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Search for CP violation in the decay $K_S^0 \to \pi^+\pi^-\pi^0$

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Abstract

We performed an experiment at Fermilab to search for CP symmetry nonconservation in the decay $K_S^0 \to \pi^+\pi^-\pi^0$. To date CP violation has only been observed in K_L^0 decays. We collected $\pi^+\pi^-\pi^0$ decays between 0.6 and 7.6 K_S lifetimes from the production target, and searched for interference between the coherent K_S and K_L decays. Our detector consisted of a magnetic spectrometer and a lead glass electromagnetic calorimeter. A double-beam, double-target method was used to control systematic uncertainties. $K_S^0 \to \pi^+\pi^-$ decays that were collected simultaneously provided an important normalization. The result is $\mathrm{Im}(\eta_{+-0}) = -0.015 \pm 0.017(\mathrm{stat.}) \pm 0.025(\mathrm{syst.})$ with the theoretical constraint $\mathrm{Re}(\eta_{+-0}) = \mathrm{Re}(\epsilon)$.

CP symmetry nonconservation in the weak interaction was first discovered [1] in 1964 in the decay, $K_L^0 \to \pi^+\pi^-$. In the intervening time the only additional decays where CP violation has been found are $K_L^0 \to \pi^0\pi^0$, $K_L^0 \to \pi^+\pi^-\gamma$, and in the charge asymmetry in K_L semileptonic decays. All data on these decays can be explained by the hypothesis that the K_L is a state of mixed CP with mixing parameter $\epsilon \approx 2.3 \times 10^{-3}$ [2]. Since CP violation plays a central role in the standard model, and its origin is not well understood, it is important to study it in other decays as well. CP violation is predicted to occur in some rare K_L decays and in some B meson decays, but it is difficult to study those decays using existing accelerators. However, CP violation must occur in K_S decays to the final states $\pi^+\pi^-\pi^0$ and $\pi^0\pi^0\pi^0$, at least through mixing with the same parameter ϵ. If it is measured to proceed at any other rate, that would signal the existence of either direct CP violation or CPT symmetry violation.

We performed an experiment at Fermilab to search for CP violation in $K_S^0 \to \pi^+\pi^-\pi^0$ by looking for interference between K_L and K_S near the production

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target. We measure the amplitude ratio

$$\eta_{+-0} = A(K_S^0 \to \pi^+\pi^-\pi^0)/A(K_L^0 \to \pi^+\pi^-\pi^0),$$

where by $A(K_S)$ we mean the CP violating part of the K_S amplitude. There is also a CP conserving part to the K_S amplitude, which is too small to contribute to the analysis reported here [3].

When one expands η_{+-0} in terms of the mixing parameter ϵ, one finds $\eta_{+-0} = \epsilon + \epsilon'_{+-0}$. Assuming CPT invariance, ϵ'_{+-0} is imaginary, so that $\mathrm{Re}(\eta_{+-0}) = \mathrm{Re}(\epsilon) \approx \mathrm{Re}(\eta_{+-})$ [4]. We use this constraint in fitting our data. Predictions of ϵ'_{+-0}/ϵ vary in the standard model from the 10^{-2} to 10^{-1} levels, and are larger in some extensions of the standard model [5]. All prior experimental work places a limit $|\mathrm{Im}(\eta_{+-0})| < 0.35$ at 90% confidence level [6].

The number of $K^0 \to \pi^+\pi^-\pi^0$ decays per unit interval at proper time t is

$$\frac{dN}{dt} = \frac{N_L B_{+-0}}{\tau_L}\{e^{-t/\tau_L} + |\eta_{+-0}|^2 e^{-t/\tau_S} + 2D|\eta_{+-0}|\cos(\Delta m t + \phi_{+-0})e^{-t/2\tau_S}\} \quad (1)$$

where N_L is the number of K_L at the target, B_{+-0} is the $K_L^0 \to \pi^+\pi^-\pi^0$ branching ratio, $\tau_L(\tau_S)$ is the K_L (K_S) lifetime, Δm is the K_L - K_S mass difference, ϕ_{+-0} is the phase of η_{+-0}, and D is the dilution factor: $D = (K^0 - \overline{K^0})/(K^0 + \overline{K^0})$ at production [7]. The three terms of Eq. (1) are due to pure K_L, pure K_S decays, and interference between K_L and K_S, respectively.

