

## Measurement of $\epsilon'/\epsilon$ in the Neutral Kaon System

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A measurement of the ratio of the  $CP$ -nonconservation parameters,  $\epsilon'/\epsilon$ , in the  $K^0\bar{K}^0$  system was performed through a study of two-pion decays with and without a regenerator. To reduce systematic effects,  $K_L$  and  $K_S$  decays were recorded simultaneously with a double beam. Over 3100  $K_L \rightarrow 2\pi^0$  events were reconstructed leading to the result  $\epsilon'/\epsilon = -0.0046 \pm 0.0053 \pm 0.0024$  (the first error is statistical, the second systematic). The measurement agrees with previous less precise determinations but, because of theoretical uncertainties, is not able to test decisively the Kobayashi-Maskawa mechanism.

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$CP$ -nonconserving effects so far observed can be accounted for by the lack of time symmetry in the  $\Delta S = \pm 2$  processes  $K^0 \leftrightarrow \bar{K}^0$ . Thus the long-lived neutral kaon is the unequal superposition  $K_L \sim (1 + \epsilon)|K^0\rangle - (1 - \epsilon)|\bar{K}^0\rangle$  where  $|\epsilon| \approx 2.3 \times 10^{-3}$ . The two-pion decays of the  $K_L$  can determine whether  $CP$  nonconservation is confined<sup>1</sup> to a  $\Delta S = 2$  interaction. In this case, the relation<sup>2</sup>

$$\begin{aligned} \eta_{+-} &\equiv A(K_L \rightarrow \pi^+\pi^-)/A(K_S \rightarrow \pi^+\pi^-) \\ &= \eta_{00} \equiv A(K_L \rightarrow 2\pi^0)/A(K_S \rightarrow 2\pi^0) = \epsilon \end{aligned}$$

holds. The parameter governing any  $\Delta S = 1$   $CP$  nonconservation in  $K^0 \rightarrow 2\pi$ , resulting from a phase difference between the  $\Delta I = \frac{1}{2}$  and  $\frac{3}{2}$  amplitudes, is denoted by  $\epsilon'$ .<sup>3</sup> With both  $\Delta S = 2$  and  $\Delta S = 1$   $CP$ -nonconserving interactions, the  $K \rightarrow 2\pi$  amplitude ratios are then given by  $\eta_{+-} = \epsilon + \epsilon'$  and  $\eta_{00} = \epsilon - 2\epsilon'$  so that<sup>4</sup>  $\eta_{00}/\eta_{+-} \approx 1 - 3\epsilon'/\epsilon$ .

The  $\Delta S = 1$   $CP$ -nonconserving transition is suppressed by the approximate validity of the  $\Delta I = \frac{1}{2}$  rule; nevertheless the Kobayashi-Maskawa mechanism, with complex elements in the weak charged current to account for  $\epsilon \neq 0$ , naturally yields<sup>5</sup> a  $\Delta S = 1$  effect through the contribution of virtual charm and top quarks to  $K^0$  decay. A number of calculations<sup>6</sup> predict  $\epsilon'/\epsilon \geq 0.005$ , although some uncertainty remains; the most precise of the best previous experimental determinations<sup>7-9</sup> of  $\epsilon'/\epsilon$  had an error of  $\pm 0.02$ .

These earlier measurements were limited by uncertainties in normalization of  $K_L$  vs  $K_S$  decays (collected at different times with different backgrounds), by small numbers of  $K_L \rightarrow 2\pi^0$  decays, and by the copious  $K_L \rightarrow 3\pi^0$  background. This experiment, performed at Fermilab in the M3 neutral beam line, is distinguished by higher statistics in the  $K_L \rightarrow 2\pi^0$  mode, better mass resolution and background rejection,

