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Measurement of the CP-violation parameter η_{00} using tagged $\overline{K}^0$ and K^0

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Abstract

The CP-violation parameter η_{00} is determined through the eigentime-dependent asymmetry in the rates of initially tagged $\overline{\mathrm{K}}^0$ and K^0 decaying to $\pi^0\ \pi^0$. From the analysis of the complete data set we obtain the values $|\eta_{00}| = [2.47 \pm 0.31_{\mathrm{stat.}} \pm 0.24_{\mathrm{syst.}}] \times 10^{-3}$ and $\phi_{00} = 42.0^0 \pm 5.6^0_{\mathrm{stat.}} \pm 1.9^0_{\mathrm{syst.}}$.

CP violation in the mixing of neutral kaons decaying to $\pi^0\pi^0$ has previously been observed using $\mathrm{K_L}$ and $\mathrm{K_S}$ beams [1]. We report here results of a different approach, where CP violation is observed by measuring the asymmetry between the rates of initially pure $\overline{\mathrm{K}}^0$ or K^0 states decaying into $\pi^0\pi^0$. In a previous CPLEAR publication, the first observation of a particle–antiparticle asymmetry in the decay of neutral kaons to $\pi^0\ \pi^0$ [2] was reported with partial statistics, where the details of the experimental method and the analysis were discussed. In this letter the measurements of $|\eta_{00}|$ and ϕ_{00} based on the full statistics are presented.

The neutral kaons are produced in the annihilations $\bar{\mathrm{p}}\mathrm{p} \to \overline{\mathrm{K}}^0\mathrm{K}^+\pi^-$ and $\bar{\mathrm{p}}\mathrm{p} \to \mathrm{K}^0\mathrm{K}^-\pi^+$. Owing to strangeness conservation in the annihilation process the strangeness of the neutral kaon is determined on an event-by-event basis by identifying the simultaneously produced charged kaon. This technique allows the measurement of any difference between the CP conjugate rates $R(\overline{\mathrm{K}}^0 \to \pi^0\pi^0)(\tau)$ and $R(\mathrm{K}^0 \to \pi^0\pi^0)(\tau)$ to be made through the eigentime-dependent rate asymmetry

$$A_{00}(\tau) \equiv \frac{R\left(\overline{\mathrm{K}}^0 \to \pi^0\pi^0\right)(\tau) - R\left(\mathrm{K}^0 \to \pi^0\pi^0\right)(\tau)}{R\left(\overline{\mathrm{K}}^0 \to \pi^0\pi^0\right)(\tau) + R\left(\mathrm{K}^0 \to \pi^0\pi^0\right)(\tau)}, \tag{1}$$

which provides a direct proof of CP violation independently of phenomenological descriptions. The CP violation parameter η_{00} is derived from the time dependence of this asymmetry:

$$A_{00}(\tau) = 2\mathrm{Re}(\epsilon) - \frac{2|\eta_{00}|e^{-\frac{1}{2}(1/\tau_{\mathrm{L}} - 1/\tau_{\mathrm{S}})\tau}\cos(\Delta m\tau - \phi_{00})}{1 + |\eta_{00}|^2 e^{-(1/\tau_{\mathrm{L}} - 1/\tau_{\mathrm{S}})\tau}}, \tag{2}$$

where τ denotes the decay eigentime of the neutral kaon, τ_{S} and τ_{L} are the mean lives of $\mathrm{K_S}$ and $\mathrm{K_L}$ respectively, Δm is the $\mathrm{K_L}$–$\mathrm{K_S}$ mass difference and ϵ describes the CP violation in $\overline{\mathrm{K}}^0$–K^0 oscillations.

A detailed description of the CPLEAR experiment can be found elsewhere [3]. Antiprotons of 200 MeV/c are delivered by LEAR and are stopped inside a high-pressure gaseous-hydrogen target at a rate of about 10^6 per second. The cylindrical detector is placed inside a solenoid of 1 m radius and 3.6 m length, which provides a magnetic field of 0.44 T. The tracking system consists of two proportional chambers, six drift chambers and two layers of streamer tubes. Fast kaon identification is provided by a threshold Cherenkov counter sandwiched between two scintillators, which also provide ionization and time-of-flight measurements. An electromagnetic calorimeter made of 18 layers of lead converters and high-gain tubes is used for photon detection. Fast and efficient online data selection is achieved with a multi-level trigger system based on custom-made hardwired processors.

