*Work supported in part by the U. S. Atomic Energy Commission.

[1]F. T. Dao *et al.*, Phys. Rev. Lett. 29, 1627 (1972). These data have not been included in the present work.

[2]The muon contamination in the beam has been measured to be $\leq 0.2\%$. For this measurement the beam intensity was increased by a factor of 22 above normal running intensity, and the bubble chamber was run with a muon shield in the beam line. The incident tracks were counted and corrections were made for possible muon scattering out of the beam line.

[3]Lou Voyvodic, private communication.

[4]In the calculation of the transverse-momentum imbalance, the fast outgoing proton was assigned a momentum equal to that of the beam, and its azimuth about the lens axis at the vertex was recomputed using this momentum. The resulting resolution in the transverse momentum is ± 100 MeV/c. The uncertainty in this procedure is reflected in the errors assigned to the elastic and two-prong inelastic cross sections.

[5]This correction was made by extrapolating $d\sigma/dt$ from $|t| = 0.04$ (GeV/c)^2 to $|t| = 0$ with the same slope, b. We have studied the dependence of the small-t correction to the two-prong cross section as a function of the missing mass recoiling from the slow identified proton and find no evidence for any such dependence. We believe that this correction to the two-prongs for the systematic scanning loss at low $-t$ applies to both elastic and inelastic two-prongs.

[6]The form $d\sigma/dt = Ae^{bt+ct^2}$ may be preferable to the form with $c = 0$ in the region near $|t| \approx 0.1$ (GeV/c)^2, because a "break" in the t distribution has been reported in this region. See U. Amaldi, in proceedings of the Second International Conference on Elementary Particles, Aix-en-Provence, 1973 [J. Phys. (Paris) Suppl. 34, C1-241 (1973)]. Nevertheless, although our data do not require such a "break" in the t distribution, we find that an arbitrary adoption of the two slopes obtained in the ISR experiment at approximately this energy [11.57 ± 0.03 and 10.42 ± 0.17 (GeV/c)$^{-2}$, from G. Barbiellini *et al.*, Phys. Lett. 39B, 663 (1972)] will result in an increase in the elastic cross section in this experiment of only 0.11 mb.

[7]H. R. Gustafson *et al.*, Phys. Rev. Lett. 32, 441 (1974).

[8]S. Childress *et al.*, Phys. Rev. Lett. 32, 389 (1974); V. Bartenev *et al.*, *ibid.* 31, 1088 (1973).

[9]See Table I of F. T. Dao *et al.*, Phys. Rev. Lett. 30, 1151 (1973).

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Measurement of the K_S branching ratio into two pions*

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A spark-chamber experiment to measure the branching ratio of the short-lived K_1 meson into the modes $\pi^+\pi^-$ and $\pi^0\pi^0$ was performed at the Princeton-Pennsylvania Accelerator. A 1.0-GeV/c beam of incident π^- mesons produced $\Lambda^0 K^0$ from a polyethylene target. The decay of Λ into $\pi^- p$ was used as a signal for the associated production of a K^0. A total of 160 000 pictures, taken in two views, were completely scanned for V's (charged decays of neutral particles), and all tracks were measured. A final sample of 16 000 K_1 charged decays and 65 000 Λ^0 charged decays directly determined the branching fraction for K_1 to decay into $\pi^+\pi^-$ to be 0.684 ± 0.009. The branching ratio found by this experiment is then $\Gamma(K_1 \to \pi^+\pi^-)/\Gamma(K_1 \to \pi^0\pi^0) = 2.169 \pm 0.094$.

INTRODUCTION

In 1964 the discovery of CP violation by Christenson *et al.*[1] revived interest in a better measurement of the properties of the neutral K meson. In particular, it was pointed out by Wu and Yang[2] that CP violation, if it occurs directly in the decay channel $K^0 \to 2\pi$, must be due to a nonvanishing imaginary part of the amplitude A_2 for the decay of a neutral K into two pions in a state with isospin 2.

The phenomenological treatment of $K^0 \to \pi\pi$ decay requires, in general, the introduction of the quantities $\mathrm{Re}(A_2/A_0)$ and $\mathrm{Im}(A_2/A_0)$, and the knowledge of the $\pi\pi$ scattering phases at the K^0 mass, or rather, the difference $\delta(I=2, L=0) - \delta(I=0, L=0)$. Of course, a nonvanishing $\mathrm{Re}(A_2/A_0)$ implies a direct violation of the $\Delta I = \frac{1}{2}$ rule in the two-pion decay of the K^0 meson. It is easy to show that

$$R = \frac{\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^0\pi^0)} = 2 + 6\sqrt{2}\,[\mathrm{Re}(A_2/A_0)\cos(\delta_2 - \delta_0)]$$

apart from phase-space and radiative corrections.

