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Search for CP violation in the decay of neutral kaons to $\pi^+\pi^-\pi^0$

CPLEAR Collaboration

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Abstract

The time-dependent rate asymmetry of initial K^0 and $\overline{K}^0$ decaying into $\pi^+\pi^-\pi^0$ was measured in order to reveal the CP-violating amplitude of the $K_S \to \pi^+\pi^-\pi^0$ decay. For the real and the imaginary parts of η_{+-0}, we find $\mathrm{Re}(\eta_{+-0}) = (6 \pm 13_{\mathrm{stat.}} \pm 1_{\mathrm{syst.}}) \times 10^{-3}$ and $\mathrm{Im}(\eta_{+-0}) = (-2 \pm 18_{\mathrm{stat.}} \pm 3_{\mathrm{syst.}}) \times 10^{-3}$ which correspond to $|\eta_{+-0}| < 0.037$ with 90% CL.

1. Introduction

In this paper, results are presented on the CP-violating $K_S \to \pi^+\pi^-\pi^0$ decay studied by the CPLEAR experiment at the Low Energy Antiproton Ring (LEAR) at CERN, where the decay rates of the initial K^0 and $\overline{K}^0$ into the three-pion final state are measured.

The motivations for a search for the CP-violating amplitude of $K_S \to \pi^+\pi^-\pi^0$ decay extend beyond the search for CP violation in the K_S decays of the neutral kaon system. It is also an important experimental input to the best indirect test of CPT symmetry, based on the Bell–Steinberger relation [1]. The increasing experimental precision in measuring the ϕ_{+-} phase has renewed interest in a purely experimental test of CPT. For this, the precision in measuring the amplitudes of the transitions to the three-body final states is a limiting factor. Our measurement substantially reduces the experimental uncertainty due to the $\pi^+\pi^-\pi^0$ final state, making it negligible compared with the experimental uncertainty of the other parameters contributing to the limit to CPT invariance.

The search for the CP-violating amplitude in the decay to $\pi^+\pi^-\pi^0$ is different to that in the more familiar two-pion channels. The two-pion final states and the $\pi^0\pi^0\pi^0$ state each have a well-defined CP eigenvalue. In contrast, the CP eigenvalue of a $\pi^+\pi^-\pi^0$ state with zero total angular momentum is given by $(-1)^{l+1}$, where l is the relative angular momentum between π^+ and π^-. Since the sum of the masses of the three pions is close to the kaon mass, the decays of K^0 and $\overline{K}^0$ into three-pion states with $l > 0$ are suppressed by kinematics. Therefore, the process $K_L \to \pi^+\pi^-\pi^0$ is dominated by the CP-allowed decay amplitude $A_L^{\pi^+\pi^-\pi^0}$ with $l = 0$ and CP = -1. The K_S may decay into the kinematics-suppressed and CP-allowed final state with $l = 1$ and CP = $+1$, or into the kinematics-favoured but CP-forbidden final state with $l = 0$ and CP = -1. This results in a Dalitz plot population which is symmetric with respect to the π^+ and the π^- for the $K_S \to \pi^+\pi^-\pi^0$ CP-violating amplitude and anti-symmetric for the $K_S \to \pi^+\pi^-\pi^0$ CP-allowed amplitude. Thus, in the K_L–K_S interference term, the CP-allowed contribution of K_S decays vanishes when the decay amplitude is integrated over the phase space of the neutral kaon decays [2]. Therefore the parameter η_{+-0}, defined as

$$\eta_{+-0} = \frac{\int d\Omega A_S^{\pi^+\pi^-\pi^0} A_L^{\pi^+\pi^-\pi^0 *}}{\int d\Omega \left|A_L^{\pi^+\pi^-\pi^0}\right|^2} \qquad (1)$$

where the integration is over the entire phase space of the $K^0 \to \pi^+\pi^-\pi^0$ decay, depends only on the CP-violating part of the amplitude $A_S^{\pi^+\pi^-\pi^0}$ for the decay $K_S \to \pi^+\pi^-\pi^0$.

