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Measurement of the amplitude of the CP conserving decay $K_S^0 \to \pi^+\pi^-\pi^0$

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Abstract

We measured the amplitude for the CP-symmetry-conserving decay $K_S^0 \to \pi^+\pi^-\pi^0$ in an experiment at Fermilab. This decay manifests itself as a time dependent charge asymmetry in the interference between the coherent K_S and K_L decays. We collected $\pi^+\pi^-\pi^0$ decays between 0.6 and 7.6 K_S lifetimes from the production target using a detector that consisted of a magnetic spectrometer and a lead glass electromagnetic calorimeter. $K_S^0 \to \pi^+\pi^-$ decays that were collected simultaneously were used for normalization. The ratio ρ_{+-0} of the CP-conserving K_S amplitude to the K_L amplitude is found to be: $|\rho_{+-0}| = 0.035\,^{+0.019}_{-0.011}$ (stat.) ± 0.004 (syst.), with a phase $\phi_\rho = -59^\circ \pm 48^\circ$. This yields a branching ratio of $(3.9\,^{+5.4}_{-1.8}(\text{stat.})\,^{+0.9}_{-0.7}(\text{syst.})) \times 10^{-7}$.

The origins of CP symmetry violation and of the $\Delta I = 1/2$ rule are poorly understood aspects of the weak interaction. Studies of the decay $K_S^0 \to \pi^+\pi^-\pi^0$ can shed light on both of these questions. This decay is dominated by the isospin $I = 1$ and $I = 2$ $\pi^+\pi^-\pi^0$ final states. The decay to the $I = 1$ final state violates CP symmetry, and that to the $I = 2$ final state conserves CP but violates the $\Delta I = 1/2$ rule. So by isolating these two final states, one can perform separate tests of the symmetry principles and selection rules of the weak interaction. We have recently published a result from our search for the CP violating decay from the data of Fermilab experiment E621 [1]. This letter reports a measurement of the branching ratio for the CP conserving process.

One isolates the two final states using the fact that the amplitude for the $I = 2$ final state is proportional to the Dalitz plot variable $X = (s_2 - s_1)/m_\pi^2$, where $s_i = (p_K - p_i)^2$, p_K is the kaon four-momentum, p_i is

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the four-momentum of the ith pion, and $i = 1, 2$, and 3 corresponds to the π^+, π^-, and π^0. If one integrates over the whole Dalitz plot (a region symmetric in X), interference from the $I = 2$ final state sums to zero, and the remaining interference comes from the $I = 1$ state, which is symmetric in X. Conversely, if one subtracts the integral over the region, $X < 0$, from the $X > 0$ integral, the $I = 1$ term drops out, and one isolates the $I = 2$ final state.

Predictions for the CP conserving $K_S^0 \rightarrow \pi^+\pi^-\pi^0$ branching ratio, $B^{(S)}_{+-0}$, have been made using two approaches. The first uses the isospin decomposition of all of the charged and neutral $K \rightarrow 3\pi$ decays. From the parameters of the $K^+ \rightarrow \pi^+\pi^0\pi^0$ and $K^+ \rightarrow \pi^+\pi^+\pi^-$ decays one arrives at the prediction, $B^{(S)}_{+-0} = (2.4 \pm 0.7) \times 10^{-7}$ [2]. The second approach uses chiral perturbation theory. Based on the symmetries of QCD at very low energies ($E \leq 0.5$ GeV), this theory reproduces many of the details of kaon decays. Predictions for $B^{(S)}_{+-0}$ range from 2.1×10^{-7} to 3.9×10^{-7} [3]. The most sensitive published measurement of this branching ratio placed an upper limit at the 68% confidence level of 3.4×10^{-5} [4].

Our Fermilab experiment searched for the CP conserving decay $K_S^0 \rightarrow \pi^+\pi^-\pi^0$ by looking for interference between K_L and K_S near the production target. This paper reports a result based upon 18% of our data. We measure the amplitude ratio

$$\rho_{+-0} = \frac{A(K_S^0 \rightarrow \pi^+\pi^-\pi^0, I = 2)}{A(K_L^0 \rightarrow \pi^+\pi^-\pi^0)}.$$

Since this amplitude ratio varies with position on the Dalitz plot, we define ρ_{+-0} as an integral over that half of the Dalitz plot where $X > 0$.

