pm (0.99 \pm 0.01),$$

and for Σ^+ hyperons: $|\bar{p}| = 0.70 \pm 0.30$.

Our results given in Table I are clearly consistent with the $\Delta I = \pm 1/2$ assumption for Σ decay.

Our values are not consistent with an interaction of the form

$$L = \frac{g}{\sqrt{2m}} \psi^+_n \beta\gamma_\mu (1+\gamma_5) \psi_Y \frac{\partial}{\partial \chi_\mu} \phi \tag{10}$$

similar to that suggested by Feynman and Gell-Mann.[18] For this interaction, a large value for α^0 requires a large value for α^+.

T. D. Lee[19] has suggested to us that Eq. (10) might have to be generalized because of the nonconservation of strangeness in the decay and because more than one isotopic spin state is involved. Specifically he suggested that we try to fit an empirical interaction of the form

$$L = \frac{g}{\sqrt{2m}} \psi^+_n \beta\gamma_\mu (a + b\gamma_5) \psi_Y \frac{\partial}{\partial \chi_\mu} \phi , \tag{11}$$

which should apply to all hyperon decays, Λ^0 as well as Σ. Assuming again $\Delta I = \pm 1/2$, and time-reversal invariance, we can obtain a_1, a_3, b_1 and b_3, which are the amplitudes for the isotopic spin $I = 1/2$ and $I = 3/2$ states of

the s and p waves in the final π-p system. To determine the four constants, we use the three values of the Σ decay rates W^+, W^-, and W^0 given by Barkas and Rosenfeld[20] together with our value for $|\alpha^+| \leqslant 0.03 \pm 0.11$. In addition to a sign ambiguity, there are two possible solutions to fit these four values; Case 1 with b_3 small and Case 2 with a_3 small. The values are given in Table II. The absolute values are not determined unless the coupling constant g is known, so that the values given in the tables may need to be multiplied by a common factor.

Using these values and the interaction (11), we may now compute α^- and α^0 for the Σ hyperon, the ratio of, say, the total decay rate of Λ^0 to that of Σ^-, and the absolute value of α for Λ^0 decay. The decay rate of each hyperon is given by[19]

$$W = [g^2/2m^2][p(E+M)/(E+\omega)]\ \{|a|^2[\omega + p^2/(E+M)]^2 + |b|^2[1+\omega/(E+M)]^2 p^2\}, \tag{12}$$

where

m = pion rest mass,

M = nucleon rest mass,

p = momentum of the pion (nucleon),

ω = total energy of the pion,

E = total energy of the nucleon,

while the asymmetry parameter is given by

$$\alpha = -(a^* b + b^* a)\{p[\omega + p^2/(E+M)][1+\omega/(E+M)]\}/\{|a|^2[\omega+p^2/(E+M)]^2 + |b|^2[1+\omega/(E+M)]^2 p^2\}. \tag{13}$$

Corresponding to Cases 1 and 2, there are two values for W and for α. They are given in Table III. As before the values are consistent with the

Table II

The relative s- and p-wave amplitudes for the isotopic spin 1/2 and 3/2 states in the decay of Σ hyperons. The amplitudes were calculated by assuming an interaction in the form of Eq. (11), the validity of the $\Delta I = \pm 1/2$ rule, and invariance of the interaction under time reversal. Part A is for the case in which b_3 is small; Part B for a_3 small. Note that although the signs of the amplitudes are undetermined, the sign of a_1 must be the same as a_3 and of b_1 the same as b_3, but a_1 need not have the same sign as b_1.

Isotopic spin	Relative s-wave amplitude	Relative p-wave amplitude
A. For b_3 small		
$I = 1/2$	$a_1 = \pm(0.36 \pm .08)$	$b_1 = \pm(1.31 \pm .08)$
$I = 3/2$	$a_3 = \pm(0.72 \pm .04)$	$b_3 = \pm(0.02 \pm .10)$
B. For a_3 small		
$I = 1/2$	$a_1 = \pm(1.09 \pm .07)$	$b_1 = \pm(0.43 \pm .10)$
$I = 3/2$	$a_3 = \pm(0.02 \pm .08)$	$b_3 = \pm(0.87 \pm .05)$

Table III

The calculated and observed values of the asymmetry parameters in hyperon decay and the ratio of the Λ^0- to Σ^--decay rates. They are computed on the basis of an interaction of the form Eq. (11), using the amplitudes given in Table II. Note that although the signs of the α's are not determined, the relative signs are determined and must all be the same.