Our experiment measures the product of dN/dt and the acceptance of our detector. To minimize the uncertainty in the correction for acceptance, we collected data from two targets. This situation is illustrated in Fig. 1a. One target, the interference target, was located at the entrance to a magnetized collimator (called the hyperon magnet) that defined the neutral beam. Kaon decays downstream of the hyperon magnet were accepted by our detector. The second, or normalization, target was located 25.5 m upstream of the first target. This distance corresponds to about three K_S lifetimes for our average momentum kaon, so for decays in the vacuum decay region the falling exponential factors suppressed the pure K_S and interference terms in Eq. (1), while leaving the pure K_L term unaffected. Thus for these decays, we have a check on our calculation of the detector acceptance. To control for possible time dependence of this acceptance, we collected data from both targets simultaneously, by splitting the Fermilab Proton Center beam into two parallel proton beams separated horizontally by 5 cm, and having each strike one of the targets. Particles from the two targets illuminated two holes in the collimator to make two kaon beams. The roles of the two beams were reversed periodically by moving both targets to the opposite beam and adjusting the positions and intensities of the proton beams. The momentum of the protons was 800 GeV/c; the targets were made of tungsten, and the interference (normalization) target was 1 (2) interaction lengths long. The angle between the proton and kaon beams was about 0.5 mrad.

Fig. 1b shows a plan view of our detector [8]. It consisted of an evacuated decay region 19.5 m long, defined by two 1 mm thick scintillation counters (V and D) operated in the vacuum, three multi-wire proportional chambers (MWPC's) (C1-C3), the spectrometer magnet, three more MWPC'S (C4-C6), three hodoscopes of scintillation counters (A, B, and P), and an electromagnetic calorimeter of 86 lead glass blocks. Each MWPC consisted of two planes of wires, with 2 mm spacing, which measured x and y coordinates, except C2 in which the wires were rotated by 45°. The spectrometer magnet had a transverse momentum kick of 1.6 GeV/c. The photon detector consisted of a 3 L_{rad} lead pre-radiator followed by lead glass blocks, $10 \times 10 \times 38.4\ \mathrm{cm}^3$ (12 L_{rad} deep). The photon detector had a $10 \times 10\ \mathrm{cm}^2$ hole to allow the two neutral beams to pass through. We used the lead glass array to measure the interaction points and energies of the two gamma rays from π^0 decays.

The $\pi^+\pi^-\pi^0$ trigger required a $\overline{\mathrm{V}}\cdot\mathrm{D}$ coincidence to signal the decay of a neutral particle, one hit on the left half and one on the right half of each of the A and B hodoscopes, and "yes" signals from each of three trigger processors. One trigger processor examined the pattern of hits in the A and B hodoscopes and chose events consistent with the decay of a K meson. A second performed a calculation using the hits in the C4 and C5 MWPC's to choose events for which the ratio of momenta of the two charged particles was between 1/3 and 3. The purpose of this was to exclude the copious flux of Λ decays, for which the ratio of proton to pion momenta is always greater than 3. The third trigger processor examined the pattern of hits in the lead glass array and chose events with two or more

