First determination of $CP$ violation parameters from $K^0 - \bar{K}^0$ decay asymmetry

CPLEAR Collaboration


D. Zavrtanik m and D. Zimmerman n

a University of Basle, CH-4056 Basle, Switzerland
b CCPM, IN2P3/ CNRS et Université d’Aix-Marseille II, F-13288 Marseille, France
c University of Athens, Athens, Greece
d CERN, CH-1211 Geneva 23, Switzerland
e University of Liverpool, Liverpool L69 3BX, UK
f ETH-IMP Zurich, CH-8093 Zurich, Switzerland
g Paul-Scherrer-Institut (PSI), CH-5232 Villigen, Switzerland
h DAPNIA/SPP, CE Saclay, F-91191 Gif-sur-Yvette, France
i MSI, S-104 05 Stockholm, Sweden
j LIP, P-1000 Lisbon, Portugal
k and University of Coimbra, P-3000 Coimbra, Portugal
l University of Thessaloniki, GR-540 06 Thessaloniki, Greece
m University of Fribourg, CH-1700 Fribourg, Switzerland
n Technical University of Delft, Delft, The Netherlands
o University of Ioannina, GR-45110 Ioannina, Greece
p CSNSM, CNRS/IN2P3, F-91405 Orsay, France

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We report the first determination of CP violation parameters from particle-antiparticle asymmetry in the decay of neutral kaons into two charged pions. Observation of such an asymmetry is direct proof of CP violation. A fit to the asymmetry enabled a determination of the parameter \( \eta_{+-} \) to be made, yielding the result \( |\eta_{+-}| = 2.32 \pm 0.14 \text{ (stat.)} \pm 0.03 \text{ (syst.)} \times 10^{-3} \) and \( \phi_{+-} = 42.3^\circ \pm 4.4^\circ \text{ (stat.)} \pm 0.4^\circ \text{ (syst.)} \), with an additional uncertainty of \( \pm 1.0^\circ \) due to the error on the present published value of \( \Delta m \), the \( K^0_L - K^0_S \) mass difference. The magnitudes of both statistical and systematic errors will be significantly reduced in the future.

Violation of CP invariance was first discovered by detecting the decay \( K^0_L \to \pi^+ \pi^- \) [1]. Subsequently [2], observation of interference between the above decay amplitude and that of \( K^0_s \to \pi^+ \pi^- \) enabled the magnitude and phase of the CP violation parameter \( \eta_{+-} \) to be determined.

We report here results of a different approach, where CP violation is detected by observing the asymmetry between the decays of initially pure \( K^0 \) or \( \bar{K}^0 \) states. The decay rates of neutral kaons, produced as \( K^0 \) or \( \bar{K}^0 \) at time \( t=0 \), to a given final state \( |f\rangle \) are given as a function of the decay amplitudes, \( A_{\pm (L)} \), of the mass eigenstates \( |K^0_{\pm (L)}\rangle \) by

\[
R(t) = R(|K^0_L\rangle \to |f\rangle) = |4p|^2 \left[ |A_S|^2 \exp(-\gamma_S t) + |A_L|^2 \exp(-\gamma_L t) \right] + 2|A_S||A_L| \exp\left[-\frac{1}{2}(\gamma_S+\gamma_L)t\right] \times \cos(\Delta m t + \phi_S - \phi_L),
\]

where

\[
R(t) = R(|\bar{K}^0\rangle \to |f\rangle) = |4q|^2 \left[ |A_S|^2 \exp(-\gamma_S t) + |A_L|^2 \exp(-\gamma_L t) \right] - 2|A_S||A_L| \exp\left[-\frac{1}{2}(\gamma_S+\gamma_L)t\right] \times \cos(\Delta m t + \phi_S - \phi_L),
\]

and \( \rho(q) = \frac{1 + (\pm)\epsilon}{\sqrt{2(1 + |\epsilon|^2)}} \).

Because \( \Delta m \approx \frac{1}{2}\gamma_S \), it is possible to observe an asymmetry between these two decay rates before the interference term has died away. Observation of such an asymmetry is direct proof of CP violation in this decay [3]. This method has the advantage that it allows the observation of CP violation in the decay to many final states \( |f\rangle \), irrespective of whether they are CP eigenstates or not.