We define $dN_+/dt(dN_-/dt)$ as the number of $\pi^+\pi^-\pi^0$ decays per unit interval at proper time t in the half of the Dalitz plot where X is positive (negative). Then the difference of these rates is:

$$\frac{dN_+}{dt} - \frac{dN_-}{dt} = \frac{N_L B^{(L)}_{+-0}}{\tau_L} \times \{4D|\rho_{+-0}| \cos(\Delta m \times t + \phi_\rho) e^{-\frac{t}{2}(\frac{1}{\tau_L}+\frac{1}{\tau_S})}\}, \quad (1)$$

where N_L is the number of K_L at the target (that would decay in the $X > 0$ half of the Dalitz plot), $B^{(L)}_{+-0}$ is the $K_L^0 \rightarrow \pi^+\pi^-\pi^0$ branching ratio, $\tau_L(\tau_S)$ is the K_L (K_S) lifetime, Δm is the K_L - K_S mass difference, ϕ_ρ is the phase of ρ_{+-0}, and D is the dilution factor: $D = (K^0 - \overline{K^0})/(K^0 + \overline{K^0})$ at production[7]. This is the equation to which we fit our data.

This experiment was performed in the Proton Center beam line at Fermilab. For control of systematic uncertainties it was performed using two kaon beams that went through our detector approximately parallel to each other, separated horizontally by about 5 cm. The center line of the detector was halfway between the two beams.

The E621 detector has been described in detail previously[8]. The apparatus, triggers, event selection, corrections, and Monte Carlo simulation are identical to Ref. [1]. Briefly, the detector consisted of an evacuated decay region 19.5 m long, defined by two 1 mm thick scintillation counters operated in the vacuum, followed by a magnetic spectrometer and a photon detector. The spectrometer had three Multi-Wire Proportional Chambers (MWPC's) in front of and three behind the spectrometer magnet. The chambers had 2 mm wire spacing, and each measured two orthogonal coordinates of the charged particles that traversed them: x and y for each chamber except the center one in front of the magnet which was rotated by 45°. Two scintillation counter hodoscopes, placed between C5 and C6, were used for triggering. The photon detector was placed 13.7 meters behind the last chamber. It consisted of a 3 L_{rad} lead pre-radiator followed by an array of 86 lead glass blocks, each measuring $10 \times 10 \times 38.4$ cm^3 (12 L_{rad} deep). There was another hodoscope of scintillation counters just in front of the photon detector whose sizes matched that of the lead glass blocks. It was used to identify showers in the lead glass caused by charged particles.

The $\pi^+\pi^-\pi^0$ trigger required that the pattern of hits in the scintillation counters conform to that of a neutral particle decaying to two charged particles. Two trigger processors examined the pattern of hits in the

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[7] Our calculation of D is based on K^+ and K^- production from the parameterization by Malensek [5]. We made a correction for K^+/K^0 and $K^-/\overline{K^0}$ differences using a quark counting argument. See Briere [5]. D varies from about 0.2 to 0.7 in the momentum range of this experiment, with a value of about 0.4 in the most important momenta. Its value is known to about 10% accuracy, so that its uncertainty is small compared to the statistical uncertainty of our data.

[8] In addition to Ref. [1], the detector has been described previously by Grossman et al., Grossman, and Zou [6].

scintillation counter hodoscopes and in the chambers behind the spectrometer magnet to choose kaon decays and exclude the copious flux of Λ decays by requiring that the ratio of charged particle momenta be between 1/3 and 3. A third trigger processor looked at the hits in the lead glass array and chose events with two or more non-overlapping clusters of hits that were caused by neutral particles.

We also used a trigger with the same hodoscope requirements as the $\pi^+\pi^-\pi^0$ trigger but none on the chambers 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.

In the analysis $\pi^+\pi^-\pi^0$ events were kept when the kaon's momentum was $120 < p < 360$ GeV/c, its z-vertex was $9.2 < z < 26.2$ m from the 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 momentum and vertex 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 detector elements. We used the same program to calculate the acceptance for the $K_S^0 \to \pi^+\pi^-$ events. The Monte Carlo simulation reproduces the characteristics of the data very well [6]. The acceptances were 9.3 % (29.3 %) for $K_{\pi3}$ ($K_{\pi2}$) decays.

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.

The CP conserving $\pi^+\pi^-\pi^0$ decay manifests itself as a charge asymmetry in our data. We must first ask if there are any apparatus-generated charge asymmetries that could mimic this effect. Any such asymmetry is most easily seen if we divide the data on the basis of p_+ and p_-, the charged pion momenta in the lab frame. Indeed for every run, there is such an asymmetry, of about 9% which is approximately equal for $\pi^+\pi^-\pi^0$ and $\pi^+\pi^-$ decays. This asymmetry is due to the geometry of the detector and the efficiencies of the detector elements. Fig. 1a shows the proper time dependence of this asymmetry for $\pi^+\pi^-$ decays of kaons from the interference target. The two top (bottom) curves are data and Monte Carlo simulation for those runs where the spectrometer magnet polarity was positive (negative). This asymmetry is well reproduced by the Monte Carlo simulation. The data taken with the two spectrometer magnet polarities are mirror images of each other. In these data the magnet polarity was reversed 18 times. When the data from the two magnet polarities are added, the apparatus-induced asymmetry disappears within uncertainties. Fig. 1b shows the proper time dependence of the charge asymmetry when data from both polarities are summed together.