and better control of systematic uncertainties. The "double beam" method of a previous series of neutral-kaon experiments<sup>10</sup> was employed to eliminate one important source of systematic error. The kaons were produced at about 5 mr from 400-GeV protons and were collimated into two side-by-side beams which entered the region of the detector about 400 m from the target. A thick regenerator was placed in one beam so that both  $K_L$  and  $K_S$  decays could be studied simultaneously under identical conditions. The detector, described below, was configured to be sensitive to either  $2\pi^0$  decays (neutral-mode running) or to  $\pi^+\pi^-$  decays (charged-mode running); in both modes the trigger was equally sensitive to decays from either beam. The regenerator alternated from beam to beam after each accelerator pulse so that any asymmetries in the detector would be unimportant.

The experiment compared the ratios of  $K \rightarrow 2\pi$  decays downstream of the regenerator to decays in the vacuum for the charged and neutral modes. If we define these as  $R_{+-}$  and  $R_{00}$  respectively, it follows that  $R_{+-} = R_{00}$  if  $\epsilon' = 0$ . Two important factors need mention. First, the events downstream of the regenerator are not purely  $K_S$  decays as a result of a sizable momentum-dependent interference with  $K_L$  decays. If we let  $f/k$  ( $\bar{f}/k$ ) be the forward  $K^0$  ( $\bar{K}^0$ ) elastic-scattering amplitude ( $k$  is the kaon wave number), the coherent regeneration amplitude  $\rho$  is proportional to  $(f - \bar{f})/k$ . Then, for any momentum bin,

$$R_{+-} \propto \frac{\int |\rho \exp(-t/2 + i\Delta mt) + \epsilon + \epsilon'|^2 dt}{|\epsilon + \epsilon'|^2}$$

and

$$R_{00} \propto \frac{\int |\rho \exp(-t/2 + i\Delta mt) + \epsilon - 2\epsilon'|^2 dt}{|\epsilon - 2\epsilon'|^2},$$

where the integral is over the region in which decays are accepted,  $t$  is the proper time of the decay in units of the  $K_S$  lifetime, and  $\Delta m$  is the  $K_L$ - $K_S$  mass difference. The proportionality constants,<sup>11</sup> which depend upon the absorption in the regenerator and the length of the decay region, are identical for  $R_{+-}$  and  $R_{00}$ ; thus in the approximation that  $|\rho| \gg |\epsilon|$ ,  $R_{+-}/R_{00} \approx 1 - 6\epsilon'/\epsilon$ . However, as the interference term in the above integrals contributes roughly 15%, this relation is not precise. Second, the acceptances for  $K_L$  and  $K_S$  decays are not identical as they have different decay distributions resulting from their different lifetimes. Acceptance corrections to the ratios (of order 10%) are determined by Monte Carlo methods.

The detector<sup>12</sup> is shown schematically in Fig. 1. Immediately following the regenerator was a 13-m evacuated decay region and three scintillator planes (AVH) to define its downstream end; a drift-chamber spectrometer allowed momentum reconstruction of charged tracks; another trigger plane (G), an 804-element array of 20-rad-length lead-glass total-absorption Cherenkov counters<sup>13</sup> for photon identification, and a muon identifier completed the detector. In the neutral mode, the lead-glass array provided an accurate determination of the point where the kaon was directed (center of energy). For determining in which beam the kaon decayed, an 0.1-rad-length sheet (employed only in the neutral mode) was inserted between the A and V planes; the trigger required the signature of a single photon conversion as was done in Ref. 8. This allowed the reconstruction of the transverse momentum squared ( $P_T^2$ ) of the kaon with respect to its incident direction and thus the separation of coherent from inelastic regeneration. Additionally the background from  $K_L \rightarrow 3\pi^0$  decays downstream of the V plane was eliminated. For the charged mode, one or more tracks was required to exit from the decay region and a two-track signature in G was required. For both modes, the regenerator consisted of 1 m of carbon (providing the maximum<sup>14</sup>  $K_S$  yield) followed by 1.27 cm of lead, followed immediately by a thin anticoincidence counter. This arrangement provided a