The decay $\mathrm{K}^0(\overline{\mathrm{K}}^0) \to \pi^0\pi^0 \to 4\gamma$ is selected by requiring exactly two charged tracks that have been identified as a kaon and a pion, and exactly four electromagnetic showers in the calorimeter [4]. The decay time τ of the neutral kaon is determined from a constrained fit to the data using the momenta obtained from the charged tracks, the $\overline{K}^0(K^0)$ production vertex, the photon conversion points and the photon energies in the electromagnetic calorimeter. The decay-time resolution is equally determined by the precision of the neutral-kaon four-momentum as by the precision of the photon conversion-point positions. Three criteria based on the invariant masses of all $\gamma\gamma$-pair combinations, on a detailed study of the shape of the χ^2 function of the decay-time distribution and on the measured shower directions of the four photons are further applied to the data in order to improve the experimental decay-time resolution. The selection criteria have been optimized by providing the best sensitivity to the measured parameters and not to the decay-time resolution or background rejection [6].

Fig. 1 shows the measured decay-time distribution for $\overline{K}^0 + K^0$ overlayed with the simulated decay-

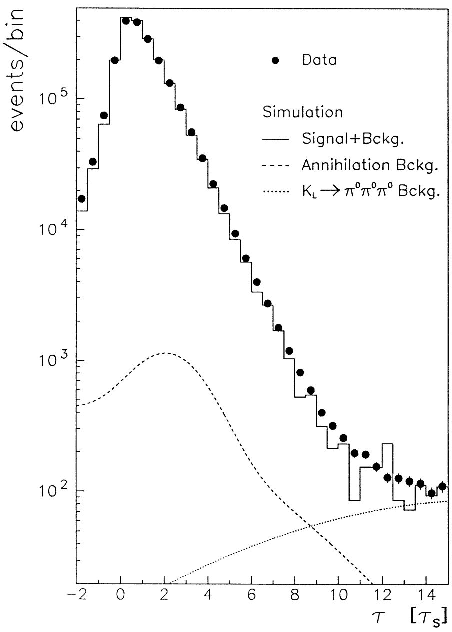

Fig. 1. The measured decay-time distribution for $\overline{K}^0 + K^0 \to \pi^0\pi^0$ (dots), overlayed with the result of the simulation of this decay and the different background channels according to Table 1 (solid line). The background is shown separately for contributions from $\bar{p}$p-annihilations (dashed line) and $K_L \to \pi^0\pi^0\pi^0$ decays (dotted line).

Table 1
Background contributions to the final data sample in the decay-time interval 0–20 τ_S. The quoted errors are statistical

Background channel	Contribution [%]
$K_L \to \pi^0\pi^0\pi^0$	0.137 ± 0.005
$\bar{p}p \to \overline{K}^0(K^0)K^{\pm}\pi^{\mp} + \pi^0$	0.065 ± 0.017
$\bar{p}p \to \pi^+\pi^- + n\cdot\pi^0\ (n \geq 0)$	0.511 ± 0.020

time distribution taking into account the acceptance, the decay-time resolution, and sources of background. The acceptance for the signal events varies only very slowly as a function of the decay time and is constant up to $\approx$ 10 τ_S. The resolution function has been determined according to Ref. [2] and gives a value of $0.77\tau_S$ (FWHM). Sources of background are the kaonic annihilation channels $\bar{p}p \to \overline{K}^0(K^0)K^{\pm}\pi^{\mp} + \pi^0$ and $\bar{p}p \to K^+K^- + n\pi^0$ ($n \geq 0$), the pionic annihilation channel $\bar{p}p \to \pi^+\pi^- + n\pi^0$ ($n \geq 0$) and the neutral-kaon decay $K_L \to \pi^0\pi^0\pi^0$. The contributions from kaons are determined from simulation, while the contributions from the pionic annihilation are determined from the data by studying the energy loss distribution of the charged particles in the inner scintillator of the particle identification detector. Table 1 summarizes the background channels contributing to the final data sample in the decay-time interval 0–20 τ_S. The contribution of $\bar{p}p \to K^+K^- + n\pi^0$ is negligible. In the shorter decay-time region ($< 8\tau_S$) the pionic annihilation background dominates, whereas for longer decay times $K_L \to \pi^0\pi^0\pi^0$ becomes the main background. In the interference region the total background does not exceed 2.5%.

The CP-violation parameters $|\eta_{00}|$ and ϕ_{00} are obtained from the data by comparing the measured time-dependent decay-rate asymmetry with the asymmetry given by Eq. (2). The measured decay-rate asymmetry is shown in Fig. 2. The oscillation of the CP-violation interference term, Eq. (2), can be clearly seen, diluted by the decay-time resolution and by the $K_L \to \pi^0\pi^0\pi^0$ background at large decay times. As discussed in Ref. [2], the relative efficiency ξ for tagging $\overline{K}^0$ and K^0 in the experiment deviates from unity, since the charged particles used to determine the strangeness of the neutral kaon interact differently with the detector material depend-