Although the $\Delta I = \frac{1}{2}$ rule was invented to explain the properties of the K mesons, such as the relation between the decay rates of $K^+ \to 2\pi$ and $K^0 \to 2\pi$ $[\Gamma(K^+ \to 2\pi)/\Gamma(K^0 \to 2\pi) \ll 1]$, it has always been a somewhat embarrassing point, both theoretically and experimentally, because while the isospin properties of the various parts of the weak hadronic current are reasonably well established experimentally, and fit naturally into a unified phenomenology (the Cabibbo theory), the very same phenomenology cannot in any straightforward and simple way explain why nature favors so strongly $\Delta I = \frac{1}{2}$ transitions over $\Delta I = \frac{3}{2}$ transitions, which should naturally appear in any decay mediated by the product of an $I = \frac{1}{2}$ and an $I = 1$ current. It is believed today that almost all nonleptonic decays of strange particles do not exactly satisfy the $\Delta I = \frac{1}{2}$ rule, but at the time of the discovery of CP violation the case was not clear whether $K^0 \to 2\pi$ decay did or did not satisfy such a rule. Also, for some time it was thought that there was a nonvanishing imaginary part of A_2. For all these reasons, a series of experiments was undertaken in many laboratories in order to obtain new accurate values for the branching ratio R and ultimately to determine $\mathrm{Re}(A_2/A_0)\cos(\delta_2 - \delta_0)$.

I. EXPERIMENTAL METHOD

The main idea of our experiment was to use associated production to generate a unique signal for the presence of a neutral K^0 meson, using, in particular, the reaction $\pi^- p \to \Lambda^0 K^0$. Strangeness and charge conservation guarantee that whenever a Λ^0 is observed a K^0 is also present. Notice also that $\pi^- n \to \Lambda^0 +$ anything is forbidden below the threshold for production of at least an extra pion.

We used counters and spark chambers to select examples of this reaction and observe the K^0 decays. The experimental setup, shown in Fig. 1, consisted of a beam telescope composed of counters B_1 and B_2 and anticounter A_1. The target T was placed in front of anticounter A_2 to signal the interaction of a beam π^- producing neutral particles and both were placed in contact with the spark chamber C_3. The downstream counter (H_H, H_V) signaled the appearance of charged particles.

Such an arrangement, in the ideal case of vacuum between the anticounter and the last counter, can only be triggered by a neutral particle produced in the target and subsequently decaying in the vacuum before the last counter. This scheme has been successfully used in many previous experiments. We introduced some improvement by using as the last counter a 10×10 or 100-element hodoscope. The hodoscope properties were such that most of the protons from the $\Lambda^0 \to p\pi^-$ decay would traverse it, and in addition, the probability that two distinct decay products would cross the same element was negligible. This allowed us to perform specific ionization measurements and preferentially trigger on protons from Λ's rather than pions from K decay or electrons from the ever-present electromagnetic background. The hodoscope was sensitive to protons with momentum less than about 700 MeV/c and pions with momentum less than about 100 MeV/c. The trigger setup had high efficiency (70% of the pictures had a Λ^0) and was insensitive to the K_S decay mode. The trigger requirement was a signal from each of B_1, B_2, $\bar{A}_1$, $\bar{A}_2$, H_H, and H_V, where H_H and H_V stand for at least one of the horizontal or vertical hodoscope counters.

The remainder of the setup is quite conventional. Thin-foil chambers C_1 and C_2 before the target gave the track of the beam particles, and the 40-plate thin-foil chamber C_3 after the anticounter gave the track of the charged decay particles. For the average momentum of the Λ^0 and K^0 in our experiment, the 25-cm length of the chamber C_3 represented about 8 Λ^0 lifetimes, 14 K_S life-

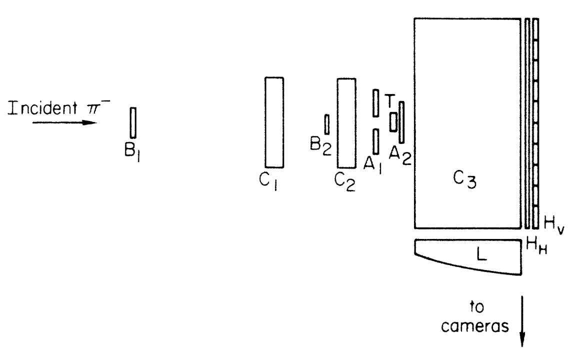

FIG. 1. Diagram of apparatus (not to scale). The incident π^- beam traversed the counters B_1, B_2 and the hole in A_1, and was recorded in the thin-foil chambers C_1 and C_2. The anticounter A_2 was triggered by neutral-particle production from the polyethylene target T. The thin-foil chamber C_3 recorded the decay products of the Λ and K^0. The hodoscope, H_H and H_V, was set to trigger on the proton from Λ decay.

TABLE I. The number of each type of event occurring in the physicist-scanned portion of the film, and corresponding estimates for the portion not scanned by physicists.