This paper is devoted to the measurement of the decay asymmetry for the final state \( |f\rangle = |\pi^+ \pi^-\rangle \). From eqs. (1) and (2), this is given by

\[
A_{+-}(t) = \frac{\bar{R}(t) - R(t)}{\bar{R}(t) + R(t)} = \frac{2 \text{Re}(\epsilon)}{1 + |\eta_{+-}|^2 \exp\left[(\gamma_S - \gamma_L)t\right] \cos(\Delta m t - \phi_{+-})},
\]

where \( \phi_{+-} \) is the phase of \( \eta_{+-} = A_L/A_S \).

In the interference region this asymmetry is directly proportional to \( |\eta_{+-}| \), whereas the ratio \( R(K^0_L \to \pi^+ \pi^-)/R(K^0_S \to \pi^+ \pi^-) \) is proportional to \( |\eta_{+-}^2| \) and hence is much smaller.

The detection of asymmetry in the decay of initially pure \( K^0 \) and \( \bar{K}^0 \) states to two charged pions has already been reported [4], although no determination was made of the CP violation parameters. The results reported here are from the experiment PS195 (C Papa) [5] performed at the Low-Energy Antiproton Ring (LEAR) at CERN. The initial neutral kaon is produced in a state of definite strangeness by antiproton annihilation at rest in gaseous hydrogen via the reactions

\[
p\bar{p} \to K^+ \pi^- K^0, \quad p\bar{p} \to K^- \pi^+ K^0.
\]

The strangeness of the neutral kaon is tagged by observing the sign of the charged kaon. This method of symmetrical and simultaneous production of particles and antiparticles, as well as the symmetric detection of their decay products, has the considerable ad-
vantage of minimizing systematic errors. To high accuracy time-dependent detector efficiencies, geometrical acceptances, and residual backgrounds from other decay channels are identical for both $K^0$ and $\bar{K}^0$ initial states. Corrections arising from strangeness tagging are small, since all observables are normalized independently for $K^0$ and $\bar{K}^0$.

The detector is shown in fig. 1. It has cylindrical geometry and is mounted inside a solenoid of 3.6 m length and 1 m radius, which produces a magnetic field of 0.44 T parallel to the $\bar{p}$ beam. The beam from LEAR has a momentum of 200 MeV/c and the $\bar{p}$'s are stopped in a target at the centre of the detector. The target consists of a laminated Kevlar sphere (7 cm radius, 800 $\mu$m wall thickness) filled with gaseous hydrogen at 16 bar pressure. The beam enters the target through a mylar window of 11 mm diameter and 120 $\mu$m thickness.

Tracking of the annihilation products is performed by two layers of proportional chambers (PC1, PC2), six layers of drift chambers (DC1–DC6), and two layers of streamer tubes. The axial (z) coordinates of the tracks are determined using cathode-strip readout from the drift chambers and from the time differences for signals to travel to the upstream and downstream ends of the streamer tubes. Particle identification is provided by a 32-sector scintillator–threshold Čerenkov–scintillator (SCS) sandwich (the PID) [6]. Finally, there is an 18-layer gas-sampling electromagnetic calorimeter (6.2 radiation lengths) for high spatial resolution detection of photon and electron showers. A more detailed description of the detector can be found in ref. [7].

Systematic corrections due to the different interactions of $K^0$'s and $\bar{K}^0$'s in matter have been minimized by keeping the amount of material in the $K_S$ decay region down to a level such that the difference in the interaction probabilities is less than 1 in $10^4$. Corrections due to regeneration have been calculated to be between 1% and 2% of the fitted values of the $CP$ parameters, with an uncertainty of 30% of the values of the corrections.

The desired “golden” channels [eq. (4)] represent only $\approx 4 \times 10^{-3}$ of the total $\bar{p}p$ annihilation rate.