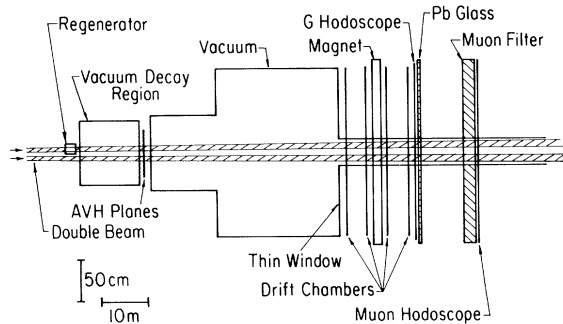


FIG. 1. Schematic of the apparatus, plan view.

well-defined beginning to the ( $K_S$ ) decay region for both modes as any  $K \rightarrow 2\pi^0$  decays within or upstream of the lead were removed with high efficiency. A similar anti counter was placed in the beam without the regenerator, again defining the beginning of the ( $K_L$ ) decay region in the charged but not in the neutral mode where the acceptance extended somewhat upstream.

The identification and reconstruction of  $K_{L,S} \rightarrow 2\pi^0$  candidates relied heavily upon the lead glass. The array was calibrated with about  $10^6$  electrons and about  $10^5$  photons (from  $\pi^0$ 's made in the lead conversion sheet) recorded with the nominal trigger; nonlinearities<sup>15</sup> of a few percent were corrected yielding a resolution of  $\sigma/E \approx 2\% + 6\%/\sqrt{E}$ . The transverse coordinates of photons were determined by energy sharing with a full width at half maximum between 4 and 8 mm depending upon energy. The  $K_{L,S} \rightarrow 2\pi^0$  candidates were reconstructed as follows: Events with three "clusters" not associated with the  $e^+e^-$  were selected and the best pairing of the four gammas was found by requiring consistency in the  $z$  coordinates of the vertices<sup>16</sup> from the two  $\pi^0$ 's; the  $K$ -decay vertex coordinate  $z_K$  was determined as the (weighted) average of  $\pi^0$  vertices, allowing the calculation of the two-pion invariant mass  $M_{2\pi^0}$ ; the decay point was determined by extrapolation of the  $e^+e^-$  tracks to  $z_K$ ; the line between the decay point and the center of energy in the lead glass was extrapolated back to the position of the regenerator and compared with the line from this extrapolated point back to the production target yielding  $P_T^2$ . The decay vertex was determined with an rms deviation of 1.7 m longitudinal and 1.0 cm transverse (the beams were about 6 cm apart); the  $2\pi^0$  mass was determined with  $\sigma \approx 6.5 \text{ MeV}/c^2$  and  $P_T^2$  was reconstructed with a precision of about 400  $(\text{MeV}/c)^2$ . The mean reconstructed kaon momentum was about 90  $\text{GeV}/c$ . Eventually the  $2\pi^0$  mass was required to be within  $\pm 20 \text{ MeV}/c^2$  of the kaon mass.

The  $K_{L,S} \rightarrow \pi^+\pi^-$  candidates were reconstructed with the drift chamber spectrometer. Each chamber (two  $x$  and two  $y$  planes) had a resolution of about 160  $\mu\text{m}$  yielding a two-pion mass resolution of 4.5  $\text{MeV}/c$ ;  $P_T^2$  was reconstructed with a precision of about 30  $(\text{MeV}/c)^2$ . The mean reconstructed kaon momentum was about 70  $\text{GeV}/c$ . Semileptonic background was largely eliminated by comparison of the momentum of each track with the energy it deposited in the lead glass ( $K \rightarrow \pi e \nu$ ) and by use of the muon identifier ( $K \rightarrow \pi \mu \nu$ ). The same mass cuts as in the neutral mode were eventually applied.