	Case 1 (Table II-A)	Case 2 (Table II-B)	Experimental (Absolute Values)
α^-	$\pm(0.05 \pm .23)$	$\pm(0.05 \pm .23)$	
α^+			$\leqslant 0.03 \pm .11$
α^0	$\pm(0.97 \pm .03)$	$\pm(0.97 \pm .03)$	$\geqslant 0.7 \pm .3$
$\alpha^-_{\Lambda^0}$	$\pm(0.74 \pm .17)$	$\pm(0.46 \pm .1)$	$\geqslant 0.70 \pm .10$*
$\alpha^0_{\Lambda^0}$	$\pm(0.74 \pm .17)$	$\pm(0.46 \pm .1)$	
$W_{\Lambda^0}/W_{\Sigma^-}$	$0.40 \pm .06$	$0.63 \pm .09$	$0.66 \pm .07$*

*Proceedings 1958 Annual International Conference on High Energy Physics at CERN, pp. 265 - 273.

observations on the Σ hyperon. Neither case is a good fit to the observed values for both α and W_Λ / W_{Σ^-} in Λ^0 decay. Yet taking into account our errors, and those in the lifetime measurements, agreement with one or the other set of values is not highly improbable. The analysis of ${}_\Lambda H^4$ and ${}_\Lambda He^4$ hyperfragment decays by Dalitz[21] indicates that for Λ^0 hyperons the absolute value of the ratio of the p-wave to s-wave amplitude is less than unity. For our Case 1, the absolute value of this ratio is computed to be 2.3 ± 0.5; for Case 2, 0.26 ± 0.05. Case 2 is therefore to be preferred.

The interaction (11), together with the observations reported here, gives values for $|\alpha|$ in decay modes of hyperons for which asymmetries have not yet been measured. Since theory predicts that the longitudinal polarization of the decay nucleon is equal to $-\alpha$,[22] nearly complete longitudinal polarization is to be expected for the proton from the decay $\Sigma^+ \rightarrow \pi^0 + p$. From Eq. (11), the sign of the polarization should be the same as that of the proton in $\Lambda^0 \rightarrow \pi^- + p$. The longitudinal polarization of the neutrons in the decays of $\Sigma^- \rightarrow \pi^- + n$ and $\Sigma^+ \rightarrow \pi^+ + n$ should be small, while for the Σ^+-hyperon production process used here, the transverse polarization is large. The partial success of this model emphasizes again the importance of measurements of the polarization of the nucleons from hyperon decay.

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FIGURE CAPTIONS

Fig. 1. Schematic arrangement of the pion beam.

Fig. 2. The horizontal and vertical intensity distributions of the pion beam at the center of the hydrogen target.

Fig. 3. Elevation and plan view showing the arrangement of counters and the liquid hydrogen container.

Fig. 4. Simplified block diagram of the counters and basic electronics. L, R, S_1, S_2, S_3, and G are plastic scintillation counters; A, B, and C are water-filled Cherenkov counters. D represents pulse-height discriminators.

Fig. 5a. Time-delay distributions of the C pulse with respect to the S_3 pulse for $\pi^- + p \rightarrow \Sigma^- + K^+$, 1.0 Bev. The dashed lines are normalized empirical time-resolution curves for the apparatus. The solid circles are the total counting rate after subtraction of the chance coincidence background. The solid line is the distribution calculated for pure K^+ mesons including a folding of the resolution curve. The open squares are obtained by a subtraction of the solid-line curve from the total counting rates.