We selected the CP conserving decay by dividing our $\pi^+\pi^-\pi^0$ data into two data sets on the basis of the momenta of the charged particles in the kaon center of mass system, p_+^* and p_-^*. If $p_+^* > p_-^*$ ($p_+^* < p_-^*$), then $X > 0$ ($X < 0$). We binned the two data sets in momentum and in proper time and corrected each bin for the acceptance of the detector. We then subtracted the two data sets bin-for-bin.

We fit the data to the hypothesis that the difference between the two data sets is represented by Eq. (1). For N_L in Eq. (1) we used the spectrum from $K_S^0 \to \pi^+\pi^-$ decays, since the spectra of K_L and K_S at the target are expected to be identical. In Ref. [1] we showed that we understand the spectra to better than 1% accuracy. We calculated the acceptance of the detector using our Monte Carlo simulation program.

When we fitted the data for the parameters, $\mathrm{Re}(\rho_{+-0})$ and $\mathrm{Im}(\rho_{+-0})$, the result was: $\mathrm{Re}(\rho_{+-0}) = 0.018 \pm 0.020$, and $\mathrm{Im}(\rho_{+-0}) = -0.029 \pm 0.024$. The fit has $\chi^2 = 1101$ for 1107 degrees of freedom. The parameters are highly correlated. Fig. 2 shows the contours of constant χ^2 in the complex ρ_{+-0} plane. The value of χ^2 at the origin is 12.84 units above the minimum, showing that the the origin is excluded at

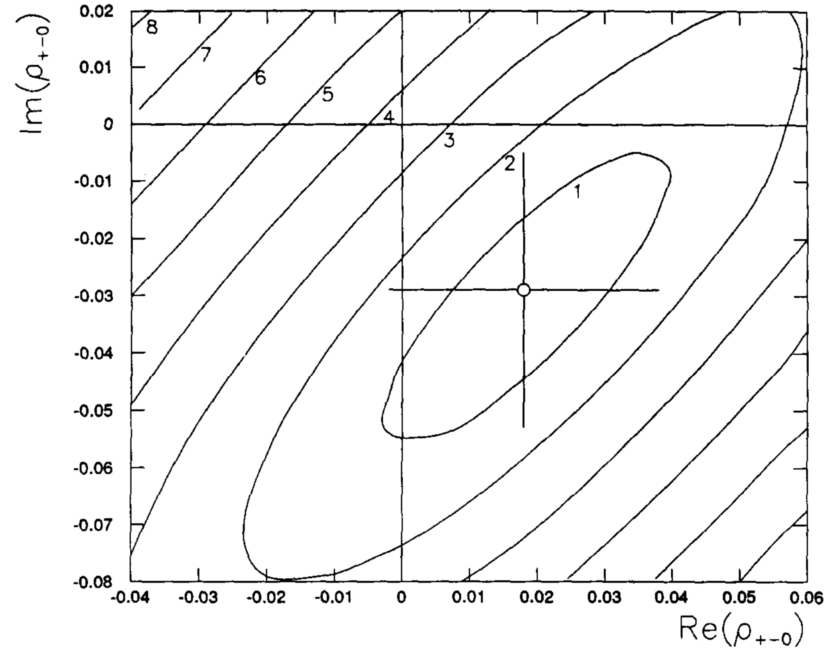

Fig. 1. Charge asymmetry vs. proper time for $\pi^+\pi^-$ decays. The solid (open) points are data (Monte Carlo simulation). (a) The asymmetry as defined in the text for positive (negative) spectrometer magnet polarity is above (below) the horizontal axis. (b) The same data with both polarities added together. The apparatus-induced charge asymmetry vanished within uncertainties.