The  $K_L$  and  $K_S$  candidates were distinguished (on the basis of the transverse coordinates at the regenerator) only after the application of fiducial and kinematic cuts. The resultant  $K_S \rightarrow 2\pi$  mass distributions are nearly free of background, aside from inelastically re-

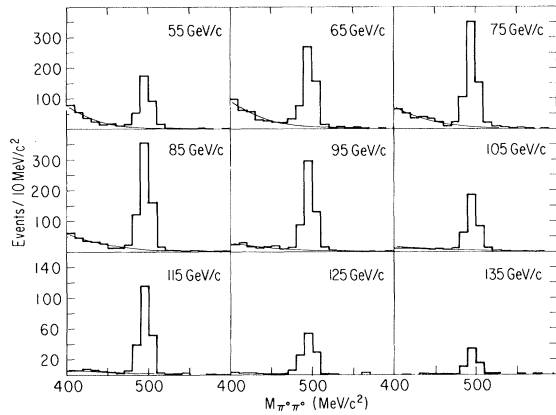


FIG. 2. Invariant-mass distributions for  $K_L \rightarrow 2\pi^0$  candidates with  $P_T^2 < 2500$   $(\text{MeV}/c)^2$ . A fit to the background is superimposed.

generated events with low  $P_T^2$ ; these are estimated by extrapolation from larger  $P_T^2$ . The  $K_L \rightarrow \pi^+\pi^-$  distributions have a small background from residual semi-leptonic decays while the  $K_L \rightarrow 2\pi^0$  distributions, shown vs momentum in Fig. 2, show a somewhat larger background resulting primarily from  $3\pi^0$  events with missing or coalesced gammas. These backgrounds are readily fitted and subtracted; the event totals and subtracted backgrounds for both modes are given in Table I, for all momenta summed together.

From the event totals and the assumption that  $\epsilon' = 0$ , the measured ratios  $R_{+-}$  and  $R_{00}$  allow the determination<sup>17</sup> of  $|(f-\bar{f})/k|$  for carbon in each momentum bin. Both the phase of  $(f-\bar{f})/k$  and the  $K_L$  total cross sections on carbon and lead are necessary and are well known.<sup>18,19</sup>

The resulting amplitudes for both modes are shown vs momentum in Fig. 3. For the charged mode alone, the data are consistent with a power-law behavior as expected<sup>18</sup>; a fit yields the result

$$|(f-\bar{f})/k| \propto p^{-0.610 \pm 0.023}$$

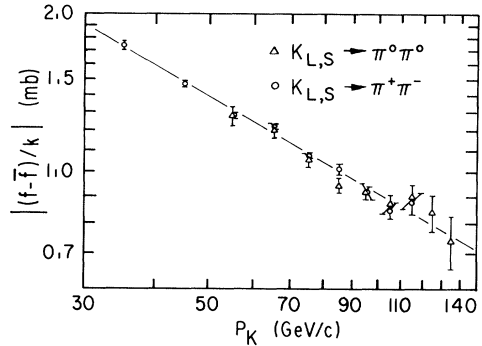


FIG. 3.  $|(f-\bar{f})/k|$  for carbon vs momentum from  $\pi^+\pi^-$  and  $\pi^0\pi^0$  samples. The best power-law fit is superimposed. Were  $\epsilon'/\epsilon = 0.01$ , the neutral points would lie about 3% above the charged points.

(charged mode), in good agreement with previous measurements<sup>14</sup> of regeneration from a variety of elements in the same energy region:

$$|(f-\bar{f})/k| \propto p^{-0.614 \pm 0.009}$$

(Ref. 14). For the neutral mode, the result is

$$|(f-\bar{f})/k| \propto p^{-0.572 \pm 0.072}$$

(neutral mode). The agreement confirms the Monte Carlo corrections, and the consistency in the normalization between the two modes (see Fig. 3) indicates that  $\epsilon'/\epsilon$  is not large. The value of  $\epsilon'$  is then extracted in a simultaneous fit (to the ratios of regenerated to vacuum events in nine momentum bins for each mode) for three parameters:  $|(f-\bar{f})/k|$  at 1 GeV/c, the power in the momentum dependence, and  $\epsilon'/\epsilon$ . The result of this fit is  $\epsilon'/\epsilon = -0.0046 \pm 0.0053$ .