Fig. 5b. Time-delay distributions of the C pulse with respect to the S_3 pulse for $\pi^- + p \rightarrow K^+ + \Sigma^-$, 1.1 Bev. The dashed lines are normalized empirical time-resolution curves for the apparatus. The solid circles are the total counting rate after subtraction of the chance coincidence background. The solid line is the distribution calculated for pure K^+ mesons including a folding of the resolution curve. The open squares are obtained by a subtraction of the solid-line curve from the total counting rates.

Fig. 5c. Time-delay distributions of the C pulse with respect to the S_3 pulse for $\pi^+ + p \rightarrow \Sigma^+ + K^+$, 1.0 Bev. The dashed lines are normalized empirical time-resolution curves for the apparatus. The solid circles are the total counting rate after subtraction of the chance coincidence background. The solid line is the distribution calculated for pure K^+ mesons including a folding of the resolution curve. The open squares are obtained by a subtraction of the solid-line curve from the total counting rates.

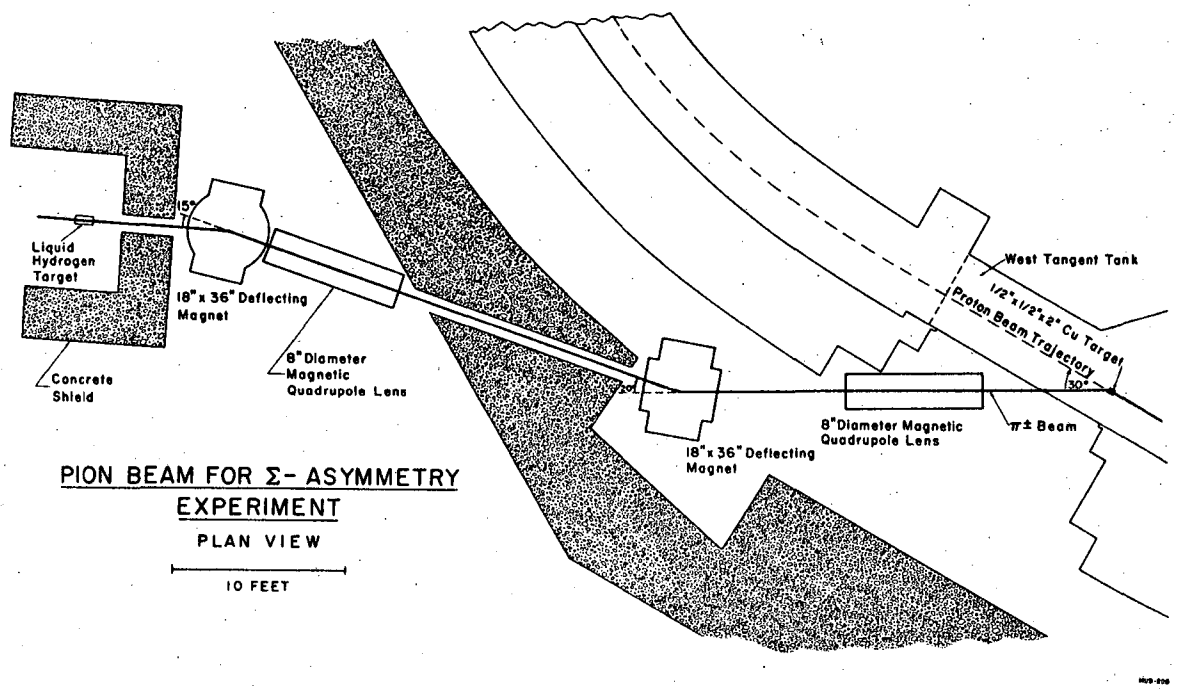

15°
Liquid Hydrogen Target
18" x 36" Deflecting Magnet
8" Diameter Magnetic Quadrupole Lens
Concrete Shield
West Tangent Tank
1/2" x 1/2" x 2" Cu Target
Proton Beam Trajectory
30°
8" Diameter Magnetic Quadrupole Lens
π± Beam
18" x 36" Deflecting Magnet
PION BEAM FOR Σ- ASYMMETRY EXPERIMENT
PLAN VIEW
10 FEET

Fig. 1.