	Events scanned	Events not scanned	Total
Λ only	6726	38 462	45 188
Λ + single track	1823	5590	7413
Λ + two-track K	2092	10 753	12 845
Initial excess candidates	1740	6208	7948
Total	12 381	61 013	73 394

TABLE II. The final classification of events in each category.

	Events scanned	Events extrapolated	Total	Error
Uncertain	6	23	29	10
Λ only	7820	41 053	48 873	259
Λ+uncertain K	13	51	64	15
Λ+one-track K	355	1141	1496	59
Λ+two-track K	2536	11 965	14 501	143
Uncertain ΛK	4	12	16	6
Initial excess candidates	2077	8159	10 236	161
Total	12 811	62 404	75 215	

times, and 0.02 K_L lifetimes. The entire apparatus was in a 13-kG magnetic field and two cameras gave a 15° stereo record of each event. A large cylindrical Lucite lens L placed at the side of the chamber made the tracks within completely visible from both cameras. The target was polyethylene, 6.35 mm thick, located in contact with the anticounter A_2. While it is not necessary to know the absolute locations of the target and the target counter, their thicknesses are critical parameters in the determination of the number of $K^0 \rightarrow \pi^+ \pi^-$ which decay before the anticounter and veto the event. To reduce this correction, which will be discussed again later, it is important to keep the target as thin as possible. To keep the event yield reasonable, we chose polyethylene, whose high content of free protons approximates a pure hydrogen target. The carbon is light enough to contribute to Λ production without significant absorption or rescattering problems.

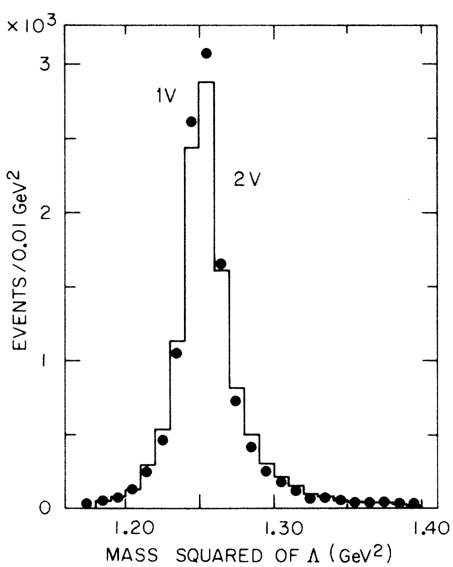

FIG. 2. M_Λ^2 for measured events is shown separately for 40 890 1V events (dots) and 11 532 2V events (histogram). The two samples are normalized to the same total number of events. Loose selection criteria, the same as applied for all remaining figures, eliminated obvious backgrounds.

The experiment was run at an incident momentum of 1.0 GeV/c in the 13° beam at the Princeton-Pennsylvania Accelerator (PPA). Such a beam typically had an intensity of 25 000 π^-/sec, 40% of which was in a circular spot 2.54 cm in diameter, defined by a hole through an auxiliary anticounter just in front of the target. The beam momentum resolution was about 1% and the momentum was chosen to maximize the $\Lambda^0 K^0$ cross section, while remaining below Σ^0 production on free protons. Some Σ^0 were produced from the carbon nuclei, but this is not a source of background since the Σ^0 immediately decays into $\Lambda\gamma$. The effective beam-on time at PPA was 3–4% for our 7-msec spill. This rather short duty cycle, together with the loose beam optics, effectively put through our chambers 2.5 times as many particles as could be used for $\Lambda^0 K^0$ production, and made it impossible for us to use the information from a 50-plate stainless steel cham-

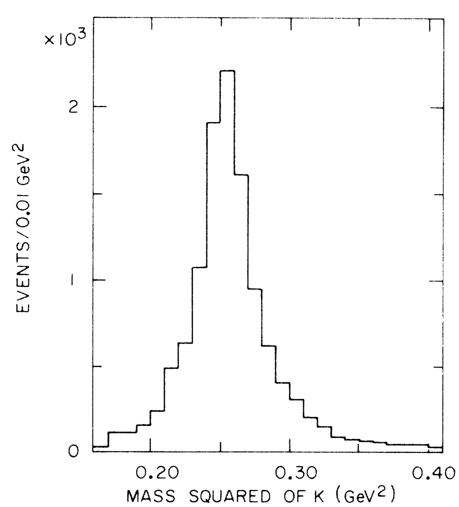

FIG. 3. M_K^2 for 11 532 events.

ber shower detector in which we had hoped to detect single γ's as a signal for $K^0 \to 2\pi^0$. Hence, we determined R using only the charged K^0 decay events.

