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 $-30^\circ \pm 10^\circ$.[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

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

We should like to thank the staff of the alternating-gradient synchrotron and Mr. G. Tanguay in particular for their cooperation. Many members of the Rochester particle-physics staff have made important contributions for which we are grateful. In particular we thank Dr. T. Yamanouchi for several useful comments. We also thank Professor T. D. Lee for a useful discussion concerning radiative corrections.

---

*Work supported by the United States Atomic Energy Commission, under Contract No. AT(30-1)-875.

[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 Letters 22, 685 (1969)], and Rochester University Report No. 263 (unpublished).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

B. Gobbi, D. Green, W. Hakel, R. Moffett, and J. Rosen
University of Rochester,* Rochester, New York 14627

and

B. Goz† and D. Tycko‡
Rutgers, The State University,§ New Brunswick, New Jersey 08903
(Received 10 January 1969)

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, $\tau_1^{-1} = \lambda_1 = K_1^0$ decay rate, $\delta m = K_2{}^0 - K_1{}^0$ mass difference, $\epsilon' = 2^{-1/2} i \times \mathrm{Im}(A_2/A_0)\exp(\delta_2-\delta_0)$, where

$$A_2 = \langle 2\pi(I=2)|T|K^0\rangle,$$

$$A_0 = \langle 2\pi(I=0)|T|K^0\rangle,$$

and δ_2 and δ_0 are the corresponding $\pi\pi$ scattering phase shifts (at the K^0 mass). B_0 is the branching ratio of the $K_1{}^0$. It is readily seen that the CP-nonconserving interference term in the branching ratio increases exponentially with increasing proper time. In essence our experiment compares $B(t \approx 6\tau_1)$ with $B(t \approx 3\tau_1)$. For orientation purposes we can estimate $6|\epsilon'|\exp(t/2\tau_1) \approx 0.24$ for $t = 6\tau_1$ using $|\epsilon'| \sim 2\times10^{-3}$, a value which seemed plausible at the outset of this experiment.

Several factors determined the choice of $6\tau_1$ as the time of optimum experimental feasibility. Superficially, it would appear more desirable to concentrate on later times, where the interference term is even larger. But it can be easily shown that the ratio of the two-body decays to the $K_2{}^0 \to$ three-body background deteriorates with increasing time. Furthermore, at early times the higher counting rate compensates for the smaller percentage interference, i.e., the information content per unit proper time is almost constant. In summary, the choice of $6\tau_1$ represents a compromise between three-body decay background, processing a large amount of data, and other secondary considerations.

Figure 1 shows the experimental layout. The K^0 beam was produced by the charge exchange of the Brookhaven National Laboratory alternating-gradient synchrotron partially separated 2-BeV/c K^+ beam in a 4-cm-thick W target. Veto counters A_2, A_3, A_4 were used to define the K^0 production. Both neutral and charged decays were detected by the same scintillation counters D, E and spark chambers located downstream from the K^0 source. The main piece of detection equipment was a steel spark chamber, 5.4 radiation lengths in depth, with 64 gaps. Counters D were positioned in a slot at the 0.9-radiation-length mark, i.e., after the 11th plate. Since the $K^0 \to \pi^0\pi^0$ decay yields four γ rays, the neutral detection efficiency is high. A high percentage of both V's and γ showers penetrate to the rear counter E.

A decay interval of 25.6 cm corresponding to $3\tau_1$ was defined between the steel chamber and a Pb-plus-scintillation-counter A_5 antiwall. This antiwall suppressed early-time decays in both the charged and neutral modes. The presence of

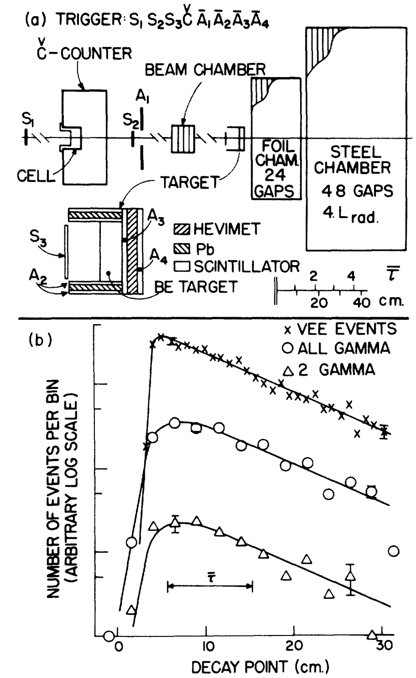

FIG. 1. Experimental layout.

this material, principally the Pb, resulted in an apparent complication. A coherent regenerated $K_1{}^0$ amplitude ρ was developed which added to the residual, target-produced $K_1{}^0$. The resultant interference term, in either the charged or neutral modes taken separately, is of the same order of magnitude as the (estimated) CP-nonconserving term of interest. However, a cancellation occurs in the branching ratio so that Eq. (1) remains valid to good accuracy. This approximate cancellation is not fortuitous but reflects the fact that we are looking for a time-dependent departure of $B(t)$ from B_0, the $K_1{}^0$ branching ratio, and that such a departure is produced only by the $I=2$ CP-nonconserving amplitude ϵ'.