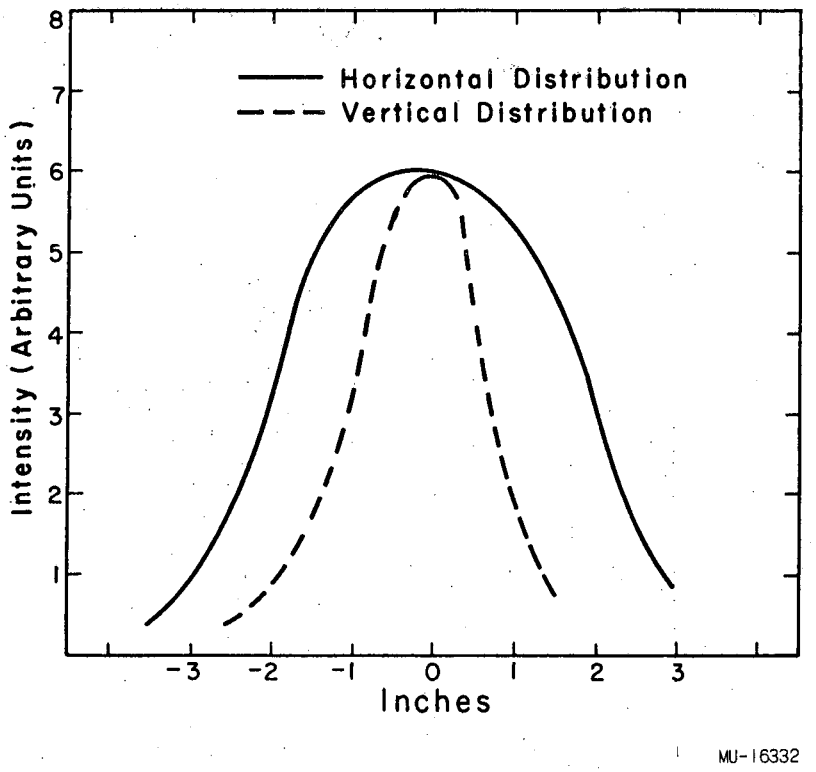
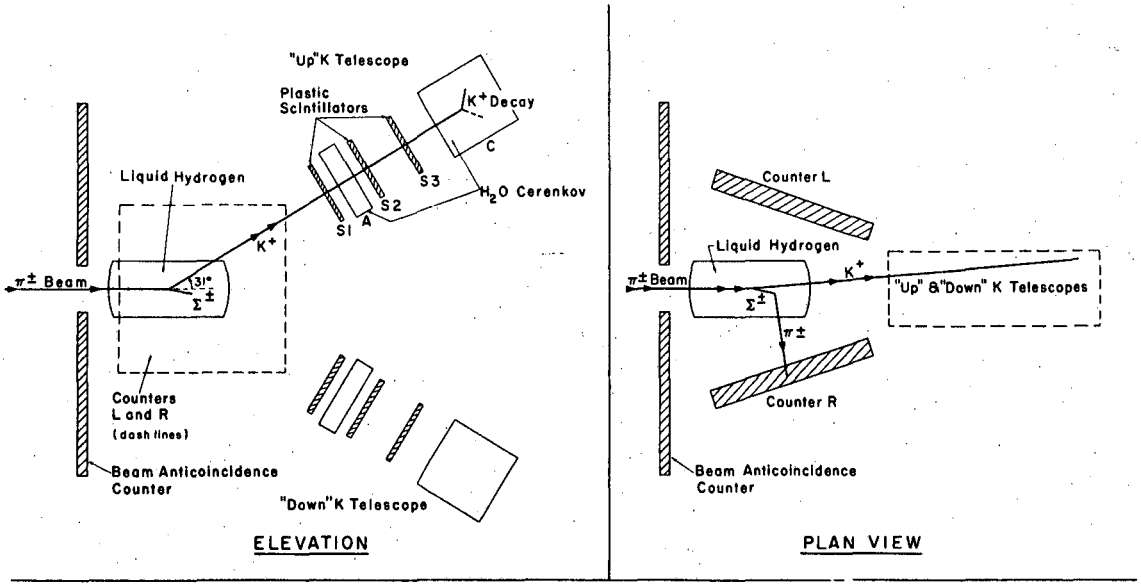