The determination of the branching ratio consisted of two parts: (a) counting $\Lambda^0 \to \pi^- p$ events (called 1V events) and $\Lambda^0 \to \pi^- p$ together with $K^0 \to \pi^+\pi^-$ events (called 2V events), and (b) computing the correction due to events lost because a charged pion from K^0 decay crossed an anticounter. The first part can literally be done by scanning the spark-chamber pictures. All events, however, were measured to provide the information necessary for part (b) and to prove the validity of part (a). Our main chamber was operated so as to have a very high multitrack efficiency. This was achieved by firing the chamber within 200 nsec of the particle traversal time, and by having a lot of energy available (using large capacitance and moderate voltage). In addition to showing the tracks clearly, the chamber had the property of giving sparks whose intensity was well correlated with the specific ionization of the traversing particle. Thus protons were always identifiable by inspection. Each picture also contained information as to which element of the hodoscope contributed to the trigger.

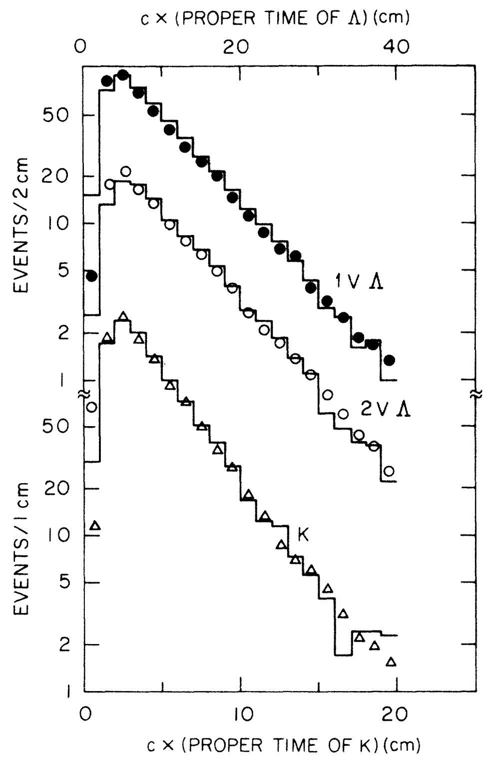

FIG. 4. The proper-time distributions (measured in cm) are shown separately for 40 890 1V events, and 11 532 2V events. The dots, open circles, and triangles represent the Monte Carlo calculation. Please note that both scales for the Λ and K^0 are different.

II. DATA GATHERING AND ANALYSIS

A. Measurement

There were 160 000 pictures taken at a rate of 0.16/sec, of which about 100 000 were actually used in the analysis. A total of 73 400 events were measured, most of them twice. If the beam chamber C_2 contained one and only one beam track and the Λ chamber C_3 contained at least one V for both views, a measurement was made of the beam track, all tracks in the Λ chamber, and the hodoscope trigger information. At least three sparks were required on a track so that both momentum and direction information could be obtained. With the help of this measurement (Table I), we can show that all triggers were due to Λ's (less than 60 events were triggered by K^0 decays) and that Λ's from 1V and 2V events were identical. The initial excess candidates in Tables I and II contain pictures which were measured by the scanners but did not satisfy all the above criteria finally imposed for an acceptable event. The branching ratio can be obtained without bias from any sample of Λ decays as long as no restrictions are imposed on their associated K decays.

The mass distributions of the Λ (Fig. 2) and K^0 (Fig. 3) are shown separately for the 1V and 2V events. The mass distribution of the unambiguous

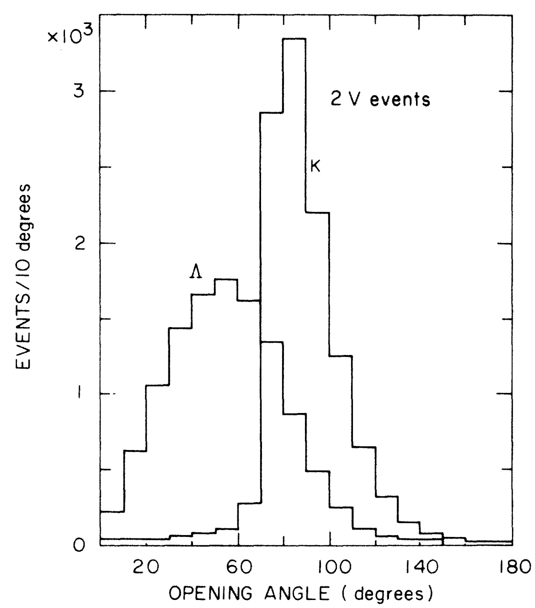

FIG. 5. The opening angle of the V's in 11 532 selected 2V events indicates that at our energy, the K^0 must produce a track at a wide angle to the beam, making detection of both pions at times difficult.