2. Experimental method

In the CPLEAR experiment, the parameter η_{+-0} is determined from the time-dependent K^0–$\overline{K}^0$ decay rate asymmetry, which is a direct measurement of the

K_S–K_L interference term. This asymmetry $A_{+-0}(\tau)$ is prominent in the early decay-time region and is given as

$$A_{+-0}(\tau) = \frac{\overline{R}_{+-0}(\tau) - R_{+-0}(\tau)}{\overline{R}_{+-0}(\tau) + R_{+-0}(\tau)}$$
$$= 2\,\mathrm{Re}(\varepsilon) - 2\left[\mathrm{Re}(\eta_{+-0})\cos(\Delta m\,\tau) - \mathrm{Im}(\eta_{+-0})\sin(\Delta m\,\tau)\right] e^{-\frac{1}{2}(\Gamma_S-\Gamma_L)\tau} \quad (2)$$

where $\overline{R}_{+-0}(\tau)$ and $R_{+-0}(\tau)$ are the $\overline{K}^0$ and K^0 decay rates, Δm is the K_L–K_S mass difference, Γ_L and Γ_S ($= 1/\tau_S$) are the K_L and K_S decay widths, respectively, and ε is the CP violation parameter in the K^0–$\overline{K}^0$ mixing.

The initial K^0 and $\overline{K}^0$ are produced in the reactions

$$p\bar{p}(\text{at rest}) \to K^-\pi^+K^0$$

and

$$p\bar{p}(\text{at rest}) \to K^+\pi^-\overline{K}^0$$

each with a branching ratio of approximately 2×10^{-3}. The strangeness of the neutral kaon is tagged by the sign of the associated charged kaon. The 200 MeV/c antiprotons from LEAR are stopped in a target of gaseous hydrogen (16 bar) at a rate of 10^6 s^{-1}. The detector [3] has a cylindrical symmetry and is placed inside a solenoid providing a magnetic field of 0.44 T. Charged particles are tracked using 2 layers of proportional chambers (PC), 6 layers of drift chambers and 2 layers of streamer tubes. A scintillator-Čerenkov-scintillator sandwich provides input to a kaon fast identification system based on energy loss, time of flight and Čerenkov light measurements. Photons are detected in an electromagnetic calorimeter with 18 layers of lead converters and tubes working in a limited-streamer mode. Each of these layers is equipped with two layers of pickup strips, allowing a three-dimensional reconstruction of electromagnetic showers. Fast and efficient event selection is performed online using a hardwired multilevel trigger system.

3. Data selection

The results reported in the present paper are based on the analysis of data taken during 1992 and 1993. The events selected contain four charged-particle tracks, with zero total charge and one or more electromagnetic showers in the calorimeter, which are well away from any charged track. The latter requirement considerably reduces the background from $p\bar{p}$ annihilations to $K^+K^-\pi^+\pi^-$ and also from $\pi^+\pi^-$ and semileptonic decays of neutral kaons. The $p\bar{p}$-annihilation vertex, reconstructed from the charged kaon and a pion of opposite charge (primary pion), is required to be within 20 mm of the beam axis and well within the target along the beam axis. The neutral-kaon decay vertex is reconstructed from the remaining π^+ and π^- tracks (secondary pions). The distance between the two vertices in the transverse plane is required to be greater than 1.2 cm. The opening angle of the secondary pions has to be larger than 8° in order to remove e^+e^- pairs from γ conversions or π^0 Dalitz decays, and smaller than 172° in order to remove events with particles back-scattered from the detector's outer components.

Events are then selected using constrained fits to satisfy either $p\bar{p}(\text{at rest}) \to K^+\pi^-\overline{K}^0$ ($\overline{K}^0 \to \pi^+\pi^-\pi^0$) or the charge conjugate (c.c.) process, with the following requirements:
- conservation of energy and momentum with the constraints that the missing mass at the primary vertex is the mass of the neutral-kaon, and the total missing mass is the π^0 mass.
- colinearity of the neutral-kaon momentum vector and the vector connecting the primary and decay vertices, both in the transverse plane.

About 250 000 events satisfy this first set of selection criteria. Analysis of the possible background events contained in this sample is performed using both real data and Monte Carlo simulation.