Horizontal Distribution
Vertical Distribution
Intensity (Arbitrary Units)
8
7
6
5
4
3
2
1
-3
-2
-1
0
1
2
3
Inches
MU-16332

Fig. 2



CROSS SECTION OF COUNTER ARRANGEMENT

Fig. 3

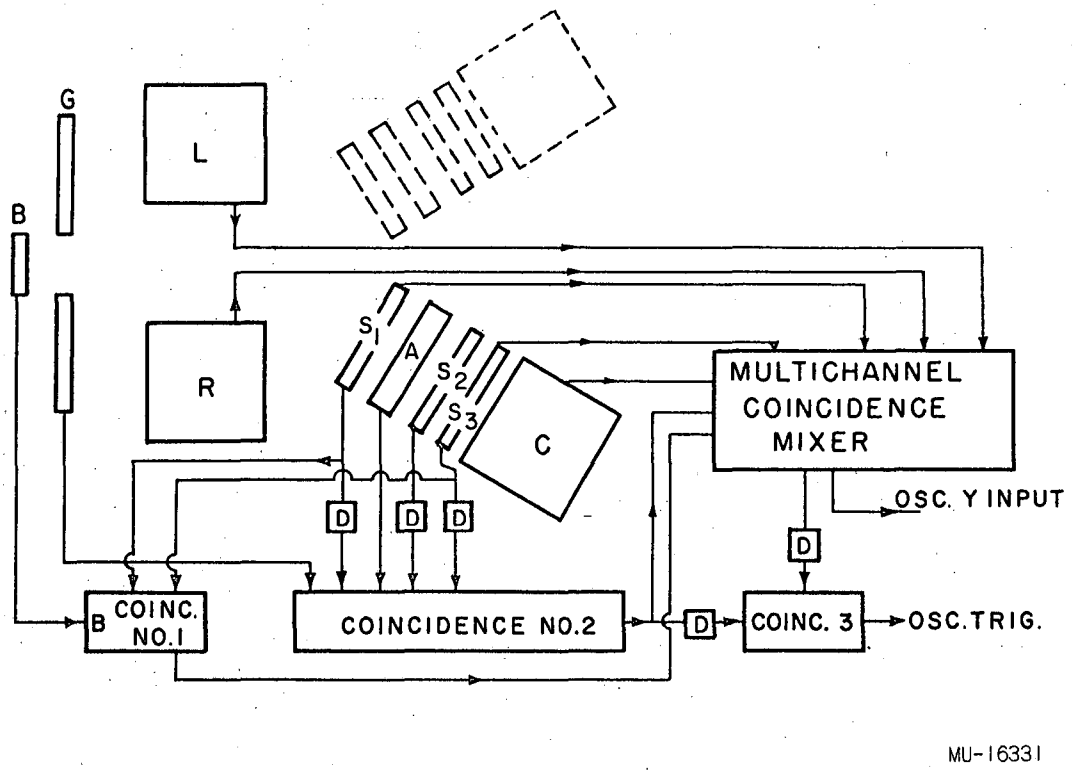

G
L
B
R
S1
A
S2
S3
C
MULTICHANNEL
COINCIDENCE
MIXER
OSC. Y INPUT
D
D
D
D
B
COINC.
NO.1
COINCIDENCE NO.2
D
COINC. 3
OSC.TRIG.
MU-16331

