

Measurement of the CP -Nonconservation Parameter ϵ'/ϵ

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The value of ϵ'/ϵ , a measure of the CP -nonconserving direct transition from the K_L^0 state to the isospin-2 state of two pions, was determined to be 0.0017 ± 0.0082 , a result that excludes interesting models of CP nonconservation.

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After two decades of intensive research, CP nonconservation can still be described completely by one number, $|\epsilon| = (2.274 \pm 0.022) \times 10^{-3}$, that defines the proportion of the even- CP eigenstate $|K_1\rangle$ in the largely CP -odd $|K_L^0\rangle$ state. Many other possible consequences of CP nonconservation have been shown to be consistent with zero by a large set of null measurements. This is consistent with the "superweak" conjecture¹ that CP nonconservation follows from a small $\Delta S=2$ force acting in first order which leads to no detectable CP effects other than those initiated by the $|K_1\rangle$ impurity such as the observed $K_L \rightarrow \pi + \pi$ decays.²

Recently, however, attractive models for CP nonconservation have emerged that predict observable differences in the charge ratio of the decays of K_L^0 and K_S^0 states to two pions, but do not contradict measurements of other quantities. It appears that CP -nonconserving phases between sets of three or more Higgs doublets,³ or CP -nonconserving phases between elements of the six-quark mixing matrix,⁴ can be constructed that account for the K_1 impurity in the K_L state but also initiate CP -nonconserving direct transitions from the K_L state to the isospin-2 state of two pions. The parameter ϵ'/ϵ is a measure of the amplitude for these direct transitions. For superweak models of CP nonconservation, ϵ'/ϵ is zero; for the models of CP nonconservation in the Higgs sector,⁵ $\epsilon'/\epsilon < -0.02$; while for CP -nonconserving phases in the quark mixing matrix, ϵ'/ϵ is expected to be positive and as large⁶ as 0.015.

To a good approximation

$$R = \frac{|\eta_{+-}|^2}{|\eta_{00}|^2} = 1 + 6 \frac{\epsilon'}{\epsilon} = \frac{T_{L+-}/T_{s+-}}{T_{L00}/T_{s00}}.$$

Here T_{L00} and T_{L+-} are transition rates for $K_L \rightarrow \pi^0 + \pi^0$ and $K_L \rightarrow \pi^- + \pi^+$ and T_{s00} and T_{s+-} are similar rates for K_S decays.

Practical experiments determine intensities $I(E,z)$

that are the product of a transition rate T and an acceptance of the apparatus $A(E,z)$. The acceptance is a function of E , the K -meson energy, and z , the decay position. If the same apparatus is used to measure both K_L and K_S decays, the acceptances for the different charge states will be the same for K_L and K_S decays. Then, $T_{L+-} = I_{L+-}(E,z)/A_{+-}(E,z)$, $T_{L00} = I_{L00}(E,z)/A_{00}(E,z)$, $T_{s+-} = I_{s+-}(E,z)/A_{+-}(E,z)$, and $T_{s00} = I_{s00}(E,z)/A_{00}(E,z)$. The acceptance factors A largely cancel in the evaluation of R if the K_L and K_S decays are compared in the same regions of E and z , and most difficulties of establishing absolute values of the acceptances are avoided.

Our measurements, conducted at the Brookhaven National Laboratory alternating gradient synchrotron (AGS) facility, were made by simultaneous observation of the intensity of charged K decays ($K^0 \rightarrow \pi^+ \pi^-$) and neutral K decays ($K^0 \rightarrow \pi^0 \pi^0$), with use of a spectrometer designed to measure both.

The K_L mesons were produced in the forward direction by the interaction of a 28-GeV proton beam from the AGS with a 20-cm copper target. The neutral beam passed through sweeping magnets and collimators designed so that the primary neutral beam could not strike the jaws of the exit collimator 8 m downstream from the target. Typical incident proton intensities of 3×10^{11} protons per second generated intensities of about 10^8 neutrons and 3×10^6 K_L^0 per second in an acceptance of $3.5 \mu\text{sr}$.

The beam was constructed such that a piece of reactor graphite, 80 cm long with a density of 1.72, could be easily inserted or removed from the beam. The graphite, placed such that the exit face was 1.0 m upstream of the exit of the transport system and 1.2 m from the beginning of the fiducial decay space, served as a regenerator to produce the beam in which K_S decays were dominant. Every two hours, for 300 cycles, the K_L beam and a K_S beam were alternated where the K_S beam was produced by introducing a regenerator in the K_L beam. In the decay space, the width of the

cylindrical beam was described adequately by a distribution projected on a plane with $\sigma = 5.2$ mm.