Mainly due to the effectiveness of the constrained fits, the background resulting from $K^+\pi^-\overline{K}^0$ ($\overline{K}^0 \to \pi^+\pi^-$) or the c.c. process is reduced to a negligible amount ($\leq 0.02\%$). The same holds for many other annihilation channels, such as multi-pion final states, whose contribution is at most 0.002%. The possible systematic error caused by this is included in the first and second entries of Table 1.

The contribution from neutral kaons decaying into semileptonic final states can be determined from Monte Carlo simulation and from the relative branching ratios. It amounts to $\approx 4\%$ of the signal events and is found to be strongly suppressed at short decay-

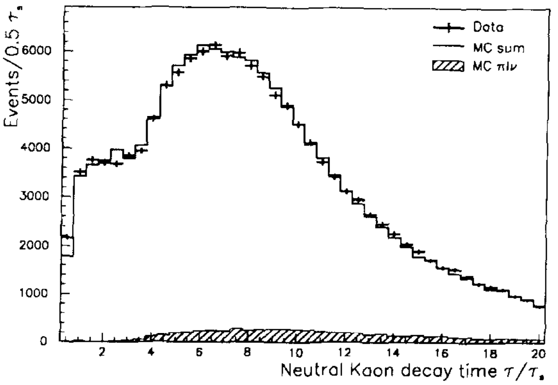

Fig. 1. The decay-time distribution of initial K^0 and $\overline{K}^0$ decaying into $\pi^+\pi^-\pi^0$ for real (+) and simulated (-) data. The simulated distribution (MC sum) results from $\pi^+\pi^-\pi^0$ and semileptonic decays of neutral kaons and is normalized to the real data above 6 τ_S. The contribution to background from semileptonic events is given by the shaded area.

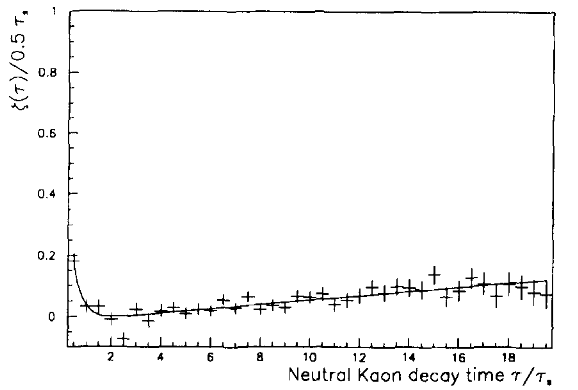

Fig. 2. The total-background fraction $\zeta(\tau)$. The solid line is obtained by a parameterization of the difference between decay-time distributions of real data and simulated neutral kaons decaying to $\pi^+\pi^-\pi^0$ (normalized above 6 τ_S).

times, where the decay particles which hit the PCs have better momentum resolution, resulting in a more efficient rejection by the constrained fits (Fig. 1). Due to its decay-time distribution this contribution has very little effect on the result.

At short decay-times, the remaining background contributions are the following:

(a) $p\bar{p} \to \pi^0 K^+ \pi^- \overline{K}^0$ (or c.c.) events, where a K_S decays into $\pi^+\pi^-$, but where the primary charged-pion is taken as a secondary pion and vice versa, even though the vertex resolution in the transverse plane is of the order of 1.5 mm. This results in 'combinatorial' background mainly at very short decay-times.

(b) $p\bar{p} \to K^+K^-\pi^+\pi^-$ events satisfying the selection criteria due to a badly reconstructed track.

(c) $p\bar{p} \to K^+\pi^-\overline{K}^0$ (or c.c.) events with a K_S decaying to $\pi^0\pi^0$, followed by a π^0 Dalitz decay to $e^+e^-\gamma$.

Background events of type (a) are rejected if they fulfil invariant mass assignment and vertex alignment consistent with the $p\bar{p} \to \pi^0 K^+ \pi^- \overline{K}^0$ ($K_S \to \pi^+\pi^-$) or c.c. hypothesis. These cuts have very little effect on genuine three-pion events.