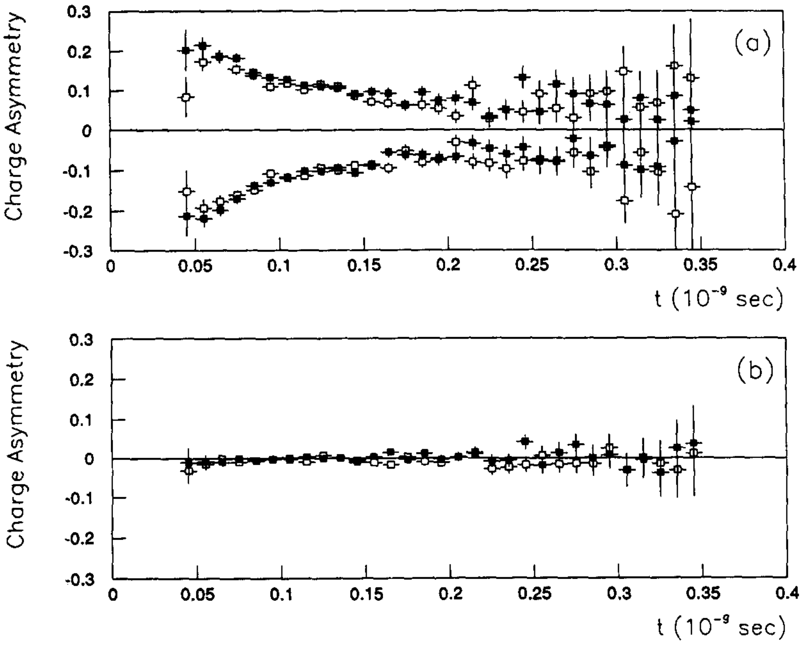

Fig. 2. χ^2 contours in the complex ρ_{+-0} plane. The parameters Re(ρ_{+-0}) and Im(ρ_{+-0}) are highly correlated. The numbers on the contour lines indicate the number of standard deviations of the contour from the best fit. The point at the origin is excluded at the 3.6 σ level.

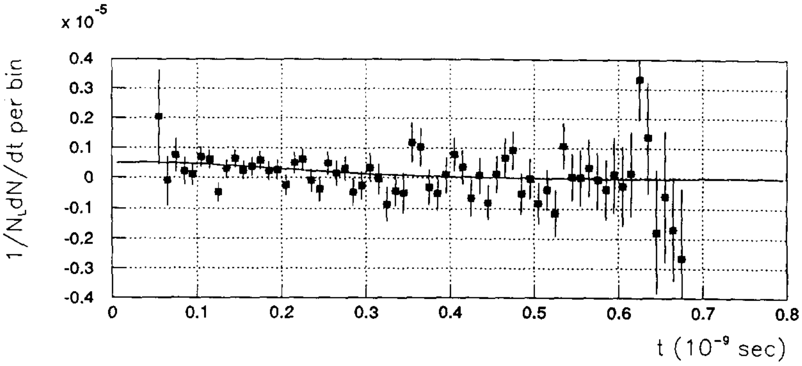

Fig. 3. $N_L^{-1} dN/dt$ vs. proper time for $\pi^+\pi^-\pi^0$ data. The vertical scale is the decay probability per kaon at the target. What is plotted is the difference between the two data sets, separated according to the Dalitz plot variable X (see text). The line is the result of the fit.

the $\sqrt{12.84} = 3.6$ standard deviation level.

We estimated the systematic uncertainty of our fit by varying the parameters of the Monte Carlo simulation and fitting the resulting events as if they were data. The result was $\Delta|\rho_{+-0}| = 0.004$. This systematic uncertainty is much smaller than the statistical uncertainty of our data. The most sensitive parameter was the horizontal position of the scintillation counter hodoscope labeled B in Fig. 1b of Ref. [1]. To estimate the systematic uncertainty due to this parameter we used our Monte Carlo program to generate three times the data's statistics with the hodoscope moved 20 times farther than the uncertainty in its position. We fit for $|\rho_{+-0}|$ then scaled down the result by the same factor of 20.

This results in a value of

$$|\rho_{+-0}| = 0.035\ ^{+0.019}_{-0.011}\ (\text{stat.}) \pm 0.004\ (\text{syst.}),$$

$$\phi_\rho = -59^\circ \pm 48^\circ.$$

The branching ratio that corresponds to this value is: $B^{(S)}_{+-0} = (3.9\ ^{+5.4}_{-1.8}(\text{stat.})\ ^{+0.9}_{-0.7}(\text{syst.})) \times 10^{-7}$.[9] This result is consistent with the theoretical predictions of Refs. [2] and [3]. Fig. 3 shows the proper time distribution of the data, with the fit superimposed.

In summary, we performed an experiment at Fermilab to search for the CP symmetry conserving decay $K^0_S \to \pi^+\pi^-\pi^0$ 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. We measure the K_S/K_L amplitude ratio to be $|\rho_{+-0}| = 0.035\ ^{+0.019}_{-0.011}$ (stat.) ± 0.004 (syst.).

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[9] Theoretical estimates for the branching ratio have been made assuming that the CP conserving K_S amplitude, $A_S = \gamma X$, where γ is a parameter and X is the Dalitz plot variable defined in the text. The branching ratio is calculated from integrals over the Dalitz plot. In terms of the quantity that we measure, ρ_{+-0}, the branching ratio is $B^{(S)}_{+-0} = C\ B^{(L)}_{+-0}|\rho_{+-0}|^2\tau_S/\tau_L$, where the factor $C = 1.50$ comes from the above mentioned integrals over the Dalitz plot.