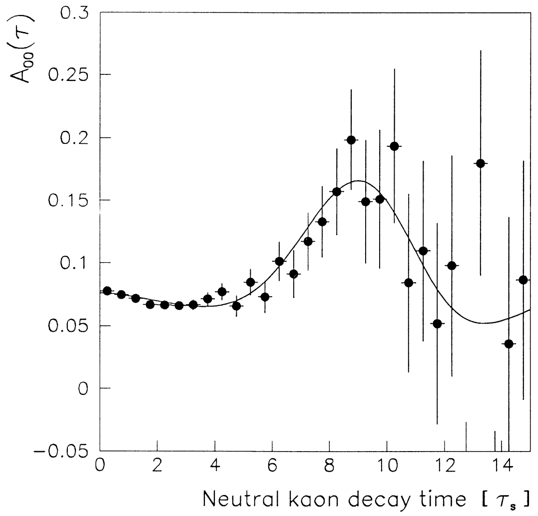

Fig. 2. The measured asymmetry $A_{00}(\tau)$. (The solid line shows the result of the fit.)

ing on their charge and momentum. Since the theoretical asymmetry of Eq. (2) has a constant term of $2\mathrm{Re}(\epsilon)$, the total offset of the measured asymmetry in Fig. 2 is $(\alpha-1)/(\alpha+1)$, where $\alpha=\xi[1+4\mathrm{Re}(\epsilon)]$. Owing to the finite decay volume of the detector, a correlation is introduced between the neutral-kaon kinematics and its acceptance as a function of decay time, thus leading to a dependence of the relative tagging efficiency on the neutral-kaon decay time. To avoid a decay-time dependent ξ value, we divided the full data set into subsamples as a function of the momentum of the neutral kaon in such a way that the influence from a varying ξ and a varying decay-time acceptance within each subsample became negligible. The values of $|\eta_{00}|$ and ϕ_{00} are extracted from a global likelihood fit to the asymmetries corresponding to these different data samples. The decay-time resolution, the remaining background contributions and the regeneration correction are taken into account individually for each neutral-kaon momentum interval. The α-values of the $\overline{\mathrm{K}}^0(\mathrm{K}^0)$ momentum subsamples are free parameters in the fit. The values for the mass difference and the $\mathrm{K_S}$ mean life are fixed at $\Delta m=(530.7\pm1.3)\times10^7\,\hbar\mathrm{s}^{-1}$, and $\tau_\mathrm{S}=(89.22\pm0.10)$ ps as determined in Ref. [5]; the value for the $\mathrm{K_L}$ mean life is fixed at $\tau_\mathrm{L}=(51.7\pm0.4)$ ns as given by Ref. [1]. The fit yields

$$\phi_{00}=42.0^0\pm5.6^0_{\mathrm{stat.}}$$

$$|\eta_{00}|=(2.47\pm0.31_{\mathrm{stat.}})\times10^{-3}.$$

The result of the fit is shown as a solid line in Fig. 2. The correlation coefficient between ϕ_{00} and $|\eta_{00}|$ given by the fit is 0.03. The α-values have a weighted average of $\langle\alpha\rangle=1.178\pm0.003$, where the error is statistical.

The contributions to the systematic uncertainties in the determination of ϕ_{00} and $|\eta_{00}|$ are discussed below and are summarized in Table 2.

- *The resolution in reconstructing the neutral-kaon decay time.* The systematic uncertainties in the values of ϕ_{00} and $|\eta_{00}|$ due to uncertainties in the parametrization of the resolution function have been determined from the decay-time distribution of Fig. 1 by varying the resolution function so that the resulting decay curve agrees within statistics with the observed one, and are given in Table 2. A possible variation in the decay-time resolution as a function of the decay time has also been studied by simulation. No evidence for such a dependence has been found and variations within the statistical limits have a negligible effect on ϕ_{00} and $|\eta_{00}|$.
- *The different efficiencies in tagging* $\overline{\mathrm{K}}^0$ *and* K^0. Systematic uncertainties introduced by a possible deviation of the relative tagging efficiencies ξ from a constant and by a different decay-time

Table 2
Contributions to the systematic errors on ϕ_{00} and $|\eta_{00}|$

Source	$\Delta\phi_{00}$	$\Delta|\eta_{00}|[10^{-3}]$
$\overline{\mathrm{K}}^0(\mathrm{K}^0)$ decay-time resolution	0.6^0	0.16
$\overline{\mathrm{K}}^0(\mathrm{K}^0)$ identification efficiencies	0.29^0	0.01
Photons from secondary interactions	1.4^0	0.13
Backgrounds		
$\bar{p}p\to\pi^+\pi^-+n\cdot\pi^0\ (n\geq0)$	1.1^0	0.07
$\bar{p}p\to\overline{\mathrm{K}}^0(\mathrm{K}^0)\mathrm{K}^\pm\pi^\mp+\pi^0$	0.16^0	0.05
$\mathrm{K_L}\to3\pi^0$	0.26^0	0.06
Regeneration	0.2^0	0.07
Total	1.9^0	*0.24*
Δm [5]	0.34^0	0.003
τ_S [5]	0.036^0	{0.001

acceptance, have been determined within each neutral-kaon momentum subsample.