Events of type (b) are further reduced by discarding events where a four- or three-track vertex-fit probability is high, and where the total missing momentum is low. In addition the time-of-flight information of the charged particles is used to confirm the primary $K\pi$ and secondary $\pi\pi$ hypothesis.

The Dalitz decays in type (c) events are further eliminated using invariant mass and time-of-flight techniques.

After these additional cuts a total of 137 000 events remain. The decay-time distributions are denoted by $N(\tau)$ and $\overline{N}(\tau)$ for K^0 and $\overline{K}^0$, respectively. The decay-time τ is calculated using the neutral-kaon momentum, improved by the constrained fits mentioned above.

Fig. 1 shows the measured decay-time distribution $N(\tau) + \overline{N}(\tau)$, together with the simulated decay-time distribution, which includes K^0 and $\overline{K}^0 \to \pi^+\pi^-\pi^0$ decays and the predicted contribution from semileptonic decays. The simulated data are normalized to the real data for decay-times above 6 τ_S, where semileptonic events are the only source of background. The contribution of the semileptonic events is shown in the shaded area.

Fig. 2 shows the total-background fraction distribution $\zeta(\tau)$, given by

$$\zeta(\tau) = \frac{(\overline{N}(\tau) + N(\tau)) - (\overline{N}_{3\pi}(\tau) + N_{3\pi}(\tau))}{\overline{N}(\tau) + N(\tau)} \tag{3}$$

where $\overline{N}_{3\pi}(\tau) + N_{3\pi}(\tau)$ is the normalized number of Monte Carlo events for K^0 and $\overline{K}^0$ decaying to $\pi^+\pi^-\pi^0$. This total-background fraction is taken into account when fitting the asymmetry and evaluating the systematic errors by using a parameterization of $\zeta(\tau)$, which includes the semileptonic contribution and a small residual background, observed at very short decay-times (Fig. 1).

The determination of $\zeta(\tau)$ is limited by the precision to which the Monte Carlo simulation can reproduce the detector and selection acceptances. This precision was determined to be better than 1% by comparing the decay-time distributions from a background-free sub-sample of real events with the Monte Carlo distributions. This sub-sample consists of signal events with a $\pi^0 \to \gamma\gamma$ reconstructed using the calorimeter information and is too small to be used on its own for a measurement of η_{+-0}.

4. Decay asymmetries and fitting

In order to obtain the time-dependent CP-asymmetry defined in Eq. (2) from the measured rates $N(\tau)$ and $\overline{N}(\tau)$, their relative normalization has to be taken into account as discussed in [4], and it is necessary to consider the K^0 and $\overline{K}^0$ tagging efficiencies. These efficiencies $\epsilon(K^0)$ and $\epsilon(\overline{K}^0)$ are not identical due to the different strong interaction cross-sections of K^+ and K^-, and of π^+ and π^-, in the detector. A normalization factor ξ is defined as $\epsilon(K^+,\pi^-)/\epsilon(K^-,\pi^+)$, which depends on the momenta of the primary charged-kaon and pion, and is independent of the decay mode.

The momentum distributions are related to the radial distance of the secondary vertex of the neutral kaons, resulting in a small dependence of ξ on the decay-time. A look-up table (LUT) has been constructed, using the K^0 and $\overline{K}^0$ decays to $\pi^+\pi^-$ at very short decay-times [4], in order to map ξ with good precision as a function of the momenta of the primary charged-kaon and pion, $\xi(p_K, p_\pi)$. The decay-time dependence of ξ is corrected on an event-by-event basis using this LUT. The overall average value of ξ is then determined as a free parameter in the fit of the asymmetry.

Different decay-track topologies may have different acceptances. One should however notice that the acceptance of events with different topologies cancels in the K^0–$\overline{K}^0$ asymmetry and that track lengths and momentum resolution of the secondary (decay) tracks have no influence on the normalization, which is determined by the primary $K^\pm\pi^\mp$ tracks.

