MEASUREMENT OF THE K_1^0 CHARGED-TO-NEUTRAL DECAY BRANCHING RATIO*

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Using K^0 produced by K^+ charge exchange in Be, we have measured the charged-to-neutral branching ratio of K_1^0. We obtain 2.285 ± 0.055 to be compared with the $|\Delta I| = \frac{1}{2}$ rule prediction of 2.00. This 5-standard-deviation violation gives $\mathrm{Re}(A_2/A_0)\cos(\delta_2-\delta_0) = 0.0345 \pm 0.007$.

We have carried out a precision spark-chamber measurement of the charged-to-neutral branching ratio of the K_1^0. Such a measurement provides useful information on the nature of the $|\Delta I| = \frac{1}{2}$ rule violation in the decay $K \to \pi\pi$.

A schematic layout of the experiment is shown in Fig. 1(a). An unseparated beam of 2-BeV/c K^+ was detected by a counter telescope and a liquid-cell differential Cherenkov counter which rejected π^+, p, and μ^+. A source of K_1^0's was obtained by the charge exchange $K^+n \to pK^0$ in a 2.5-cm-thick Be target surrounded by an arrangement of veto counters, lead and tungsten γ converters. This served to define the charge-exchange trigger and effectively suppressed large momentum transfers and inelastic charge exchanges. Decays were studied in a well-defined fiducial volume 27 cm (≈ 2.8 K_1^0 mean decay lengths) in extent. This region contained a 24-gap aluminum-foil spark chamber which registered charged V decays. Neutral events were detected by γ conversion in a 4.0-radiation-length 49-gap steel spark chamber. No detection counters exclusive of the target vetoes and the K^+ defining telescope were used.

A six-gap beam spark chamber registered the entry point of the K^+ into the Be target. This information permits the kinematical reconstruction of the V decays and yields angular and momentum distributions for the K_1^0.

Veto counter efficiency was 99.8% (for each counter) and nonblocking electronic circuitry was used. The yield of K^0/K^+ was 6×10^{-4}. Because of the veto counters, decays in the target were electronically rejected (only 0.3% of the neutral decays escape conversion in the tungsten). The front edge of the fiducial region was defined electronically by the action of the tungsten and A_4 (3.2 mm thick). Since neutral decays in A_4 are rarely converted, the effective front edge is displaced upstream for the neutral mode. The correction for this displacement is indicated in Table I. The effective edge for the neutral mode is calculated from the known γ conversion properties of tungsten and scintillator. The charged-mode dead layer (0.3 mm) is established by the pulse-height response of A_4 which is inferred from the response to beam pions.

Effectively, the K^0 beam emerging from the target-veto arrangement is 40% K_1^0 and 60% K_2^0.

The back edge of the fiducial region is defined to be the last gap of the decay chamber. The origin of the neutral events must be reconstructed in analysis in order to establish whether they are to be accepted. The uncertainty introduced by the back edge cut is negligibly small because the K_1^0 flux at this position has attenuated by a factor of 20.

The fiducial volume is unbounded on the sides, i.e., no limitation on K^0 production angle is invoked. We rely on the fact that our efficiency for detection is constant and near 100% up to an angle $\approx 45°$ and the K^0 production distribution falls

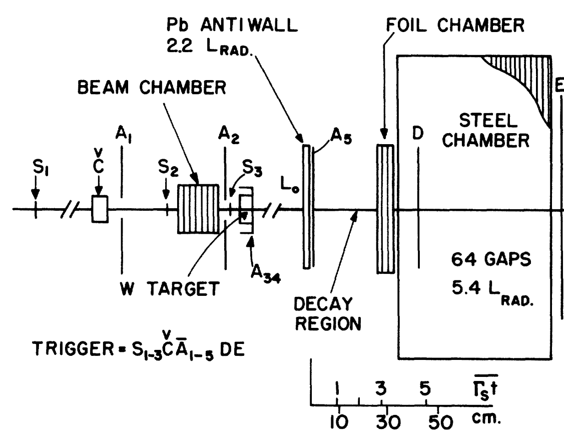

FIG. 1. (a) Experimental layout. The inset shows the target and target-counter details. (b) Beam axis (Z) distribution of K^0 decays. The total neutral (all gamma) curve is fit by a smooth curve which shows the effects of the finite experimental resolution. The 2γ curve is the same curve normalized to the exponential portion, i.e., the first few inches of decay are ignored. A small excess of 2γ events, interpreted as target-associated background, is evidenced (see corrections in Table I). Note that the target inset is drawn to the same Z scale and position as is (b).