- *Photons from secondary interactions.* In a small number of events one undetected photon from the decay of $\overline{\mathrm{K}}^0(\mathrm{K}^0) \to \pi^0\pi^0$ is replaced by a photon that originates from the strong interaction or the decay of the accompanying charged particles in the calorimeter. For such events the reconstruction of the neutral-kaon decay time is affected. According to simulations such events contribute to about 0.7% of the data and the relative tagging efficiency for these events is 10% smaller than for correctly reconstructed events. The uncertainty in determining the number of such events has been evaluated from a fit to the measured decay-time distribution of Fig. 1. The systematic errors as given in Table 2 have been obtained by varying the number of such secondary photons by 50% and the relative identification efficiency for $\overline{\mathrm{K}}^0$ and K^0 by 5%.
- *The background channels as listed in Table 1.* Uncertainties in the determination of the background channels have been estimated from various fits to the measured decay-time distribution of Fig. 1. For each background channel the contribution as given in Table 1 has been varied by up to 50% and the relative contribution to the $\overline{\mathrm{K}}^0$ and K^0 signal by 5%. For $\mathrm{K_L} \to \pi^0\pi^0\pi^0$ and for $\bar{\mathrm{p}}\mathrm{p} \to \overline{\mathrm{K}}^0(\mathrm{K}^0)\mathrm{K}^{\pm}\pi^{\mp} + \pi^0$, the relative amount of background in $\overline{\mathrm{K}}^0$ and K^0 is identical to the relative tagging efficiency ξ for the signal events. However, for the pionic background $\bar{\mathrm{p}}\mathrm{p} \to \pi^+\pi^- + n \cdot \pi^0$ $(n \geq 0)$ it is 15% smaller.
- *Uncertainties due to regeneration effects.* Coherent and incoherent regeneration effects introduced by the interaction of $\overline{\mathrm{K}}^0$ and K^0 with the detector material are taken into account when fitting the asymmetry. The systematic errors on ϕ_{00} and $|\eta_{00}|$ are introduced because of uncertainties in the regeneration amplitudes for energies below 1 GeV that have been measured by CPLEAR [7].
- *Uncertainties related to Δm and τ_S.* The dependence of ϕ_{00} and $|\eta_{00}|$ on Δm (in units of $10^7\,\hbar\mathrm{s}^{-1}$) and τ_S (in units of ps) is given by

$$\phi_{00} = \left[42.0 + 0.24(\Delta m - 530.7) + 0.40(\tau_S - 89.22)\right]^\circ$$

$$|\eta_{00}| = \left[2.47 - 0.002(\Delta m - 530.7) + 0.015(\tau_S - 89.22)\right] \times 10^{-3}$$

with correlation coefficients between ϕ_{00} and Δm and $|\eta_{00}|$ and Δm of 0.88 and -0.25, respectively. The errors on ϕ_{00} and $|\eta_{00}|$ as given in Table 2 result from the experimental uncertainties on Δm and τ_S as given in Ref. [5].

Our final result from 2×10^6 reconstructed $\overline{\mathrm{K}}^0(\mathrm{K}^0) \to \pi^0\pi^0$ events is

$$\phi_{00} = 42.0^0 \pm 5.6^0_{\mathrm{stat.}} \pm 1.9^0_{\mathrm{syst.}}$$

$$|\eta_{00}| = \left[2.47 \pm 0.31_{\mathrm{stat.}} \pm 0.24_{\mathrm{syst.}}\right] \times 10^{-3}.$$

This measurement using the rate asymmetry of initially pure $\overline{\mathrm{K}}^0$ and K^0 decaying to $\pi^0\pi^0$ is in agreement with previous measurements of these parameters using $\mathrm{K_S}$ and $\mathrm{K_L}$ beams [1].

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References

[1] Particle Data Group, R.M. Barnett et al., Phys. Rev. D 54 (1996) 1.
[2] R. Adler et al., CPLEAR Collaboration, Z. Phys. C 70 (1996) 211.
[3] R. Adler et al., CPLEAR Collaboration, Nucl. Inst. Meth. A 379 (1996) 76.
[4] R. Adler et al., CPLEAR Collaboration, Nucl. Inst. Meth. A 390 (1997) 293.
[5] R. Adler et al., CPLEAR Collaboration, Phys. Lett. B 369 (1996) 367, and references therein.
[6] O. Behnke, Ph.D. thesis, ETH-IPP Zürich, No. 11969 (1996).
[7] A. Angelopoulos et al., CPLEAR Collaboration, Phys. Lett. B 413 (1997) 422.