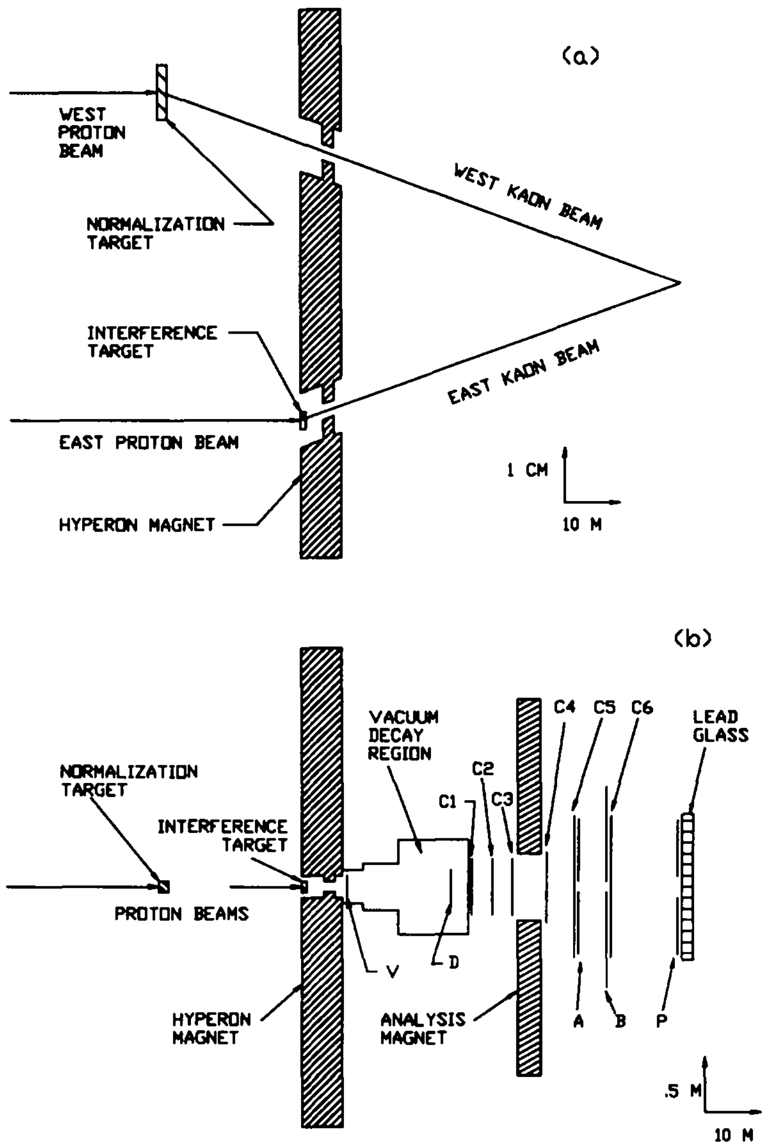

Fig. 1. Plan views of the beams and apparatus. Note the greatly exaggerated transverse scale. Fig. 1a shows the geometry of the proton beams, targets, hyperon magnet used to define the two neutral beams, and the two kaon beams. The roles of the two beams were periodically reversed by moving both targets to the other beam. Fig. 1b shows the proton beams, targets, hyperon magnet, trigger counters (A, B, and P), multiwire proportional chambers (C1 - C6) with the analysis magnet between C3 and C4, and the lead glass electromagnetic calorimeter.

non-overlapping clusters of hits. The P hodoscope was used to reject clusters caused by charged particles.

While collecting $\pi^+\pi^-\pi^0$ decays, we also collected data with a $\pi^+\pi^-$ trigger that had the same requirements as the $\pi^+\pi^-\pi^0$ trigger except those on C4 and C5 and the lead glass. With this trigger we collected $K_S^0 \to \pi^+\pi^-$ decays for normalization purposes. Every 512th trigger of this type was recorded.

The analysis of the $\pi^+\pi^-\pi^0$ data began with the reconstruction of the charged tracks from the MWPC hits and the calculation of the π^+ and π^- momenta. Using the $\pi^+\pi^-$ vertex plus the interaction points and the energies of the clusters measured in the lead glass, the vector momenta of the photons were calculated. From the momenta of the π^+, π^-, and the two photons the kaon was completely reconstructed. An event was kept when the kaon's momentum was $120 < p < 360$ GeV/c, its z-vertex was $9.2 < z < 26.2$ m from the interference target, and it satisfied beam phase space requirements. Events were rejected if their $\gamma\gamma$ ($\pi^+\pi^-\gamma\gamma$) invariant mass was more than 3σ from the π^0 (K^0) mass. To remove $K_S \to \pi^0\pi^0$ decays where one of the π^0's has undergone a Dalitz decay to $e^+e^-\gamma$, we required the invariant mass of the two charged particles when assumed to be e^+e^- to be > 0.085 GeV/c^2. In addition we required that photon energies be >3.5 GeV. 272,000 events satisfied these requirements.