A schematic representation of the spectrometer is shown in Fig. 1. The 1.2-m-long fiducial decay space begins 20 cm downstream of the exit of the beam transport system and terminates 60 cm upstream of the first proportional wire chamber (PWC) array, A. PWC arrays located at A, B, C, and D, defined the trajectories of the pions produced in the charged decays and the electron-positron pairs produced by the conversion of a gamma ray from the neutral decays. The spectrometer magnet, with a pole face 40 cm deep, 1.8 m wide, and with a gap of 60 cm, produced a field integral of 0.5 T, giving a transverse-momentum impulse of 150 MeV/c to high-energy singly charged particles. The resolution of the spectrometer was about $dp/p \approx 0.005p$, where the momentum p is measured in GeV/c. An array of 208 pieces of lead-glass, 6.3 cm \times 6.3 cm \times 50 cm, located downstream of the magnet served to measure the energies of the π^0 gamma rays emitted in the course of the neutral decays. A hole in the array, 12.5 cm by 12.5 cm, allowed the main neutral beam to pass. The spectrometer was terminated by a steel wall 60 cm thick, backed with scintillation counters set in anticoincidence.

Charged $\pi^+ + \pi^-$ events were selected through a kinematic fit where the angle of decay of the pions was determined by the trajectories provided by the PWC

arrays and their momenta were defined by their deflection in the spectrometer magnet. Events that triggered the counters behind the steel were rejected as background from $K_L \rightarrow \pi + \mu + \nu$ decays and the lead-glass was used to eliminate backgrounds from $K_L \rightarrow \pi + e + \nu$ decays by the rejection of events in which the energy deposited by a particle in the glass exceeded 50% of the momentum determined from the magnetic deflection. Further background rejection was provided by the requirement that the beam lie within 1 mrad of the plane of decay and that the transverse momenta of the decays be smaller than 30 MeV/c.

Neutral events were accepted if one gamma ray was converted in a 1.0-mm-thick sheet of lead placed just in front of the PWC array A, such that the electron-positron pair passed through the spectrometer, and three gamma rays were converted in the lead-glass array. (The selected charged events passed through a 4-cm-high transverse gap in the lead converter.) The intersection of the trajectory of the converted pair with the pencil beam defined the point of decay. With the further knowledge of the energy and direction of the four gamma rays, three from the glass array and the fourth by the magnetic spectrometer system, the decay kinematics were completely determined. Events were selected such that two sets of two gamma rays defined an invariant mass within 15 MeV of the π^0 mass, and the reconstructed K -meson momentum lay within 5 mrad of the beam direction.

Serious backgrounds from τ decays, $K_L \rightarrow \pi^0 + \pi^0 + \pi^0$, where the six gamma rays simulated the $\pi^0 + \pi^0$ decay to four gammas, were reduced by the use of anticoincidence counters framing the acceptance space, and by rejection of events where an extra gamma ray converted either in the lead-glass array or in a smaller lead-glass set, with a 10-cm by 10-cm hole, placed in back of the 30-cm by 30-cm hole in the steel which passed the neutral beam.

Altogether, 1361 $K_L \rightarrow \pi^0 + \pi^0$ events (1122, corrected for background), 3357 $K_L \rightarrow \pi^0 + \pi^0$ events, 8680 $K_L \rightarrow \pi^+ \pi^-$ events, and 20 963 $K_S \rightarrow \pi^+ + \pi^-$ events were used in the analysis. The graphs of Fig. 2 show the Q -value distributions for these four categories. Since the distributions in K energy and decay position for K_L and K_S decays differ, the Q -value distributions for K_L and K_S will differ.

Since charged and neutral decays are determined simultaneously by the spectrometer designed to serve both functions, the acceptances of the apparatus cancel in the ratio R for decays of any particular value of E and z . This cancellation is adequate over small energy regions and small decay sectors. In our analysis, R was established from the mean of values of $R(i,j)$ determined by finding values of $I_\alpha(E,z)$, for the four different intensities $\alpha = L00, L+-, s00,$ and $s+-$, for each of $i = 1-7$ values of K energy (ranging from 7 to

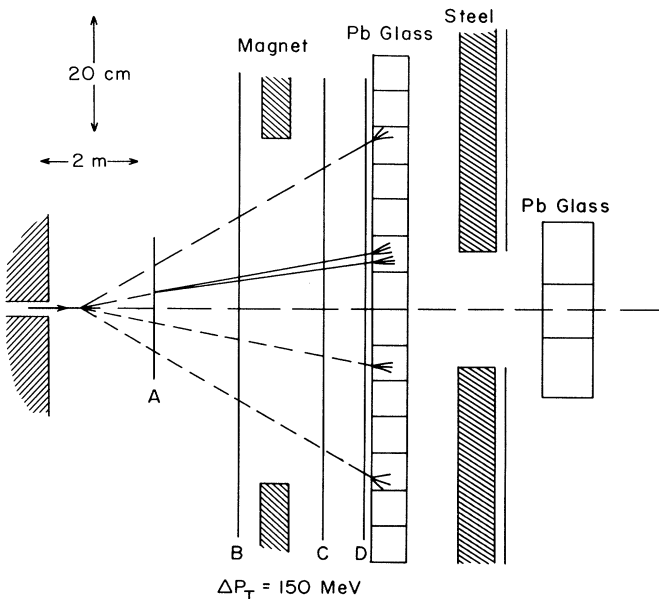


FIG. 1. Schematic representation of the elevation view of the spectrometer illustrating a $K_L^0 \rightarrow \pi^0 + \pi^0$ decay in the nonbending plane. Elements labeled A, B, C, and D are PWC planes; a 1.0-mm lead sheet is placed after A. The scintillation counters used to define the fast trigger are not shown.