Table I. Data-analysis summary.

V	6608
Total gamma	3016
4γ[a]	1656 (54.9%)
3γ	1144 (37.9%)
2γ	216 (7.2%)
Uncorrected branching ratio	2.191 ± 0.048
Corrected branching ratio	2.285 ± 0.055[b]
Corrections (%)	
Neutral decays in A_4 counter	$+3.8 \pm 0.1$
2γ background from target	$+1.0 \pm 0.5$
1γ and 0γ neutral decays	-0.5
Neutral decays escaping target	$+0.3$
Backgoing γ's	-0.1
Backgoing π interactions	$+0.1$
Admixture of three-body decays	-0.3
Total	$+4.3 \pm 0.6$

[a]4γ (or more).
[b]A 1% overall systematic error has been folded in with the statistical error.

off exponentially with angle (see Fig. 2).

Consider now the photographic analysis and the various classes of events.

(1) Decays in the fiducial volume: These are the "good" events and they constitute 23% of the photographs. Charged V's are readily localized. Neutrals[1] are reconstructed with more difficulty, the resolution in Z, the beam axis coordinate, being best for those events which decay in the latter portion of the fiducial volume and poorest for those closest to the target.

(2) Blank: These are consistent in number with being K_2^0 associated.

(3) Upstream: Some K^+'s either decay in flight after the Cherenkov counter or interact in the Cherenkov cell. This class of event is very easily recognized and rejected.

(4) Events in the steel chamber: Some decays take place in the steel. Some K_2^0's interact in the steel producing stars, recoils, or K_1^0 regenerations. These are also easily rejected.

(5) Target associated: The only background of any consequence is targe-associated neutral events. Such background neutrals are almost exclusively 2γ events. These result from transmission without conversion through the W converter. Some of these are produced by the charge exchange of accidental beam pions and are characterized by strong showers and small opening angles. Others result from the inelastic charge exchange $K^+n \rightarrow p\pi^0K^0$. This is confirmed by the fact that 2% of the V's have accompanying 2γ showers. This class of events provides a useful resolution exercise. The final test of the efficacy of the background separation is the correctness of the Z distribution of the accepted 2γ neutral events. The ratio of target produced 2γ to all neutrals is 4%.

All scanning and neutral reconstruction has been executed by physicists. All data presented have been double scanned. The high event-to-trigger ratio and low background precludes any significant scanning loss.

A further cut in candidate events was made when either (a) an event had a double, missing, or skew beam track or (b) an accidental track crossed both the foil and steel chambers. The branching ratio of the 13% of events thus cut is in agreement with the "good" events (corrected branching ratio of cut events $= 2.23 \pm 0.13$).

Figure 2 illustrates the characteristics of the K_1^0 beam determined from V reconstruction. The momentum and angle resolution is poorest for those decays which occur nearest the target. The most significant point is that there are very few events at very wide angles or with momentum below 1 BeV/c.

Figure 1(b) shows the Z distribution of the charged and neutral events. The Z-falloff slope is consistent with the mean momentum and the K_1^0 lifetime. The absence of V's on the wrong side of the anti wall confirms the operation of the veto counters.

We again emphasize that there were no decay detection counters employed and no separate neutral and charge decay data recording. No spark chamber failure was experienced during the experimental run or noticed in scanning.

The potential of the decay reactions for producing backward-going particles in the laboratory has been considered. Such backward particles could, in principle, strike the veto counters nullifying the particular event. Note that the A_4 counter was 11.5 cm in diameter. Extensive counter tests with a larger A_4 counter preceded the spark chamber work. In the course of this work steel plates were positioned to simulate the interaction capability of the spark chambers. Only when 5 cm of steel was placed immediately adjacent to the enlarged A_4 counter was an effect of a few percent recorded. Pion stars with a prong going into the backward hemisphere, through the foil chamber, were noted in scanning and constitute 3% of all V decays. Upon extrapolation to the solid angle projected by A_4 this effect is negligible ($\leq 0.1\%$). In the case of the neutral mode, Monte Carlo calculations on the