Λ decays ($1V$ events) has the same shape as that of the $2V$ events spectrum. The central values of the mass spectra are $M_\Lambda{}^2 = 1.252$ GeV^2 for the $1V$ events, $M_\Lambda{}^2 = 1.253$ GeV^2 for the $2V$ events, and $M_K{}^2 = 0.2477$ GeV^2. The proper-time distributions are shown separately for the $1V$ and $2V$ events in Fig. 4. From these distributions we obtain $c\tau_\Lambda = 7.71 \pm 0.07$ cm for the $1V$ events, $c\tau_\Lambda = 7.9 \pm 0.1$ cm for the $2V$ events, and $c\tau_K = 3.03 \pm 0.05$ cm. These distributions, especially for the K^0, are altered from their expected slope by pions which go backward into one of the two anticounters. Since the proper-time distributions are for us a consistency check and we are not performing an experiment to measure the lifetimes of Λ's and K's, no attempt was made to correct for this effect in Fig. 4. This indicates our ability to properly associate four tracks into two V's. These checks were based on a sample of 11 500 $2V$'s and 41 000 $1V$'s selected mostly to reject obvious backgrounds such as γ conversions, circular tracks, reflections, and bad measurements. The validity of this selection was checked by the scan, which will be discussed.

The measured data is the starting point to determine various properties of our equipment, such as when a track is detectable, and is the benchmark against which our ability to recreate the contribution of any distribution of relevance is to be compared. We have at this point directly proved that all single V's are Λ's and all double V's are ΛK's, apart from minor corrections at the 1% level. The real problem is that the opening angle for $K^0 \to 2\pi$ decay is rather large at our energy (greater than 60°), as shown in Fig. 5. Thus a reasonable fraction of the K^0 charged decays, amounting to 9%, can give a single track in the chamber since tracks parallel to the plates are essentially undetectable. There were initially 7400 Λ's with an extra track which were candidates for this type of event. The fraction of such events can be predicted by calculation, but it depends crucially on judgments such as how many sparks define a track or how many faint sparks were visible. Very loose criteria can be used to calculate the fraction of events where both tracks are not detected, and this turned out to be 0.0012. Clearly, at this level we do not care too much about the accuracy of this correction (e.g., a 20% error corresponds to an error of 2 parts in 10^4 in the measured ratio), so the burden of the experiment remains on our ability to count single-track decays of the K^0. Kinematic fitting turned out to be extremely cumbersome and not convincing. Our highly selective trigger and the very low density of the chamber C_3, which was 0.01 radiation length long and $\frac{1}{6}$ the density of liquid hydrogen, convinced us that very little background could appear in the chamber and simulate a visible single-track decay of a K^0. The best proof of this came from scanning the film itself.

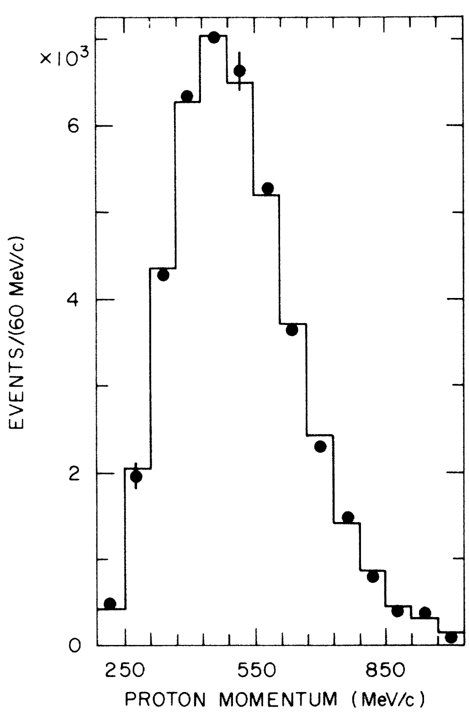

FIG. 6. The proton momentum spectra from the data (histogram) and the Monte Carlo calculation (dots).

III. CHECK SCAN BY PHYSICISTS

We decided to have a large portion of the exposure scanned frame by frame, with all the mea-

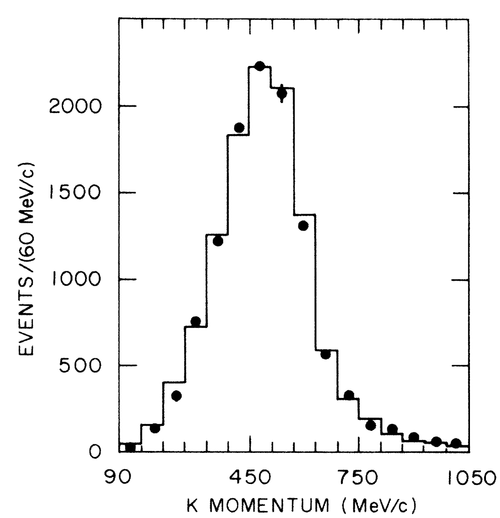

FIG. 7. The K^0 momentum spectra from the data (histogram) and Monte Carlo events (dots).

surements and kinematic fitting results on hand, by two physicists always working together. We were able to eliminate most of the obvious sources of background. We used the $2V$ events to prove that an unrelated single extra track was present in only 0.06 ± 0.01 of the events. The scan also allowed us to classify all events as either Λ or ΛK^0 and find all events missed by the measurers. For 20% of the film we thus have a 100% efficient scan with a total of 12 811 events uniquely classified, and 23 uncertain events. A comparison of this scan with the previous series of measurements allows us to extrapolate to the whole measured sample, and the result is shown in Table II. It should be noted that the 20% sample which was scanned by physicists described above was randomly dispersed across the whole sample to average out any possible peculiarity of measured events in contiguous film rolls.