The separation between the anti wall and the target (L_0) was varied during the course of the experiment. The target and its associated counters S_3, A_{2-4} plus the beam chamber were mounted on rails and moved as a unit. The Cherenkov counter and S_1 were not movable. Data recording was cycled between three regions:

(I) $(2\text{-}5)\tau_1$ interval. This is the small interference or $K_1{}^0$-like region. We did not run at any earlier proper time because our camera triggering was already saturated and the K^0-direction information deteriorates at smaller distances. Two-body decays are dominant.

(II) $(5\text{-}8)\tau_1$. This is to be regarded as the interference region.

(III) $(8\text{-}11)\tau_1$. Although interference is in principle large in this region, the two-body decays are swamped by three-body decays. For our purposes, this is an almost pure sample of background.

All film was scanned by physicists. Neutral showers were hand reconstructed at the scanning table by the self-same physicists and transferred to tracing sheets. These sheets, and the film V events, were digitized by staff measurers on an image-plane digitizer.

We are reporting 90% of the K^+ data. A third as much data were taken with K^- producing $\bar{K}^0$. It is not ready for publication at this time. It is of interest to note that interference effects in the $\bar{K}^0$ system are equal and opposite relative to K^0.

A detailed summary of the data reduction has been given elsewhere.[1] Approximately 5000 charged and 3000 neutral decays survive the cuts imposed on the data. For fitting purposes the decay volume is actually subdivided and the events in the end bins, i.e., those at the front and rear of the $3\tau_1$ interval, are deleted. This is done because the edges are blurred by the relatively poor resolution inherent in the neutral reconstruction.

The charged events are filtered on the basis of copunctuality of the pion tracks, Z position ($Z \equiv$ the coordinate along the beam direction), and coplanarity of decay plane with respect to K^0 direction. The three-body background is mostly due to $K_{\mu 3}{}^0$ decays. The $\pi^+\pi^-\pi^0$ and $K_{e3}{}^0$ decays are directly identified and rejected during scanning. The residual three-body background is inferred from the data of region III.

Neutral events are sorted according to the number of observable γ showers and the reconstructed Z position of the decay vertex. The 5γ and 6γ events are interpreted as three-body decays, although there is a small residual component of two-body events in region I which have an accompanying or two from the target (anti-wall leakage).

The bulk of the 3γ and 4γ events in region III are $3\pi^0$ events with missing γ showers. These missing γ's result from chance overlays, unusually wide angles, or low energies. Attempts to separate the $2\pi^0$ from $3\pi^0$ decays with three or four γ's observable on the basis of kinematics have not been fruitful. We have adopted the conservative procedure of establishing the background rate of 3γ and 4γ events using region III.

Neutral events must be assigned a proper time by the formula $t = R/c\langle\beta\gamma\rangle_{\text{av}}$, i.e., the distance from the target center to the decay point is divided by the factor $\beta\gamma$ obtained from the mean momentum as inferred from the V decays. This procedure then requires that Eq. (1) be folded in with an appropriate resolution function. The smearing of the oscillatory term of interest and consequent loss of information is minor. The phase change per $K_1{}^0$ lifetime is only 27°. The K^0 momentum spread is ±15% at production. The K^0 beam tends to harden up with increasing time and the effective smearing at $6\tau_1$ is ~±20° of phase.

The two- and three-body efficiences for both charged and neutral events in the various regions were calculated by Monte Carlo techniques. The relative decrease in efficiency in region III relative to I is due almost entirely to solid angle, i.e., the relative charged-to-neutral efficiency is largely independent of position (L_0). It is clear that only the relative efficiency between the regions is relevant. The lumped results are $B_{\text{I}} = 2.22(1 \pm 0.032)$ and $B_{\text{II}} = 2.13(1 \pm 0.08)$. The value for B_{I} is in reasonable agreement with the measured value[2] of $B_0 = 2.285 \pm 0.055$; so the absolute efficiency appears to be correctly understood and evaluated.

No significant time dependence of the branching ratio is observed in this experiment as can be seen in Figs. 2(a) and 2(b). Limits on the magnitude of ϵ' can be inferred. This is shown in Fig. 2(c). For "plausible" values of $\delta_0-\delta_2$, the factor which determines the phase of ϵ', we find

$$|\epsilon'| < 1\times 10^{-3} \quad (20° < \varphi_{\epsilon'} < 70°),$$

$$|\epsilon'| < 1.5\times 10^{-3} \quad (200° < \varphi_{\epsilon'} < 250°).$$

These values correspond to the 90% confidence level. The best value for $\delta_0-\delta_2$ extracted from the $\pi\pi$-scattering phase-shift analysis is $30° \pm 10°$.[3] Somewhat larger values have been quoted in the past. Clearly, a larger $\delta_0-\delta_2$ would reduce our limits on $|\epsilon'|$.