![Fig. 1. Transverse view of the CPLEAR detector. Also shown is a typical “long-lifetime” event with the track fits superimposed. A hit in a wire chamber is shown by a cross (×), and in a streamer tube by a hatched circle. Hit scintillators are shown hatched, and Čerenkov sectors with a hit above threshold are shown finely hatched.](image-url)
Hence to achieve the physics goals of this experiment in a reasonable length of time, it is necessary to run at an $p$ annihilation rate of about 1 MHz. In order to pick out the desired channels from the large unwanted background, a sophisticated multi-level trigger has been designed based on several sequential decisions provided by fast trigger processors [8] using information from the various elements of the detector. The asymmetry [eq. (3)] is large only for times $t \gtrsim 5\tau_s$. Hence, for these data, a special "long-life-time" trigger was used with the following requirements.

(i) There should be at least two hits in the inner scintillator with at least one charged kaon candidate (i.e. an SCS pattern from the PID).

(ii) At least one kaon candidate should have a momentum component in the $r$-$\phi$ plane (as determined by a simple algorithm applied to the drift chamber hits associated with each track) greater than approximately 350 MeV/c. This eliminated low-momentum pions which would also give an SCS pattern in the PID.

(iii) The event should contain two primary tracks (i.e. those with at least one hit in PC1/2), including a kaon candidate, and two secondary tracks (i.e. those having no hits in PC1/2). The radius of PC2 corresponds to a decay time of between 4 and 5 $\tau_s$ for $K^0$s with the average momentum seen in this experiment.

The data presented here are from two short experimental running periods towards the end of 1990, at which time the readout electronics of the electromagnetic calorimeter was not installed. The events were passed through pattern recognition, track fitting and vertex fitting programs. The requirement was made of two opposite-sign primary tracks and two opposite-sign secondary tracks, with a minimum number of fitted points on each track type. The charged kaon identification was confirmed by comparing its energy loss in the inner scintillator with the value expected for a kaon having this track's fitted momentum. A vertex within the target between the kaon and the other primary track, and a vertex between the two secondary tracks were required. Many of the above cuts have since been implemented on-line by further stages of the trigger processors, thus considerably improving the efficiency of data collection and reducing the amount of data to be written to tape.

The remaining events were then subject to further analysis, with the main aim of separating genuine golden events where the $K^0$ decays $\pi^+\pi^-$ from non-golden events and three-body $K^0_L$ decays. To this end tighter cuts were applied to the track quality, kaon identification, and to the primary and secondary vertices. Also cuts were made to the opening angles of the two tracks at the primary and secondary vertices to remove back scatters and photon conversions. Kinematical and geometrical fits were then used to minimize any remaining background and to improve the resolution on the decay eigentime. A 6-C fit was performed with the following constraints:

(i) The missing mass at the primary vertex should equal the $K^0$ mass.

(ii) The vector sum of the three-momenta of the four particles should equal zero.

(iii) The total energy of the four particles should equal twice the proton mass.

(iv) The $K^0$ momentum component in the $r$-$\phi$ plane should be parallel to the line joining the two vertices.

About $10^5$ events were left in the final data sample after these cuts. The contamination of non-golden events in this sample was consistent with zero.

The intrinsic charge symmetry of the detector is shown in fig. 2, where momentum spectra are plotted for tagged $K^0$s and $K^0$s whose decay times were such that the interference term [eqs. (1) and (2)] was negligible. Also shown is the ratio of these spectra, which is seen to be constant within errors with a mean value of $1.16\pm 0.01$. This global normalization factor, which was also found to be independent of any other kinematical or geometrical variables, is due to the different interactions of $K^-$'s and $K^+$'s, mostly in the PID itself.

The decay distribution for the sum of $K^0$ and $\bar{K}^0$ events is shown in fig. 3 as a function of $t/\tau_s$, where the $K^0_L$ lifetime is taken from ref. [9]. This plot has been corrected for detector acceptance using simulated data. The relative acceptance as a function of $K^0_L$ lifetime is shown as the dashed curve. One can clearly see the region dominated by $K^0_L$ decays for $t \lesssim 10\tau_s$, and that dominated by $K^0_{L}$ decays for $t \gtrsim 12\tau_s$. The solid curve is a fit to the data leaving the $K^0_L$ lifetime and the proportion of $K^0_L$ component as free parameters. The fitted value for the $K^0_L$ lifetime is

$$\tau = (1.009 \pm 0.014) \tau_s.$$
The fit gives the $K^0_L$ component to be $4.8 \pm 0.4$ times larger than that expected from $K_L^0 \rightarrow \pi^+\pi^-$ decays, showing that some three-body decays remain. However, as we show later, this has very little effect on the determination of the $CP$ parameters in this method, since, in the lifetime region where the fit is sensitive to the values of these parameters, the ratio of three-body to $\pi^+\pi^-$ decays varies from a few parts per mil to a few percent.