For the $\pi^+\pi^-$ decays, events were kept which satisfied the same p and z criteria, had their $\pi^+\pi^-$ invariant mass within 3σ of the K^0 mass, and fell within the phase space of the beam. 541,000 $K_S^0 \to \pi^+\pi^-$ decays satisfied these requirements.

To calculate the acceptance of our detector, we performed a Monte Carlo simulation which included the known decay parameters of $K_L^0 \to \pi^+\pi^-\pi^0$, the geometry of the beams and apparatus, and the efficiency of the MWPC's, scintillation counters, and trigger processors. We used the same program to calculate the acceptance for the $K_S^0 \to \pi^+\pi^-$ events. Fig. 2 shows four comparisons (typical of many) of the data and Monte Carlo simulation.

We corrected the data for backgrounds due to collimator production. This correction was approximately the same for $\pi^+\pi^-$ and $\pi^+\pi^-\pi^0$ decays, and varied from 10% at 120 GeV/c to 1% at 360 GeV/c. We also corrected for gamma ray conversions in the material of the spectrometer, which were 13%, nearly independent of kaon momentum. We also corrected the ratio of $\pi^+\pi^-\pi^0$ to $\pi^+\pi^-$ branching ratios for π^0 Dalitz decays, and for $K_S^0 \to \pi^+\pi^-\gamma$ decays.

We binned our data in momentum, p, and proper time, t, and fit this array to the theoretical function, $T(p,t) = N_L(p)f(t)A(p,t)$, where $N_L(p)$ is the spectrum of K_L at the target (that were accepted by the collimator in the hyperon magnet), $f(t)$ is the decay probability given by an integral of Eq. (1) over the p and t bin, and $A(p,t)$ is the acceptance of the detector. We determined the spectrum from acceptance corrected $K_S^0 \to \pi^+\pi^-$ decays, using the fact that the spectra of K_L and K_S at the target are identical, and calculated the acceptance of the detector from our Monte Carlo simulation. Data from the interference and normalization targets were fit simultaneously. We expect to observe a ratio of K_L to K_S fluxes at the target of 1.000 ± 0.026, where the uncertainty arises from published $K_L^0 \to \pi^+\pi^-\pi^0$ and $K_S^0 \to \pi^+\pi^-$ branching ratios ($\pm$ 0.017), the efficiencies of the $\pi^+\pi^-\pi^0$ and $\pi^+\pi^-$ triggers ($\pm$ 0.014), and the correction for gamma ray conversion ($\pm$ 0.013). We measured the ratio of K_L to K_S fluxes to be 1.022 ± 0.004 (1.021 ± 0.009) for the interference (normalization) targets. This is consistent with our expectation and with the hypothesis that it should be the same for both targets.

Data from the interference (normalization) target span a range of proper time from $0.6\tau_S$ to $3.8\tau_S$ ($1.9\tau_S$ to $7.6\tau_S$). Thus the interference target data are sensitive to both η_{+-0} and to the K_L flux, where the normalization target data are sensitive primarily to the flux. So the normalization target plays an essential role in our extraction of η_{+-0}.

We performed many tests of our analysis and fitting procedures. In particular, we generated Monte Carlo samples with non-zero values of η_{+-0}, and treated them as data. After analysis and fitting, the answers were always consistent with the values of η_{+-0} that we built into the Monte Carlo samples. To test the theoretical constraint, $\mathrm{Re}(\eta_{+-0}) = \mathrm{Re}(\epsilon) = 0.0016$, we fit the data for the real and imaginary parts of η_{+-0}. We found that $\mathrm{Re}(\eta_{+-0}) = 0.019 \pm 0.027$ and $\mathrm{Im}(\eta_{+-0}) = 0.019 \pm 0.061$, where the uncertainties are statistical and systematic added in quadrature. This answer is consistent with the constraint.