The final experimental ratio we obtain is

$$r = \frac{\text{observed } K^0 \to \pi^+\pi^-}{\text{observed } \Lambda \to p\pi^-} = 0.2468 \pm 0.0021 .$$

This value is the average of the two extremes corresponding to assigning all uncertain events to opposite classes. The difference between these values is $r_{\max} - r_{\min} = 0.0013$, and, since it is small, $\frac{1}{2}$ of this value has been added in quadrature with the statistical error. The error in the ratio r is computed by first writing it in the form $r = (1+t)^{-1}$, where t is the ratio of $1V$ to $2V$ events. The error on r is smaller than the error on t, as can be seen from the relation $r^{-1}dr = -(1+t)^{-1}dt$.

IV. CORRECTION COMPUTATIONS

The correction for charged decays rejected by a pion crossing the anticounter was computed in a Monte Carlo program incorporating the *a priori* knowledge of the physics of the production reaction in hydrogen and carbon, the decay distributions, and the detector geometry. Counter thresholds in the hodoscope had been measured carefully with the 1.0-GeV/c π^- beam, and the production of the signal by protons or pions from Λ decay in the photomultiplier tube was simulated by the proper Poisson distribution. A similar treatment was used for the anticounter A_2, whose pulse-height distribution for minimum-ionizing particles had been carefully measured. Proton momenta in carbon are known from shell-model theory and direct measurements.[3] The main parameter varied in the calculation was the setting error in measuring the spark position. The other adjusted quantity was the proton illumination of the hodoscope, which implied slight adjustments in the hodoscope element thresholds. Finally, to prove that our simulation of the real world is correct, we show a comparison of various computed distributions with the measured ones.

The distributions of proton momentum from Λ decay (Fig. 6), K^0 momentum (Fig. 7), and transverse "target" momentum (Fig. 8) were selected because they change significantly when the unknown parameters are varied. All of the distributions shown were produced simultaneously from a single calculation and subject to only one constraint, the overall normalization. The K^0 decay angle, shown in Fig. 9, departs from a flat spectrum due to the effects of both the anticounter and the geometrical inefficiency, although the latter only indirectly affects the correction. The detection efficiency determines the admissible Λ decays, and was modeled to conform to those Λ's accepted from the data.

The result of this calculation yields a value of 1.65 ± 0.025 for the ratio of all K^0's which decayed into $\pi^+\pi^-$ to the observed ones. The error includes the consequent changes in the ratio when each input parameter is varied (all other errors, which are very small compared to the aforementioned one, are included and tabulated in Table III). It is very conservative. Combining this correction with the measured ratio we obtain the corrected ratio

$$r_C = \frac{\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(\Lambda \to p\pi^-)} = 0.3510 \pm 0.0043 .$$

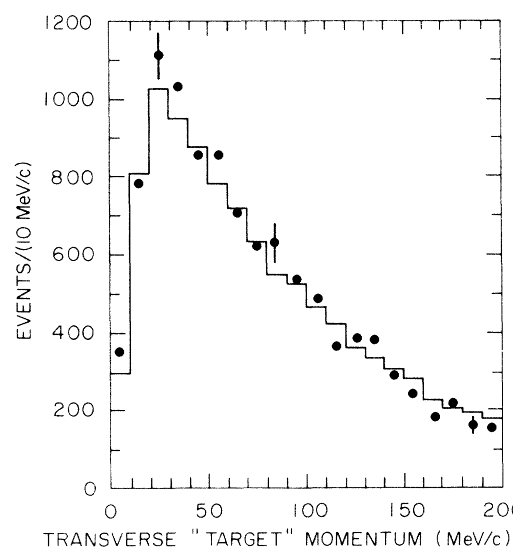

FIG. 8. The transverse "target" momentum is the magnitude of the momentum of the struck proton transverse to the beam, computed from the beam track and the four measured decay tracks from the Λ and K^0 in the $2V$ event. Histogram represents data and dots are Monte Carlo points.