The asymmetry $A_{+-}(t)$ is shown in fig. 4. No acceptance corrections have been applied in determining this asymmetry as they cancel out in the ratio. The dashed curve is a fit to the data using eq. (3) with $|\eta_{+-}|$ and $\phi_{+-}$ as free parameters. The fit is insensitive to the value of Re$(\epsilon)$, which is taken from ref. [9]. It can be seen that the data agree well with the fit for $t \leq 10\tau_s$, but at larger lifetimes the magnitude of the measured asymmetry is reduced by the residual background contamination. This, though, makes little difference to the results of the fit, which are determined by the data for $t \leq 10\tau_s$. The values of the fitted parameters are $|\eta_{+-}| = (2.29 \pm 0.14) \times 10^{-3}$ and $\phi_{+-} = 44.9^\circ \pm 4.4^\circ$, where the errors are purely statistical and include the uncertainty on the global normalization factor.

Eq. (3) may be modified to include the effects of the residual three-body $K^0_L$ background. Also shown (solid curve) in fig. 4 is a fit to the data using this modified formula, with the background fixed at the value determined from the fit to fig. 3. The improvement in the quality of the fit at long lifetimes is quite clear. By studying the variation of the fitted parameters with the magnitudes of the three-body background, of the ratio of three-body to two-body acceptances, and of the regeneration correction, systematic uncertainties on the fitted parameters have also been determined. Using the fit to eq. (3) modified by the background contribution, the values of the fitted parameters, after correcting for regeneration effects, are
Fig. 4. The asymmetry $A_{\pm-}(t)$ between initial $K^0$ and $\bar{K}^0$ states decaying to $\pi^+\pi^-$. The dashed curve is a fit to the data for $|\eta_{\pm-}|$ and $\phi_{\pm-}$ using the formula [eq. (3)] which assumes no background. The solid curve is a fit using the formula modified by the measured three-body background. The error bars are purely statistical.

$|\eta_{\pm-}| = [2.32 \pm 0.14 \text{ (stat.)} \pm 0.03 \text{ (syst.)}] \times 10^{-3},$

$\phi_{\pm-} = 42.3^\circ \pm 4.4^\circ \text{ (stat.)} \pm 0.4^\circ \text{ (syst.)}. \quad (5)$

These are in good agreement with the present world average values [9,10]. There is an additional uncertainty on the value of $\phi_{\pm-}$ of $\pm 1.0^\circ$ due to the uncertainty on the value of $\Delta m$.

An alternative way of presenting the data is shown in fig. 5. Here is plotted the modified asymmetry

$A'_{\pm-}(t) = [A_{\pm-}(t) - 2 \text{Re}(\epsilon)]$

$\times \exp[-\frac{1}{2}(\gamma_S - \gamma_L)t]$

$= -\frac{2|\eta_{\pm-}| \cos(\Delta m t - \phi_{\pm-})}{1 + |\eta_{\pm-}|^2 \exp[(\gamma_S - \gamma_L)t]}.$ \quad (6)

Also shown (dashed curve) is a fit to the data using eq. (6) with $|\eta_{\pm-}|$ and $\phi_{\pm-}$ as free parameters. As before, the formula, eq. (6), may be modified to include the effect of three-body background. The solid curve is a fit to this modified formula with the background fixed as above. The values of the fitted parameters from these fits are identical to those given above, eq. (5). These plots illustrate the weak dependence of the results on the data at long lifetimes where the three-body background is significant.

In the future, use of the electromagnetic calorimeter should enable the three-body background to be further suppressed. Also, with increased statistics, most of the systematic corrections will become better known, so that both the statistical and systematic errors on $|\eta_{\pm-}|$ and $\phi_{\pm-}$ will be significantly reduced.

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References