Our final fit uses the constraint on $\mathrm{Re}(\eta_{+-0})$. The result is:

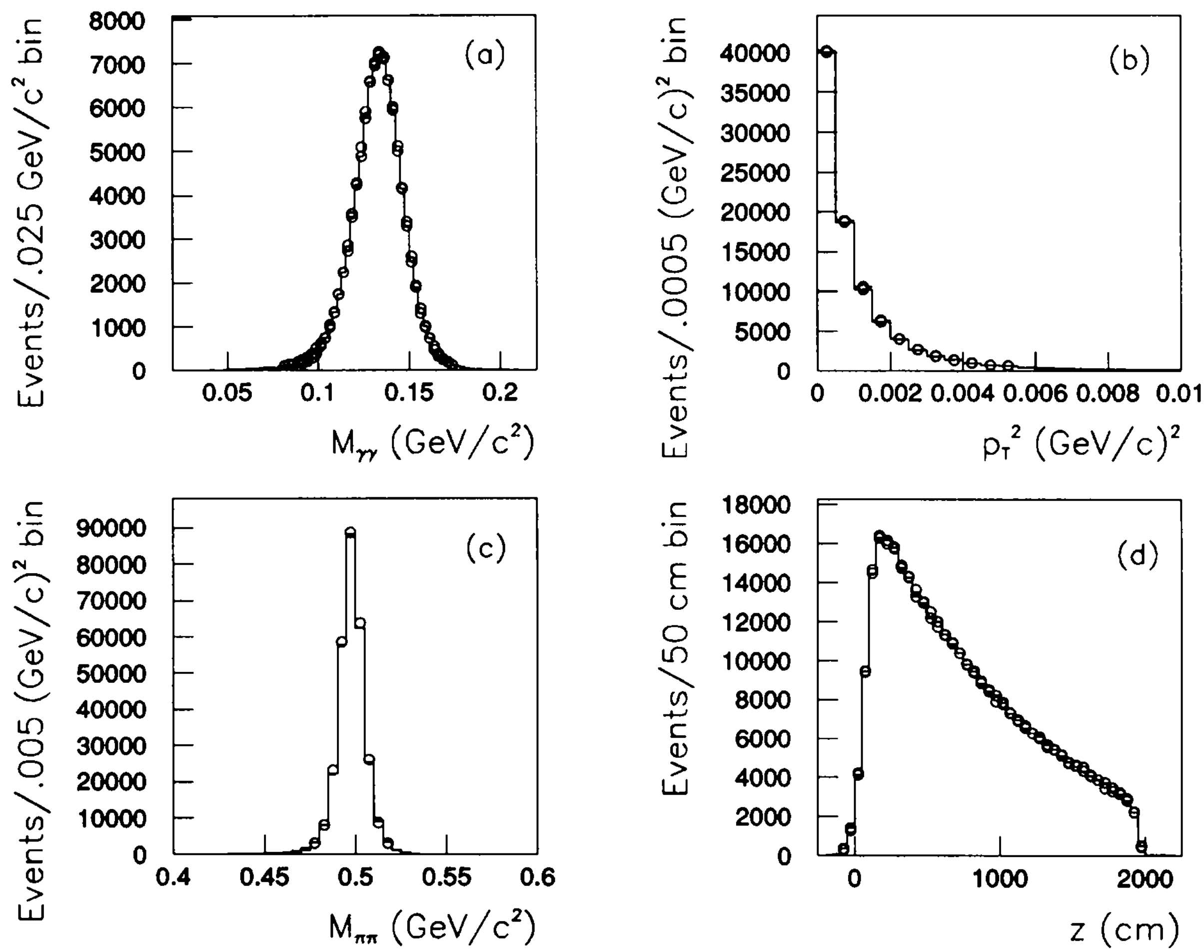

Fig. 2. Histograms of (a) the $\gamma\gamma$ invariant mass, (b) the square of the kaon's transverse momentum (the component of the measured momentum transverse to the direction defined by the center of the target and the decay vertex), (c) the $\pi^+\pi^-$ invariant mass and (d) longitudinal vertex position. (a) and (b) are for $\pi^+\pi^-\pi^0$ decays; (c) and (d) are for $\pi^+\pi^-$ decays. In each plot the solid line is the data and the open circles are the Monte Carlo simulation.

