Measurement of the $K_S^0 \to 2\pi$ Decay Branching Ratio*

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We have measured the branching ratio $(K_S^0 \to \pi^+\pi^-)/(K_S^0 \to \pi^0\pi^0)$ to be 2.22 ± 0.095, using a total of $\sim 32\,000$ $\bar{K}^0$'s produced by K^- charge exchange.

We have performed a measurement of the branching ratio $R = (K_S^0 \to \pi^+\pi^-)/(K_S^0 \to \pi^0\pi^0)$. This branching ratio provides a check of the $\Delta I = \frac{1}{2}$ rule and is sensitive to the ratio of the transitions for $\Delta I = \frac{5}{2}$ and $\Delta I = \frac{3}{2}$ in these decays if the $\Delta I = \frac{1}{2}$ rule is violated. This Letter describes our final result, which is essentially identical to the preliminary value we presented earlier.[1]

Neutral kaons were produced in the reactions

$$K^- + p \to \bar{K}^0 + \text{neutrals} \tag{1}$$

in the 31-in. hydrogen bubble chamber, exposed to a beam[2] of 1.75-GeV/c K^- mesons at the Brookhaven alternating-gradient synchrotron. These reactions appeared in the chamber as zero-prongs, i.e., as events with no outgoing charged particles, and the subsequent decays $K_S^0 \to \pi^+\pi^-$ were visible as "vees." The decays $K_S^0 \to \pi^0\pi^0$ were not observed; instead, the quantity directly measured in this experiment was $r = (K_S^0 \to \pi^+\pi^-)/(\text{total } \bar{K}^0)$, from which the ratio R can be inferred.

The major background was due to the reactions

$$K^- + p \to \Lambda^0 \text{ (or } \Sigma^0) + \text{ neutrals}. \tag{2}$$

The Σ^0's immediately decay to $\Lambda^0 + \gamma$, and thus these reactions are identical for our purposes. If the Λ subsequently decays into neutrals, the event looks like a zero-prong; the decays $\Lambda \to p + \pi^-$ look like a zero-prong with an associated vee. We can kinematically distinguish the vees due to $\Lambda \to p + \pi^-$ decays from the $K_S^0 \to \pi^+\pi^-$ decays. The ratio r is thus given by

$$r = \frac{(\text{no. of } K_S^0 \to \pi^+\pi^-)}{(\text{no. of zero-prongs}) - (1/b)(\text{no. of } \Lambda \to p\pi^-)}, \tag{3}$$

where b is the Λ-decay branching ratio, $b = (\Lambda \to p\pi^-)/(\Lambda \to \text{all})$, which has been previously measured with the accuracy needed here.[3]

The scanning and measuring procedure was divided into two distinct operations: finding an unbiased sample of zero-prongs, and finding all vees associated with these zero-prongs. For the first operation, an automatic flying-spot digitizer, the Columbia University Hough-Powell Device (HPD), was used in a pattern-recognition mode[4] without any prescanning or predigitizing of the film. We used the HPD not only for its rapid film processing speed (approximately 600 000 pictures were processed), but also because in a visual scan of the film scanners find zero-prongs with vees with considerably higher efficiency than zero-prongs without vees. On the HPD scan, however, the flying-spot digitizer performed a TV scan along the picture in the beam direction. Zero-prongs were almost always found or lost before the scan reached the vee, which was generally downstream of the end point of the zero-prong. A detailed study of the losses showed that vee-dependent losses were less than 1%, and this loss could be corrected for later. (Because of the different topologies of the Λ and K decays, this loss was significant only for the Λ decays.)

In the second part of the procedure, a visual scan was performed for all vees which might have come from the zero-prongs found by the HPD. Two independent scans were performed on the entire sample. All zero-prongs and vees were measured in three stereoscopic views, and geometric reconstruction and kinematic fits were performed using the programs TVGP and SQUAW. The fits to $K_S^0 \to \pi^+ + \pi^-$ and $\Lambda \to p + \pi^-$ were kinematically threefold overconstrained; poorly measured events were remeasured, and nonfitting events were examined by physicists, so that all events were positively identified.