This result has been checked by methods essentially independent of Monte Carlo procedures. These give consistent results with somewhat larger errors. A sample of about  $2 \times 10^5$   $K_L \rightarrow 3\pi^0$  events and about  $10^4$   $K_L \rightarrow 2\gamma$  events allowed detailed checks of the Monte Carlo corrections in the neutral mode: Distributions in photon momentum and vertex position, for

TABLE I. Event totals, corrections, and systematic errors.

Mode	Events <sup>a</sup>	Background <sup>b</sup> (Events)	Inelastics <sup>c</sup> (Events)	Systematic error (Events)
$K_L \rightarrow \pi^0\pi^0$	$3152 \pm 61$	$266 \pm 13$	$90.7 \pm 9.5$	18.9
$K_S \rightarrow \pi^0\pi^0$	$5663 \pm 84$	$35.3 \pm 5.9$	$825.7 \pm 28.7$	58.0
$K_L \rightarrow \pi^+\pi^-$	$10638 \pm 106$	$324.9 \pm 18.0$	$42.5 \pm 6.5$	19.1
$K_S \rightarrow \pi^+\pi^-$	$25751 \pm 163$	$44.8 \pm 6.7$	$439.2 \pm 21.0$	22.0

<sup>a</sup>After all subtractions.

<sup>b</sup>Residual non  $\pi\pi$  background within the kinematic cuts given in the text.

<sup>c</sup> $P_T^2 \leq 300(2500)$   $(\text{MeV}/c)^2$  for the charged (neutral) mode.

example, were well reproduced.

The systematic error arises primarily from uncertainties in the determination of backgrounds: inelastic regeneration for both  $K_S$  samples, residual three-body decays in the  $K_L$  samples, and a small amount of inelastic regeneration (primarily from the anticounter) in the  $K_L$  samples. These were determined (see Table I) by studying the change in the estimated background as the fitting procedure was altered. The estimated error in the Monte Carlo correction for the *difference* in the acceptance of  $K_L$  vs  $K_S$  decays is 0.5% (0.2%) for the neutral (charged) mode; the resulting total systematic error (adding all sources in quadrature) is 1.3% in the ratio  $R_{+-}/R_{00}$  or 0.0024 in  $\epsilon'/\epsilon$ .

The result of this experiment is then  $\epsilon'/\epsilon = -0.0046 \pm 0.0053 \pm 0.0024$  where the first error is statistical and the second systematic; combining these in quadrature yields  $\epsilon'/\epsilon = -0.0046 \pm 0.0058$ . The value is consistent with previous determinations while being over three times more accurate; it is also consistent with a recent value reported by Black *et al.*<sup>20</sup> of  $0.0017 \pm 0.0082$ . The result is not in good agreement with earlier predictions<sup>6</sup> based upon the Kobayashi-Maskawa model. Although the experimental sensitivity is in the range predicted by that model, considerable theoretical uncertainties<sup>21</sup> rule out a decisive test at the moment.

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<sup>1</sup>L. Wolfenstein, Phys. Rev. Lett. **13**, 562 (1964): the superweak model.

<sup>2</sup>A complete discussion of the phenomenology of  $CP$  non-conservation is found in the review by J. W. Cronin, Rev. Mod. Phys. **53**, 373 (1981).

<sup>3</sup> $\epsilon' = \text{Im}(a_2/a_0)\sqrt{2} \exp[i(\pi/2 + \delta_2 - \delta_0)]$ ;  $a_{0(2)}$  is the  $K^0 \rightarrow 2\pi$  transition amplitude and  $\delta_0$  ( $\delta_2$ ) the two-pion phase shift for the  $I=0$  ( $I=2$ ) final state.