$$\mathrm{Im}(\eta_{+-0}) = -0.015 \pm 0.017(\mathrm{stat.}) \pm 0.025(\mathrm{syst.}).$$

The fit has $\chi^2 = 1125$ for 1048 degrees of freedom. The systematic uncertainty is dominated by the uncertainty in the normalization of K_L to K_S decays. The statistical uncertainty of this fit is much smaller than that of the fit where both $\mathrm{Re}(\eta_{+-0})$ and $\mathrm{Im}(\eta_{+-0})$ were allowed to vary because in the latter fit the variables are highly correlated. Fig. 3 shows the proper time distribution of $\pi^+\pi^-\pi^0$ decays in our experiment. The fit is superimposed on the data. These data are consistent with pure K_L decays.

In summary, we performed an experiment at Fermilab to search for CP symmetry nonconservation in $K_S^0 \to \pi^+\pi^-\pi^0$ decays by looking for K_L - K_S interference near the kaon production target. We used a magnetic spectrometer and a lead glass electromagnetic calorimeter to detect the kaon decays, and a two beam - two target arrangement to control systematic uncertainties. We see no evidence for interference at the level $\eta_{+-0}/\eta_{+-} \approx 10$. This result is based on about 1/5 of our data.

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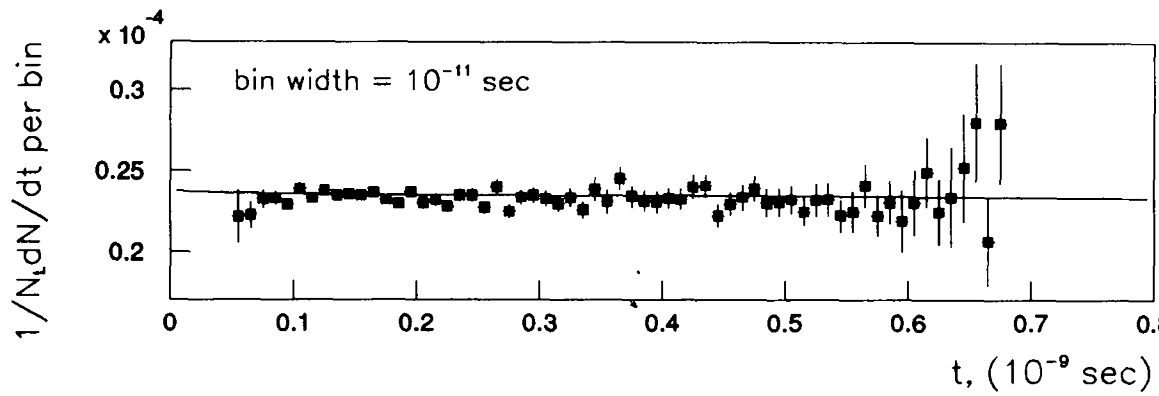

Fig. 3. Proper time, including events from both interference and normalization targets. The horizontal scale is in units of 10^{-9} sec. The vertical scale is the decay probability per kaon at the target. The line is the result of the fit described in the text, with the constraint, $\mathrm{Re}(\eta_{+-0}) = \mathrm{Re}(\epsilon)$.

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[3] The CP conserving part of the K_S amplitude comes from the isospin I=2 final state. The contribution of interference from this source has the property that it changes sign from one half of the Dalitz plot, where the π^+ is more energetic than the π^-, to the other half, and that its average vanishes. We are preparing a publication on the CP conserving decay, which we have isolated by fitting the proper time distribution of the difference between the two halves of the Dalitz plot. From this we know that any contribution from the CP conserving decay to the present analysis is negligibly small.

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