Quality checks were imposed on the momentum, dip, azimuth, and location in the chamber of all zero-prongs, both with and without vees. Also, the length of the neutral was required to be greater than 1.5 cm when projected onto the chamber front glass and less than the maximum visible length in our fiducial volume, typically 20 cm. The events passing these cuts were weighted by the reciprocal of their detection probabilities to correct for the lost events.

In most cases, the three-constraint fit identified associated vees as either $K_S{}^0 \to \pi^+ + \pi^-$ or $\Lambda \to p + \pi^-$ decays. However, 7% of the $K_S{}^0$ decays were ambiguous with Λ decays. This ambiguity was studied by fitting all vees by the hypothesis $\bar{\Lambda} \to \bar{p} + \pi^+$; since $\bar{\Lambda}$ production was impossible in our beam, all such fits were false fits. The K^0-$\bar{\Lambda}$ ambiguity occurs, for true K^0's, with the same probability as the K-Λ ambiguity, since the decay $K_S{}^0 \to \pi^+ + \pi^-$ is isotropic in the K_S c.m. system, so the K^0-$\bar{\Lambda}$ fits determined the number of the K-Λ fits which were true $K_S{}^0$'s. (The triple ambiguity K-Λ-$\bar{\Lambda}$ does not occur.) The resulting $K_S{}^0 \to \pi^+ + \pi^-$ decay distribution is isotropic, as shown in Fig. 1(c). The dashed curve represents the unambiguous $K_S{}^0$'s, and the upper curve represents the K_S sample including the charge conjugate of the K-$\bar{\Lambda}$ ambiguous events.

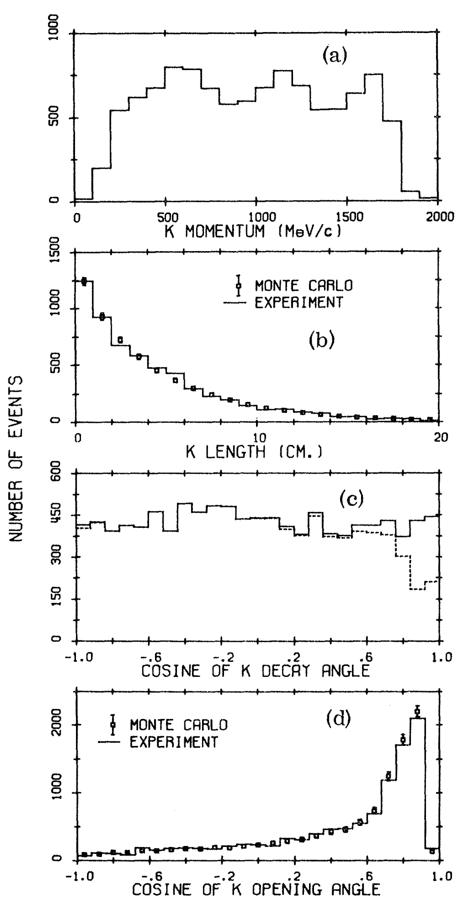

FIG. 1. (a) Momentum distribution of the decays $K_S{}^0 \to \pi^+ + \pi^-$, weighted. (b) Length distribution of the $K_S{}^0$, compared to the Monte Carlo prediction. (c) Distribution in the angle of the π^+ in the K_S rest frame. The dashed curve represents the decays $K_S{}^0 \to \pi^+ + \pi^-$ not ambiguous with $\Lambda \to p + \pi^-$. (d) Cosine of the lab angle between the π^+ and π^- in the decay $K_S{}^0 \to \pi^+ + \pi^-$, compared with the Monte Carlo prediction.