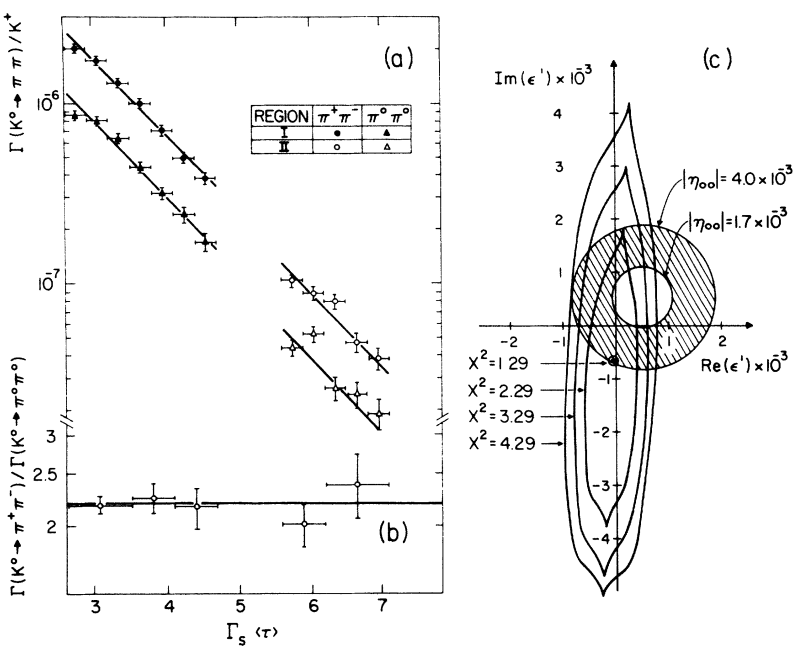

FIG. 2. (a) K^0 momentum spectrum. Very loose cuts were made on $K^0 \to \pi^+\pi^-$ coplanarity. (b) K^0 production-angle spectrum. (c) Pion angular distribution with respect to K^+ beam direction.

fraction of backward decay γ's yield a correction of $(0.1 \pm 0.1)\%$. Only a few backscattered shower electrons were noted in the foil chamber. The effect of positron-annihilation γ rays is also negligible.

The results of an analysis of 30% of the recorded data are presented in Table I.

The corrected branching ratio is $C/N = 2.285 \pm 0.055$. This is the ratio of all charged events to all neutrals (internal-conversion pairs are included with neutrals). Unless there is an anomalous yield of events of the sort $K_1{}^0 \to \pi^+\pi^-\pi^0$, $3\pi^0$, $\pi^0\pi^0\gamma$, 2γ, etc., this branching ratio is interpreted to be $[K_1{}^0 \to \pi^+\pi^-\gamma$ (including 0 energy)$]/[K_1{}^0 \to \pi^0\pi^0]$. The effect of these other modes, assuming that the $K_1{}^0$ decay amplitudes are no larger than their $K_2{}^0$ counterparts, is negligible. In fact, there are well-known theoretical arguments suggesting that the $K_1{}^0 \to 3\pi$ amplitudes are strongly suppressed relative to the $K_2{}^0 \to 3\pi$ amplitudes.

The above result can be compared with the world average of 2.165 ± 0.10.[2] However, it is well known that the agreement of the experiments making up the world average is poor.

Abbud, Lee, and Yang[3] have parametrized the branching ratio as

$$\frac{R(+-,\omega)}{R(00)} - 2 = 6\sqrt{2}\,\mathrm{Re}(A_2/A_0)\cos(\delta_2 - \delta_0) + \Delta_{\mathrm{e.m.}}.$$

A_2 and A_0 are the amplitudes for decay into $\pi\pi$ with $I = 2$ and 0, respectively. The factor ω refers to the energy of the inner bremsstrahlung part of the radiative correction. $\Delta_{\mathrm{e.m.}}$ is the calculated radiative correction, including the phase-space correction due to the $\pi^\pm - \pi^0$ mass difference. It is logarithmic in the quantity ω as well as in a vertex cutoff parameter, Λ. The values $\Lambda = 2$ BeV and $\omega = 10$ MeV were used and a correction of

$$\Delta_{\mathrm{e.m.}} = -(0.04 \pm 0.04)$$

was estimated. More recently Belavin and Narodetsky[4] have recalculated the correction and obtain

$$\Delta_{\mathrm{e.m.}} = +0.006.$$

Let us use 0.0 ± 0.04. This does not significantly affect our present accuracy. Then

$$\mathrm{Re}(A_2/A_0)\cos(\delta_2 - \delta_0) = 0.0345 \pm 0.007.$$

In a companion experiment[5] we have shown that $\mathrm{Im}(A_2/A_0) \leq 2 \times 10^{-3}$; so within errors, A_2 can be regarded as real: $|\mathrm{Im}A_2/\mathrm{Re}A_2| \leq 0.06$.