Finally, assuming that the number of K_S's is $\frac{1}{2}$ the number of K^0's produced, we obtain our result for the branching ratio:

$$R = \frac{\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^0\pi^0)} = 2.169 \pm 0.094 .$$

V. RESULTS AND DISCUSSION

The result of this experiment combined with seven other recent measurements[4] of R yields the weighted average $R = 2.204 \pm 0.026$ with $\chi^2 = 7.8$. This world average is used in the following calculations. Using the most recent number for the computed electromagnetic correction,[5] c_{em}, the branching ratio directly yields the quantity

$$\text{Re}\,\frac{A_2}{A_0}\cos(\delta_2-\delta_0) = \frac{R-2-c_{em}}{6\sqrt{2}} = 0.025 \pm 0.003 .$$

To isolate $\text{Re}A_2$, the $\pi\pi$ phase shifts are required. The $I=2$ phase shift is well known, but the $I=0$ phase shift is not well determined and fits to its energy dependence are subject to ambiguities. Here we estimate from the many measurements[6] that the values are $\delta_2 = -7° \pm 3°$ and $\delta_0 = 28° \pm 7°$. With $\delta_2 - \delta_0 = -35° \pm 8°$ we can extract the desired quantity:

$$\text{Re}(A_2/A_0) = 0.030 \pm 0.005 .$$

$\text{Im}(A_2/A_0)$, estimated from the CP violation parameters η_{+-} and η_{00}, is negligibly small compared to $\text{Re}(A_2/A_0)$, so A_2 can be taken as being essentially real. Since A_2 is a combination of $\Delta I = \frac{3}{2}$ and $\Delta I = \frac{5}{2}$ amplitudes which can to some extent be sorted out using the decay rate of K^+ into two pions, we write the amplitudes A_I to find a final state of two pions with isospin I in terms of the reduced matrix elements of isospin-change amplitudes $a_{\Delta I}$:

$$A_0 = (\tfrac{1}{2})^{1/2} a_{1/2} ,$$

$$A_2 = (\tfrac{1}{2})^{1/2} (a_{3/2} + a_{5/2}) ,$$

$$A^+ = (\tfrac{1}{3})^{1/2} (\tfrac{3}{2} a_{3/2} - a_{5/2}) .$$

The decay rate of K_S provides a normalization for these amplitudes: $\Gamma_S = 2|A_0|^2$. $|A^+|$ depends

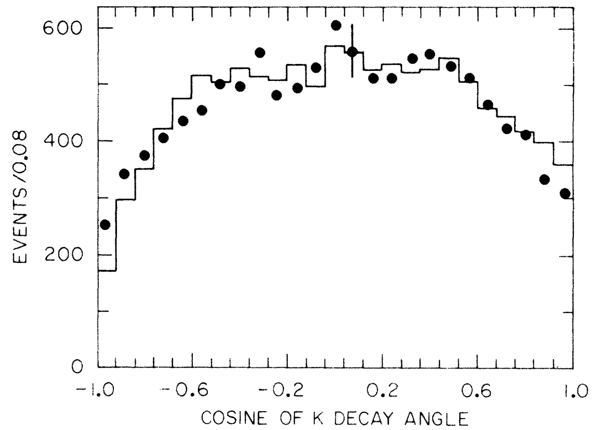

FIG. 9. The K^0 decay angle relative to the K^0 direction deviates from its flat spectrum because pions traveling along the plates of the spark chamber and those which go backward into an anticounter are undetectable. The agreement between the data (histogram) and Monte Carlo events (dots) shows that the model for detection efficiency used in the calculation is correct.

TABLE III. The magnitude of the various corrections shown as a fractional change in the ratio r_C and listed in order of decreasing importance.

1. K_L charged decays counted as K_S	-0.021 ± 0.003
2. Random single tracks counted as K_S	-0.0064 ± 0.0036
3. Nuclear rescattering of K^0 by $K^0p \to K^+n$ making background Λ	$+0.005 \pm 0.003$
4. K_S neutral decay rejected by anticounters	-0.004 ± 0.001
5. Non-anti-K_S charged decays with neither track visible	$+0.0019 \pm 0.0006$
6. Single track from $\gamma \to e^+e^-$ counted as K_S charged decay	-0.0012 ± 0.0006
7. V's from $\gamma n \to \pi^- p$ counted as Λ	$+0.0008 \pm 0.0006$
8. Events produced out of target	$+0.0003$
9. Nuclear rescatter of Σ^- by $\Sigma^- p \to \Lambda n$ produced in $\pi^- p \to \Sigma^- K^+$ making background Λ	0.0
10. K_S regenerated from K_L	0.0
Total	-0.025 ± 0.006

only on the K^+ decay rate and is given by $|A^+/A_0| = 0.0548 \pm 0.0004$. It is not possible to find both $a_{3/2}$ and $a_{5/2}$ without the phase of A^+. If $\mathrm{Im}(A_2/A_0)$ is not small, because of an "accidental" cancellation of the imaginary parts of $a_{3/2}$ and $a_{5/2}$, then $\mathrm{Im}(A^+/A_0)$ may also be small. By taking both A^+ and A_2 as real, the values of all $a_{\Delta I}$ can be found and all are real. This is just an assumption that *CP* is not violated anywhere to a larger extent than indicated by $\mathrm{Im}(A_2/A_0)$. We can compare these amplitudes directly with the $a_{1/2}$ amplitude to display the violation of the $\Delta I = \frac{1}{2}$ rule explicitly. There still remain two cases for the phase of A^+. For A^+ positive, we obtain