A π^- contamination will produce zero-prongs by charge exchange, but will produce K^0's only very rarely. By studying the energy spectrum of δ rays from beam tracks, and in addition using the $\pi^- p$ interaction cross section to separate π^- from μ^-, we found the π^- contamination in the K^- beam to be $(0.6 \pm 0.3)\%$. To study its effect we took 1% of the exposure with a pure π^- beam and processed these pictures in the same way as the rest of the K^- pictures. From this, we concluded that $(0.4 \pm 0.2)\%$ of the zero-prongs in our sample were due to π^- contamination.

Since we have a three-constraint fit to identify $K_S{}^0$ or Λ decays associated with a zero-prong, it is unlikely that either K or Λ decays unassociated with a zero-prong (or any other combination of tracks in the chamber which may look like a vee) would fake an associated K or Λ decay. A fake vee is just as likely to occur to a zero-prong with a truly associated K_S or Λ decay as to a zero-prong without a true K_S or Λ decay, so from the number of events with two fitting vees we determined the fraction of fits which were fakes.

As a result of strangeness conservation, the only reaction that can lead to an all-neutral final state at our energy, in addition to Reactions (1) and (2) already discussed, is $K^- + p \to \Xi^0 + K^0$ + possible π^0's. (The contribution from the reaction $K^- + p \to K^0 + \bar{K}^0 + \Lambda$, for which we are barely at threshold, was negligible.) The number of Ξ^0 events is very small and a correction for them can readily be made by making use of the events where both the decays $K^0 \to \pi^+ + \pi^-$ and $\Xi^0 \to \Lambda^0 + \pi^0$, $\Lambda^0 \to p + \pi$ are visible.

The scanning losses were considered in two distinct categories: events which were lost in a systematic way because of some property of the $K_S{}^0$ or Λ decay; and random scanning losses, i.e., vees lost independent of any property of the decay. The random losses could be evaluated by comparing the two independent scans. Of 14 837 vees found in scan 2, only 96 were lost in scan 1, and of 14 934 vees found in scan 1, 193 were not found in scan 2. We further found that the lost events did not differ significantly from the rest of the sample. These numbers lead to the correction shown in Table I.

Systematic scanning losses were evaluated by comparing the distribution of events in decay position, opening angle, momenta of the decay products, etc. with the expected distributions calculated by Monte Carlo techniques. (Some

TABLE I. Summary of numbers of events and corrections.

A.	Number of $K_S^0 \to \pi^+\pi^-$	
	6150 observed $K_S \to \pi^+\pi^-$, weighted	11,012
	Decays with slow $\pi^\pm$	38±12
	Random scanning loss	6±6
	Fakes from other origins	-32±18
	K^0 scatters before decay	44±12
	Regeneration of K_1 from K_2	- 2±2
	3 body K^0 decays	-13±4
		11,053
B.	Number of $\Lambda \to p\pi^-$	
	7718 observed $\Lambda \to p\pi^-$, weighted	13,196
	Decays with slow π^-	121±26
	Loss of wide opening angle vees	25±25
	HPD loss of Λ's close to 0 prong	291±75
	Fake Λ fits	-149±37
	Λ's from Ξ^0 decays	-111±33
	Loss due to confusion with e^+e^-	64±9
	Λ scatter before decay	66±25
	Random scanning loss	7±7
		13,510
C.	Number of 0 prongs	
	45044 total 0 prongs, corrected for close vees	53,220
	π^- Contamination	-212±106
	Loss due to Dalitz pairs	34±17
	$K^- \to \pi^0 e^- \nu$ faking 0 prong	- 43±8
	Loss due to steeply dipping vees	12±4
		52,958

of these distributions are shown on Fig. 1.) There were no significant systematic losses; however, some small corrections, as shown in Table I, were made based on detailed study of these distributions.