Fig. 4

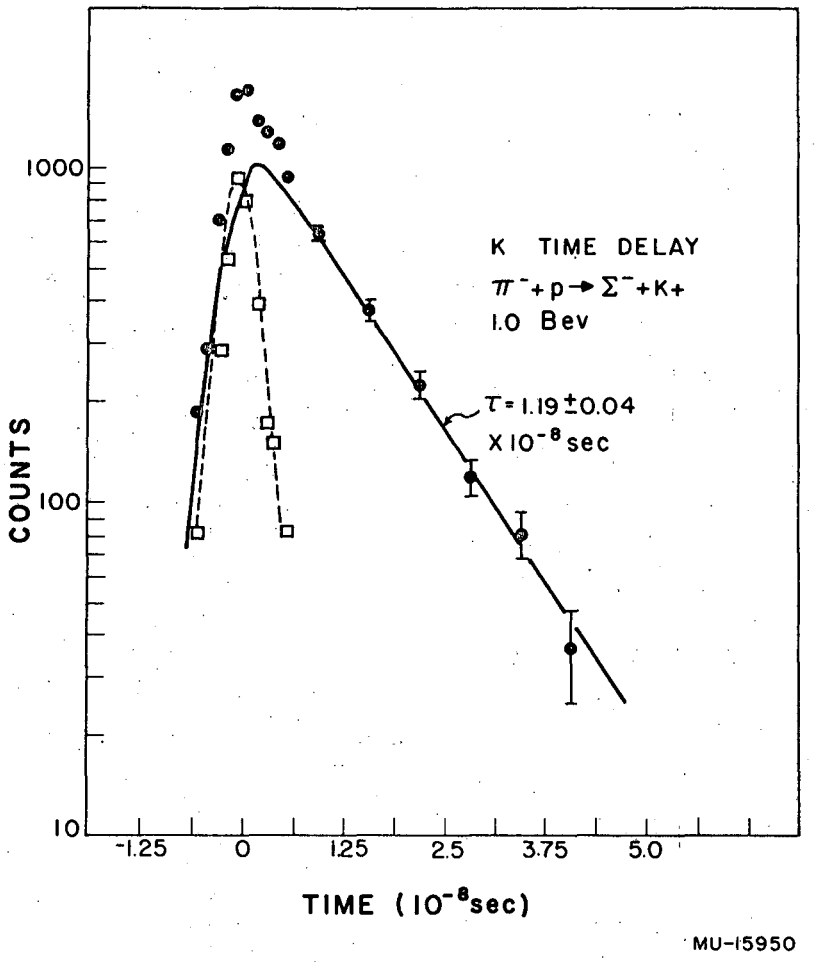
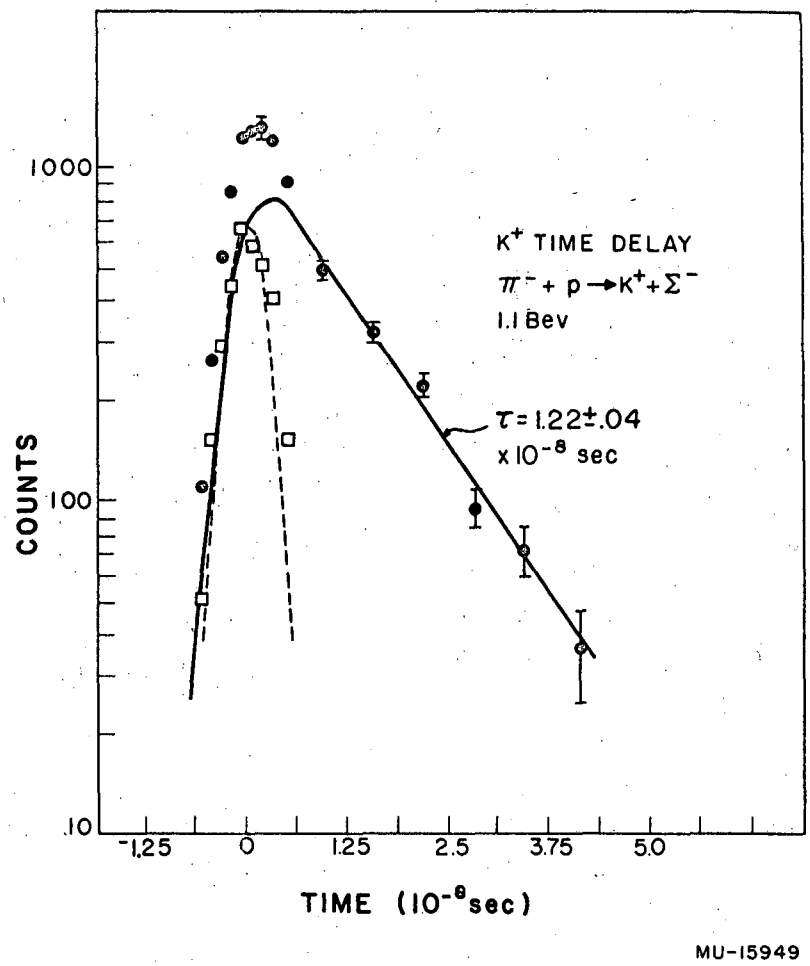