Fig. 3 shows the measured asymmetry

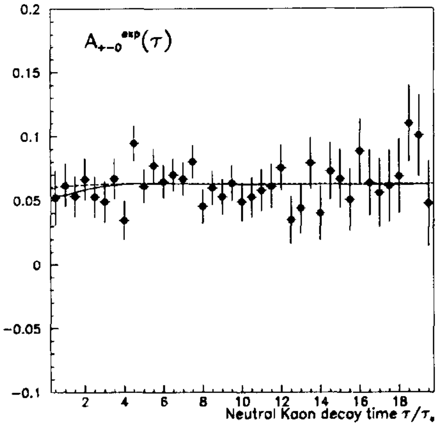

Fig. 3. The measured time-dependent CP-asymmetry between 0.5 and 20 τ_S. The solid line is obtained by fitting Eq. (4) to the data. The broken line shows the asymmetry expected when assuming $\eta_{+-0} = \eta_{+-}$.

$$A^{\exp}_{+-0}(\tau) = \frac{\overline{N}(\tau) - N(\tau)}{\overline{N}(\tau) + N(\tau)}$$
$$\cong \frac{\xi - 1}{\xi + 1} + \frac{4\xi[1-\zeta(\tau)]}{(\xi+1)^2} A_{+-0}(\tau) \qquad (4)$$

where $A_{+-0}(\tau)$ is given by Eq. (2). The parameter η_{+-0}, as well as the normalization factor ξ, were left free in fitting Eq. (4) to the data. The numerical values for $\mathrm{Re}(\epsilon)$, Γ_S and Γ_L are taken from [5]. One should note that in Eq. (4) the first term in ξ is adding to $2\,\mathrm{Re}(\varepsilon)$ in Eq. (2) and that the ξ dependence of the second term is weak. Thus one cannot differentiate in this fit between normalization effects and the value of $\mathrm{Re}(\varepsilon)$. The fit result is also very weakly sensitive to the choice of the value of Δm, which we take from our recent publication [6].

The fit yields

$$\mathrm{Re}(\eta_{+-0}) = (6 \pm 13_{\mathrm{stat.}}) \times 10^{-3}$$

$$\mathrm{Im}(\eta_{+-0}) = (-2 \pm 18_{\mathrm{stat.}}) \times 10^{-3}$$

$$\xi = 1.127 \pm 0.007.$$

The statistical correlation coefficient of the parameters $\mathrm{Re}(\eta_{+-0})$ and $\mathrm{Im}(\eta_{+-0})$ is 66%.

The solid line in Fig. 3 represents the result of the fit. For comparison, the broken line is obtained assuming $\eta_{+-0} = \eta_{+-}$.

Table 1
Summary of systematic errors

Source of systematic error	$\mathrm{Re}(\eta_{+-0})$ $\times 10^{-3}$	$\mathrm{Im}(\eta_{+-0})$ $\times 10^{-3}$
Amount of background	0.4	0.5
Normalization of background	0.5	1.1
CP-allowed K_S decay amplitude [a]	0.1	-
Decay-time dependence of normalization [a]	0.7	2.8
Decay-time resolution	0.3	0.4
Regeneration	-	0.1
Δm and Γ_S	0.1	0.2

[a] Error determination currently limited by statistics.