We considered a number of other effects which led to either small or negligible corrections. These effects were K^0 or Λ scattering in the H_2 before decay, regeneration of K_1 from K_2, three-body K^0 decays faking $K_S{}^0 \to \pi^+ + \pi^-$ decays, loss of Λ's due to confusion with e^+e^- pairs, Dalitz pairs near the zero-prong, $K^- \to \pi^0 + e^- + \nu$ decays in flight, and steeply dipping vees. In addition, a number of systematic checks were made, such as the effects on the weighting procedure due to the uncertainty in the $K_S{}^0$ and Λ lifetimes and the measurement errors on the $K_S{}^0$ and Λ momenta and lengths; all of these turned out to be negligible. A thorough discussion of these effects is included in a more detailed publication.[5] The corrections are shown in Table I.

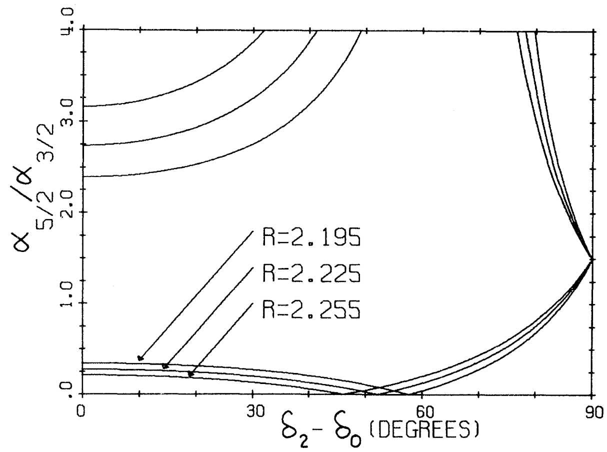

FIG. 2. The ratio of the amplitudes for $\Delta I = \frac{5}{2}$ and $\Delta I = \frac{3}{2}$, $\alpha_{5/2}/\alpha_{3/2}$, as a function of the $I=0$ and $I=2$ final-state phase-shift difference.

Using the numbers shown in Table I, we get from Eq. (3)

$$r = (K_S \to \pi^+\pi^-)/(\overline{K}^0 \to \text{all}) = 0.345 \pm 0.005.$$

If we assume CPT invariance and use the measured value[6] of Reϵ, and further assume that neutral decays of the $K_S{}^0$ other than $\pi^0\pi^0$ are well below 1%, we can deduce from r the charged-to-neutral branching ratio,

$$R = (K_S{}^0 \to \pi^+\pi^-)/(K_S{}^0 \to \pi^0\pi^0) = 2.22 \pm 0.095.$$

This result is in good agreement with the other four measurements of this ratio.[7] The weighted average of these four results combined with ours is $R = 2.225 \pm 0.030$. The χ^2 for the five experiments is 4.8, which is quite acceptable. This average value of R is in fairly significant disagreement with the $\Delta I = \frac{1}{2}$ rule which predicts $R = 2.0 + \Delta_{\text{em}}$, where Δ_{em}, for the radiative corrections, seem to be too small[8] to explain this disagreement.

From this value of R, we can calculate the ratio of the amplitudes for $\Delta I = \frac{5}{2}$ and $\Delta I = \frac{3}{2}$ in $K_S{}^0 \to 2\pi$.[9] The dependence of this ratio on the final-state strong-interaction phase shifts in the $I=0$ and 2 states, δ_0 and δ_2, is shown in Fig. 2. Note that the lower solution is very weakly dependent on the phase shifts in the region of $|\delta_2 - \delta_0|$ around 30° to 60° preferred by $\pi\pi$ scattering experiments.[10]

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[1]W. A. Cooper *et al.*, Bull. Amer. Phys. Soc. 15, 511 (1970), and in a paper presented at Proceedings of the Fifteenth International Conference on High Energy Physics, Kiev, U. S. S. R., 1970 (Atomizdat., Moscow, to be published).