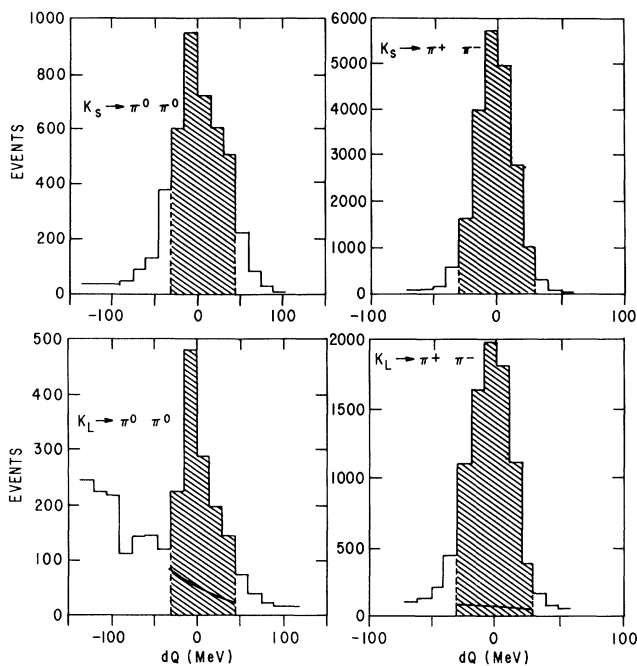


FIG. 2. Graphs showing the measured invariant-mass distributions of the four categories of events. The fiducial regions used in the analysis are crosshatched. The solid lines in the K_L^0 graphs show the backgrounds in the fiducial region.

14 GeV) and $j=1-6$ sectors of 20 cm covering the 1.2-m fiducial decay region. A small further correction of -0.001 in R accounted for variations of intensity over these small sectors where it was assumed that the intensities varied quadratically in E and z over adjacent sectors. In general, the data analysis was almost completely independent of the results of the Monte Carlo calculations of acceptances and intensities, though these calculations were in accord with the observed distributions.

Averaged over the sectors, the backgrounds, generated largely from $K \rightarrow \pi^0 + \pi^0 + \pi^0$ decays and from neutron interactions in the helium which occupied the decay region, were determined to be equal to $(17.5 \pm 3.0)\%$ of the signal for K_L^0 decays and $(1.2 \pm 0.2)\%$ for K_S^0 decays. As determined by Monte Carlo calculations, the ratio of the background to the signal varies over different E, z sectors, though the "shape" or variation of the background vs nominal $K_L^0 Q$ value does not change much. To properly define a signal corrected for the changing background, for each sector, a portion (chosen as 35% to fit the total background under the peak) of the background events with $-135 \text{ MeV} < dQ < -75 \text{ MeV}$ were subtracted from the signal events defined such that $-30 \text{ MeV} < dQ < +45 \text{ MeV}$, where dQ is the difference between the measured invariant mass and the known K mass.

There are other small corrections. While for the long regenerator which was used, the coherent K_S flux is dominant, incoherent K_S production will be about 7% of the coherent flux. Though these K_S mesons have a mean transverse momentum of about 80 MeV/c and are largely rejected, the accepted incoherent production still accounts for $(1.5 \pm 0.5)\%$ of the neutral K_S decays and about 0.2% of the charged decays. Although the regeneration produces a large K_S flux, K_L decays are not negligible. The ratio of the backgrounds for K_L and K_S beams determines a useful mean proportion of K_L decays in the nominal K_S beam of $(5 \pm 1)\%$. This dilution factor was applied to the final result. A further correction of $(2.0 \pm 1.0)\%$ was applied for backgrounds detected for $K_L \rightarrow \pi^+ + \pi^-$ decays which seemed to derive from inefficiencies in muon and electron anticoincidences.

With these corrections, we found

$$R = 1.010 \pm 0.043 \pm 0.026 \rightarrow 1.010 \pm 0.050,$$

where the first error is statistical and the second systematic, and in the final answer they are compounded. From this value of R ,

$$\epsilon'/\epsilon = 0.0017 \pm 0.0082.$$

This result is consistent with older results from much smaller data samples,⁷ and with the recent accurate Fermilab value⁸ of $\epsilon'/\epsilon = -0.0046 \pm 0.0053 \pm 0.0024$, though our measurements were made with use of different techniques on much lower-energy K mesons. Such values of ϵ'/ϵ exclude a set of models of CP nonconservation in the Higgs⁵ sector and place useful constraints on models of CP nonconservation in the quark^{6,9} sector.

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