5. Systematic errors

The following systematic errors were investigated:
- The systematic error introduced by uncertainty in the total-background fraction $\zeta(\tau)$ was found to be 0.4×10^{-3} for $\mathrm{Re}(\eta_{+-0})$ and 0.5×10^{-3} for $\mathrm{Im}(\eta_{+-0})$. A study of rejected events showed that one possible background, namely $K^+K^-\pi^+\pi^-$ events, could appear to have a normalization different from signal events. Taking this as an extreme case and varying the background normalization within the corresponding limits resulted in systematic errors of 0.5×10^{-3} for $\mathrm{Re}(\eta_{+-0})$ and 1.1×10^{-3} for $\mathrm{Im}(\eta_{+-0})$.
- The assumption that the contribution from CP-allowed $K_S \rightarrow \pi^+\pi^-\pi^0$ decays cancels in the asymmetry does not hold if there is any difference in the detector acceptance for the phase-space regions $E_{CM}(\pi^+) \gtrless E_{CM}(\pi^-)$. Studies using both real and simulated data, for selected phase space regions, where no asymmetry caused by CP-allowed K_S decays is expected, showed no difference in acceptance within the present statistical accuracy ($< 2 \times 10^{-3}$). This statistical limit translates into an error of 0.1×10^{-3} for $\mathrm{Re}(\eta_{+-0})$. There is no effect for $\mathrm{Im}(\eta_{+-0})$ since the CP-allowed decay amplitude contributes only through the cosine term of the interference.
- The error introduced by the LUT was determined by changing the values in the LUT within their statistical errors. Although data were corrected for any time dependence of the normalization, a search for a residual effect due to different event topologies has been carried out using a detailed Monte Carlo simulation. The accuracy on the determination of the normalization time dependence, currently limited by the Monte Carlo statistics, leads to a systematic error of 0.7×10^{-3} for $\mathrm{Re}(\eta_{+-0})$ and 2.8×10^{-3} for $\mathrm{Im}(\eta_{+-0})$.
- The systematic error due to finite decay-time resolution and bin size, as well as to the lower limit of the decay-time interval used in fitting the asymmetry, was studied using Monte Carlo events. The total uncertainty is less than 0.3×10^{-3} for $\mathrm{Re}(\eta_{+-0})$ and less than 0.4×10^{-3} for $\mathrm{Im}(\eta_{+-0})$.
- The effect of neutral kaon regeneration is expected to be negligible at short decay-times, where the asymmetry is sensitive to CP violation. Its uncertainty was found to be less than 0.1×10^{-3} for $\mathrm{Im}(\eta_{+-0})$ when changing the regeneration amplitudes by $\pm 13\%$ and the regeneration phases by $\pm 9°$ [4], i.e. within the errors extrapolated from higher energy data.
- The experimental uncertainties of the values of Δm and Γ_S used in the fit account for systematic errors of less than 0.2×10^{-3} for both the real and imaginary parts of η_{+-0}.

Table 1 summarizes the systematic errors which may affect the determination of η_{+-0}.

6. Final results and conclusions

Our final result is

$$\mathrm{Re}(\eta_{+-0}) = (6 \pm 13_{\mathrm{stat.}} \pm 1_{\mathrm{syst.}}) \times 10^{-3}$$
$$\mathrm{Im}(\eta_{+-0}) = (-2 \pm 18_{\mathrm{stat.}} \pm 3_{\mathrm{syst.}}) \times 10^{-3}.$$

Assuming no correlation between the systematic errors, we obtain $|\eta_{+-0}| < 0.037$ at the 90% confidence level.

This is the first determination of η_{+-0} using the method of measuring the rate asymmetry of tagged K^0 and $\overline{K}^0$ decaying to $\pi^+\pi^-\pi^0$. We have obtained the best sensitivity for η_{+-0} compared to all previous measurements [5], and also to the recent measurement [7], as shown in Fig. 4.

Our measurement reduces the contribution of the error of η_{+-0} to a negligible level in a test of CPT invariance based on the Bell–Steinberger relation [8,9].

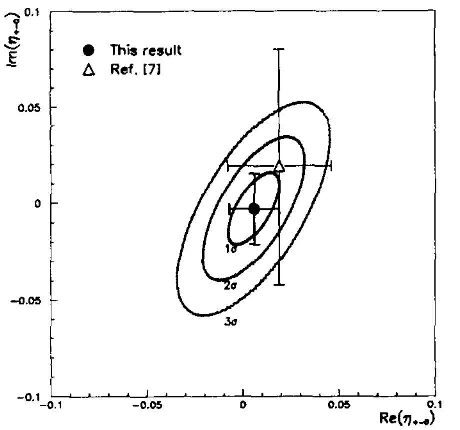

Fig. 4. The contour plot for Re(η_{+-0}) and Im(η_{+-0}) obtained in the present work. For comparison, the recent result of Zou et al [7] is also shown. In the absence of the statistical correlation coefficients of [7], the error bars for both experiments represent total uncertainties, i.e. statistical and systematic uncertainties added in quadrature.

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