[2]H. N. Brown, Brookhaven alternating gradient synchrotron Internal Report No. HNB-3 (unpublished).

[3]We have measured the branching ratio $(\Lambda\to p\pi^-)/(\Lambda\to \text{all})=0.646\pm0.008$ in a previous experiment [C. Baltay *et al.*, Phys. Rev. D 4, 670 (1971)]. We have averaged our number with the previous world average to obtain 0.648 ± 0.0065.

[4]For a detailed description of this technique, see C. Baltay *et al.*, in *Proceedings of the International Conference on Advanced Data Processing for Bubble and Spark Chambers, Argonne National Laboratory, 1968,* edited by R. J. Royston (Argonne National Laboratory, Argonne, Ill., 1968), p. 266.

[5]W. A. Cooper, Ph.D. thesis, Columbia University, 1971 (unpublished).

[6]J. Steinberger, in *Proceedings of the Topical Conference on Weak Interactions, CERN, Geneva, Switzerland, 14–17 January, 1969* (CERN Scientific Information Service, Geneva, Switzerland, 1969), p. 291.

[7]Four recent other measurements of the branching ratio R were $R=2.282\pm0.043$, B. Gobbi *et al.*, Bull. Amer. Phys. Soc. 15, 512 (1970), and Phys. Rev. Lett. 22, 682 (1969); $R=2.12\pm0.064$, J. G. Morfin, Ph.D. thesis, University of Michigan (unpublished); J. G. Morfin and D. Sinclair, Phys. Rev. Lett. 23, 660 (1969); $R=2.12\pm0.17$, G. Bozóki *et al.*, Phys. Lett. 30B, 498 (1969); $R=2.22\pm0.08$, K. M. Morse *et al.*, Bull. Amer. Phys. Soc. 16, 18 (1971).

[8]We are aware of three calculations of the radiative corrections to this branching ratio: $\Delta_{\text{em}}=-0.04\pm0.04$, F. Abbud, B. W. Lee, and C. N. Yang, Phys. Rev. Lett. 18, 980 (1967); $\Delta_{\text{em}}=0.006$, A. A. Belavin and I. M. Narodetsky, Phys. Lett. 26B, 668 (1968); and $\Delta_{\text{em}}=-0.006$, O. Nachtman and E. de Rafael, CERN Report No. TH-1031 (to be published).

[9]For details of this calculation, see Abbud, Lee, and Yang, Ref. 8. For the radiative correction, however, we have used the results of the third paper referred to in Ref. 8.

[10]See E. Malamud and P. Schlein, in *Proceedings of the Conference on ππ and Kπ Interactions at Argonne National Laboratory, 1969,* edited by F. Loeffler and E. Malamud (Argonne National Laboratory, Argonne, Ill., 1969), p. 93, and other papers in the same volume.

Inclusive $\bar{p}+p\to\pi$ + Anything at 2.32 GeV/c*

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An analysis of the double differential cross section of the inclusive $\bar{p}p$ interaction is presented. A comparison of various forms of the distribution function has been made. The best fit is obtained using a Bose-type distribution with two parameters and ordinary phase space for the cross section.

In a previous paper[1] we reported the single-particle distributions of $\bar{p}+p\to n\pi$, $n=4$, 5, 6, and 7, at an incident momentum 2.32 GeV/c from a large-statistics bubble-chamber experiment at Argonne National Laboratory.[2] In that work we also investigated the behavior of the c.m. longitudinal-momentum (P_L) distribution integrated over P_T of π^+ from all annihilation channels for $P_L>0.75$ GeV/c in an attempt to test its limiting expression given by Feynman.[3,4]

The purpose of this paper is to present the results of analysis of inclusive reactions

$$\bar{p}+p\to\pi^{+}+\text{anything} \tag{1}$$

of the same experiment described in Ref. 1. Here, we are dealing with annihilation as well as inelastic processes; the number of π^{+}'s we obtain for the present work is listed in Table I. We