$$\frac{a_{3/2}}{a_{1/2}} = 0.039 \pm 0.002\,,$$

$$\frac{a_{5/2}}{a_{1/2}} = -0.009 \pm 0.003\,,$$

$$\frac{a_{5/2}}{a_{3/2}} = -0.22 \pm 0.08\,.$$

For A^+ negative, the ratios are

$$\frac{a_{3/2}}{a_{1/2}} = -0.015 \pm 0.002\,,$$

$$\frac{a_{5/2}}{a_{1/2}} = 0.045 \pm 0.003\,,$$

$$\frac{a_{5/2}}{a_{3/2}} = -3.0 \pm 0.4\,.$$

While it is possible to understand the existence of the $\Delta I \leq \frac{3}{2}$ transitions, it is not easy to see how $\Delta I = \frac{5}{2}$ could arise. Many special cases can be constructed using assumptions about the origin of *CP* violation and the form of the Hamiltonian. However, in the usual current-times-current picture, with *CP* violation in the weak interaction, no $\Delta I = \frac{5}{2}$ transitions can be accommodated with SU(3) currents. Even if electromagnetic effects introduced $(\mathrm{Re})a_{5/2} \neq 0$, we would still have $a_{3/2} \gg a_{5/2}$. Therefore, we take $a_{5/2}$ small compared to $a_{3/2}$, and make an estimate of A_2 which is independent of the phase shifts:

$$|A_2/A_0| = (\tfrac{2}{3})^{1/2}\,|A^+/A_0| = 0.0447 \pm 0.0003\,.$$

Ignoring $a_{5/2}$ also implies $a_{3/2}/a_{1/2} = A_2/A_0$, and a 4.5% violation of the $\Delta I = \frac{1}{2}$ rule is indicated. By combining this result with the branching-ratio measurement, the phase-shift difference is determined to be

$$|\delta_2 - \delta_0| = 56.4° \pm 4.8°\,.$$

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[1]J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Lett. 13, 138 (1964).

[2]T. T. Wu and C. N. Yang, Phys. Rev. Lett. 13, 380 (1964).

[3]Y. S. Kim, Phys. Rev. 129, 1239 (1963).

[4]J. G. Morfin *et al.*, Phys. Rev. Lett. 23, 660 (1969), $R = 2.1 \pm 0.06$; R. Moffett *et al.*, Bull. Am. Phys. Soc. 15, 512 (1970), $R = 2.282 \pm 0.043$; C. Baltay *et al.*, Phys. Rev. Lett. 27, 1678 (1971), $R = 2.22 \pm 0.095$; R. Morse *et al.*, *ibid.* 28, 388 (1972), $R = 2.22 \pm 0.08$; J. Alitti *et al.*, Phys. Lett. 39B, 568 (1972), $R = 2.22 \pm 0.1$; E. Nagy *et al.*, Nucl. Phys. B47, 94 (1972), $R = 2.10 \pm 0.11$; D. G. Hill *et al.*, Phys. Rev. D 8, 1290 (1973), $R = 2.16 \pm 0.08$.

[5]F. Abbud *et al.*, Phys. Rev. Lett. 18, 980 (1966), $c_{em} = -0.04 \pm 0.04$; A. A. Belavin and I. M. Narodetsky, Phys. Lett. 26B, 668 (1968), $c_{em} = +0.006$; O. Nachtmann *et al.*, CERN Report No. TH.0131-CERN, 1969 (unpublished), $c_{em} = -0.006$.

[6]J. P. Baton *et al.*, Nucl. Phys. B3, 349 (1967), $\delta_2 = -5° \pm 2°$; P. B. Johnson *et al.*, Phys. Rev. 176, 1651 (1968), $\delta_2 \simeq -12°$, $\delta_0 \simeq 30°$; J. P. Baton *et al.*, Phys. Lett. 33B, 528 (1970), $\delta_2 = -5° \pm 2°$, $\delta_0 = 35° \pm 10°$; D. Morgan *et al.*, in *Springer Tracts in Modern Physics*, edited by G. Höhler (Springer, New York, 1970), Vol. 55, p. 1, $\delta_2 = -10° \pm 2°$; Andris Skuja, Ph.D. thesis, LBL Report No. LBL-378, 1972 (unpublished), $\delta_2 = -4° \pm 2°$, $\delta_0 = 22° \pm 6°$; S. Marateck *et al.*, Phys. Rev. Lett. 21, 1613 (1968), $\delta_0 = 22° \pm 12°$. All numbers were read from graphs.