K TIME DELAY
$\pi^- + p \rightarrow \Sigma^- + K^+$
1.0 Bev
$\tau = 1.19 \pm 0.04$
$\times 10^{-8}$ sec
COUNTS
1000
100
10
-1.25
0
1.25
2.5
3.75
5.0
TIME (10^{-8}sec)
MU-15950

Fig. 5a



MU-15949

Fig. 5b

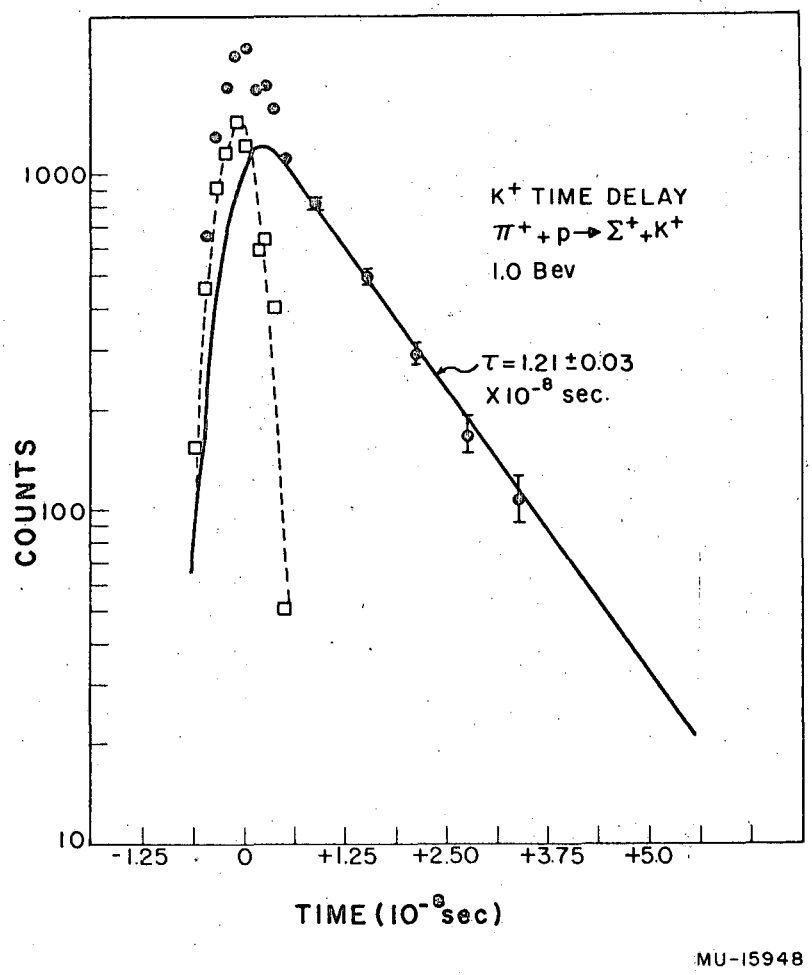

K+ TIME DELAY
π+ + p → Σ+ + K+
1.0 Bev
τ = 1.21 ± 0.03
X 10-8 sec.
COUNTS
1000
100
10
-1.25
0
+1.25
+2.50
+3.75
+5.0
TIME (10-8 sec)
MU-15948

Fig. 5c

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