<sup>4</sup>Empirically  $\arg(\epsilon') \approx \arg(\epsilon)$ , so that  $\text{Im}(\epsilon'/\epsilon) \approx 0$ ; see Ref. 2.

<sup>5</sup>M. Kobayashi and K. Maskawa, Prog. Theor. Phys. **49**, 652 (1973); J. Ellis, M. K. Gaillard, and D. V. Nanopoulos, Nucl. Phys. B **109**, 213 (1976).

<sup>6</sup>F. J. Gilman and J. S. Hagelin, Phys. Lett. **133B**, 443 (1983); A. J. Buras, W. Slominski, and H. Steger, Nucl. Phys. **B238**, 529 (1984).

<sup>7</sup>M. Holder *et al.*, Phys. Lett. **B40**, 141 (1972).

<sup>8</sup>M. Banner *et al.*, Phys. Rev. Lett. **28**, 1579 (1972).

<sup>9</sup>J. H. Christenson *et al.*, Phys. Rev. Lett. **43**, 1209 (1979).

<sup>10</sup>See W. R. Molzon *et al.*, Phys. Rev. Lett. **41**, 1213 (1978).

<sup>11</sup>A 66-cm carbon absorber was placed about 300 m upstream of the detector in the beam with the regenerator reducing the flux in that beam; being common to both modes it did not affect  $R_{+-}/R_{00}$ .

<sup>12</sup>See R. H. Bernstein, Ph.D. thesis, University of Chicago, 1984 (unpublished), for a description of the detector as well as full details of the analysis.

<sup>13</sup>Schott F2 glass, 58 mm  $\times$  58 mm  $\times$  600 mm, covering 1.2 m  $\times$  2.3 m.

<sup>14</sup>A. Gsponer *et al.*, Phys. Rev. Lett. **42**, 13 (1979).

<sup>15</sup>Subsequent tests indicated that these effects were in part due to the glass itself.

<sup>16</sup>The decay vertex  $Z$ , measured from the lead-glass, is determined from the relation  $m_\pi^2 \approx E_1 E_2 r_{12}^2 / Z^2$  where  $E_{1,2}$  are the gamma energies and  $r_{12}$  their separation at the lead-glass.

<sup>17</sup>The values for  $\epsilon$ ,  $\Delta m$ , and  $\tau_S$  (the  $K_S$  lifetime) were taken from G. G. Wohl *et al.* (Particle Data Group), Rev. Mod. Phys. **56**, S1 (1984). The 1.27-cm lead contribution was given with use of Ref. 10. The finite  $K_L$  lifetime was safely neglected.

<sup>18</sup>J. Roehrig *et al.*, Phys. Rev. Lett. **38**, 1116 (1977).

<sup>19</sup>A. Gsponer *et al.*, Phys. Rev. Lett. **42**, 9 (1979).

<sup>20</sup>J. K. Black *et al.*, preceding Letter [Phys. Rev. Lett. **54**, 1628 (1984)].

<sup>21</sup>Since the announcement of this result [Proceedings of the Eleventh International Conference on Neutrino Physics and Astrophysics, Dortmund, June 11–16, 1984 (to be published), and the Twenty-Second International Conference on High-Energy Physics, Leipzig, July 19–25, 1984 (to be published)] the validity of the earlier predictions (Ref. 6) has come into question. See L. Wolfenstein, CERN Report No. CERN-TH.3925/84, 1984 (unpublished); L. L. Chau, H. Y. Cheng, and W. Y. Keung, Brookhaven National Laboratory Report No. BNL-35163 (revised) (to be published); J. Bijnens, H. Sonoda, and M. B. Wise, Phys. Rev. Lett. **53**, 2367 (1984).