One immediate conclusion to be drawn is

$$|\text{Im}A_2/\text{Re}A_2| \leq 0.06,$$

using the value of $\text{Re}A_2$ obtained from the $K_1{}^0$ branching-ratio analysis.[2]

Information on ϵ' can also be extracted from the various experiments on CP nonconservation performed in neutral beams using the relation $3\epsilon' = \eta_{+-} - \eta_{00}$. The phase and magnitude of η_{+-} are the best measured parameters in the phenomenological scheme. We use $|\eta_{+-}| = (1.90$

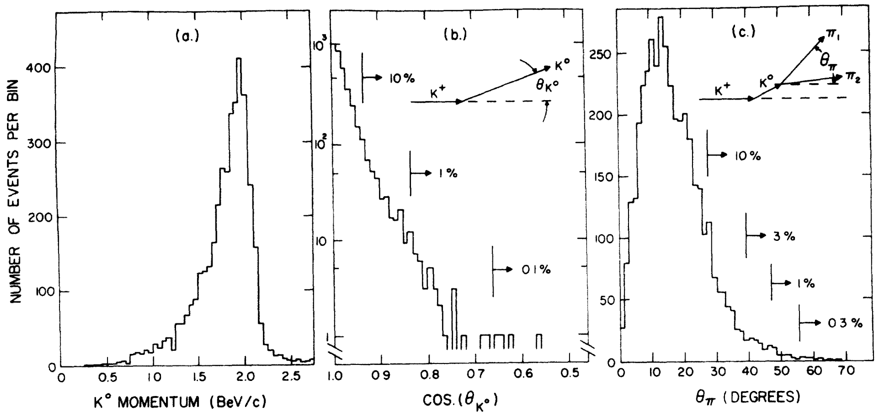

FIG. 2. (a) The distribution in distance (R) of the charged and neutral events, background subtracted. The break in the essentially exponential slope is due to the regeneration effect in the Pb anti wall. The regeneration amplitude adds essentially destructively for region II, $(5\text{-}8)\tau_1$. The proper time (t) is obtained from $t = R/\langle\beta\gamma c\rangle_{av}$. (b) The distance ($R$) dependence of B obtained from the data of (a). (c) Equal-likelihood contours in the complex ϵ' plane obtained from the theoretical fit of $B(t)$. The phase of ϵ' is given theoretically by $\frac{1}{2}\pi - \delta_0 + \delta_2$ (+0 or π). Marateck et al. (see Ref. 3) give $\delta_0 - \delta_2 = 30^0 \pm 10^0$ from the $\pi\pi$-scattering phase-shift analysis obtained using the Chew-Low extrapolation technique. The shaded region is obtained from the relation $3\epsilon' = \eta_+ - \eta_{00}$ (see text). Note that a first-quadrant solution for ϵ' corresponds to a third-quadrant solution for η_{00}.

$\pm 0.05) \times 10^{-3}$ and $\varphi_{+-} = 50° \pm 10°$.[4] For our purposes these errors are negligible. Two circles corresponding to conservative experimental bounds on $|\eta_{00}|$ are indicated in Fig. 2(c).[4] The lower bound is of particular interest. We see that a third-quadrant solution for η_{00} is unfavored by 2 standard deviations.[5] The upper bound then gives an improved limit on $|\epsilon'|$ ($\leq 0.7 \times 10^{-3}$). We can then infer that $|\mathrm{Im}A_2/\mathrm{Re}A_2| \leq 0.03$.

The cooperation of the staff of the alternating-gradient synchrotron and Mr. T. Blair in particular is gratefully acknowledged. Mr. J. Donaldson, Jr., Mr. J. Pinero, Mr. W. Stinson, and other members of the Rochester and Rutgers particle-physics staffs made important contributions which are deeply appreciated. We thank Dr. D. Birnbaum and Mr. H. Scott for their valuable work in the early stages of the experiment.

*Research supported by U. S. Atomic Energy Commission.

†Present address: University of Massachusetts, Amherst, Mass.

‡Present address: State University of New York, Stony Brook, N. Y.

§Research supported by National Science Foundation.

[1]B. Gobbi et al., Rochester University Report No. UR 263.

[2]B. Gobbi, D. Green, W. Hakel, R. Moffett, and J. Rosen, preceding Letter [Phys. Rev. Letters 22, 682 (1969)]. Also paper No. 339 presented at the Fourteenth International Conference on High Energy Physics, Vienna, Austria, September, 1968 (unpublished), also Rochester University Report No. UR 261.

[3]S. Marateck et al., Phys. Rev. Letters 23, 1613 (1968). See also the discussion and references provided by Ref. 2.

[4]Compilation prepared by J. Cronin, in Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, September, 1968 (CERN Scientific Information Service, Geneva, Switzerland, 1968).

[5]The leptonic charge asymmetry measurements yield information on Reϵ which is quite important in the phenomenology. D. Dorfan et al., Phys. Rev. Letters 19, 987 (1967); S. Bennett, D. Nygren, H. Saal, J. Steinberger, and J. Sunderland, Phys. Rev. Letters 19, 993 (1967). Constraints on ϵ' are implied. However, the manner of extracting these constraints is rather complicated and will not be discussed here. See C. Buchanan and K. Lande, Phys. Rev. Letters 21, 169 (1968).