One would like to compare A_2 with the amplitude $A_2{}^+$ obtained from the rate of $K^+ \to \pi^+\pi^0$. Rosenfeld et al.[2] give

$$|A_2{}^+/A_0| = 0.0544.$$

The situation is complicated by the fact that A_2 and A_2^+ contain different admixtures of the $|\Delta I| = \frac{3}{2}$ and $\frac{5}{2}$ amplitudes ($\alpha_{3/2}$ and $\alpha_{5/2}$), i.e.,

$$A_2^+ = \tfrac{1}{2}\sqrt{3}\ \alpha_{3/2} - \tfrac{1}{3}\sqrt{3}\,\alpha_{5/2},$$

$$A_2 = \tfrac{1}{2}\sqrt{2}\,\alpha_{3/2} + \tfrac{1}{2}\sqrt{2}\,\alpha_{5/2}.$$

If we assume that $\alpha_{5/2} = 0$, as is suggested by some theoretical models of weak-interaction currents, we can solve for $\delta_2 - \delta_0$ obtaining

$$\cos(\delta_2 - \delta_0) = 0.776 \pm 0.158$$

or

$$\delta_2 - \delta_0 = \pm(39\,^{+13}_{-18})^\circ.$$

This is in good agreement with the phase shifts obtained from peripheral-pion-scattering analysis. The most recent compilation indicated $-30° \pm 10°$.[6]

Conversely, if we regard $\delta_2 - \delta_0$ as measured, we can solve for $\alpha_{5/2}/\alpha_{3/2}$. The two solutions are

$$-(0.065\,^{+0.14}_{-0.12}) \text{ and } -(4.7\,^{+3.2}_{-1.5}).$$

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[1]Neutral events are characterized by the number of observed γ showers. For example, a 2γ event implies that two γ rays have escaped detection. We are assuming that the $K_1 \to 3\pi^0, \pi^0\pi^0\gamma, \gamma\gamma$ channels are negligible.

[2]A. Rosenfeld et al., Rev. Mod. Phys. 40, 77 (1968).

[3]F. Abbud, B. W. Lee, and C. N. Yang, Phys. Rev. Letters 18, 980 (1967).

[4]A. Belavin and I. Narodetsky, Physics Letters 26B, 668 (1968). See also T. D. Lee and C. S. Wu, Ann. Rev. Nucl. Sci. 17, 513 (1966). It is argued that the Coulomb correction is relatively large (compared with transverse photon effects which are not worked out explicitly). Phase space favors the $\pi^0\pi^0$ while the Coulomb correction favors the $\pi^+\pi^-$ in a roughly compensatory fashion.

[5]B. Gobbi, D. Green, W. Hakel, R. Moffett, and J. Rosen, following Letter [Phys. Rev. Letters 22, 685 (1969)], and Rochester University Report No. 263 (unpublished).

[6]S. Marateck et al., Phys. Rev. Letters 21, 1613 (1968). This work is the consensus of several experimental groups which have carried out the $\pi\pi$ measurements. Several theoretical papers which share the use of current algebra are in excellent agreement: E. P. Tryon, Phys. Rev. Letters 20, 769 (1968); L. S. Brown and R. L. Goble, ibid. 20, 346 (1968); R. Arnowitt, M. H. Friedman, P. Nath, and R. Suitor, ibid. 20, 475 (1968). It might be argued, however, that these are not completely theoretical predictions, but are instead partially parametrized fits.

STUDY OF $K_1^0 \to \pi^0\pi^0$ AND $K_2^0 \to \pi^0\pi^0$ INTERFERENCE

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Using K^0's produced by the charge exchange of K^+, we have measured the proper-time dependence of the decays $K^0 \to \pi^0\pi^0$. Analysis indicates that a third-quadrant solution for the phase of η_{00} is unfavored by more than 2 standard deviations. A first-quadrant solution is acceptable.

We have studied the time dependence of the decay $K^0 \to \pi^0\pi^0$ in order to measure the interference between the K_1^0 and the K_2^0 components. The decays $K^0 \to \pi^+\pi^-$ were also recorded. For reasons which will be discussed later in this paper, we choose to combine the charged and neutral data to yield the time-dependent branching ratio. To good accuracy for the conditions of our experiment, this branching ratio can be written

$$B(t) = B_0[1 + 6|\epsilon'|\exp(t/2\tau_1)\cos(\delta m t - \varphi_{\epsilon'})], \quad (1)$$

t is the time in K^0 rest frame, $\tau_1^{-1} = \lambda_1 = K_1^0$ de-