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A determination of the CP violation parameter η_{+-} from the decay of strangeness-tagged neutral kaons

CPLEAR Collaboration

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Abstract

We report a measurement of the CP violation parameter η_{+-} from the time-dependent asymmetry between the decay rates of initially tagged K^0 and $\overline{\mathrm{K}}^0$. The results are based on the complete data sample collected by the CPLEAR collaboration. With $\Delta m = (530.1 \pm 1.4) \times 10^7 \hbar s^{-1}$ and $\tau_\mathrm{S} = (89.32 \pm 0.08)$ ps, the values obtained are $|\eta_{+-}| = (2.264 \pm 0.023_\mathrm{stat} \pm 0.026_\mathrm{syst} \pm 0.007_{\tau_\mathrm{S}}) \times 10^{-3}$ and $\phi_{+-} = 43.19^\circ \pm 0.53^\circ_\mathrm{stat} \pm 0.28^\circ_\mathrm{syst} \pm 0.42^\circ_{\Delta m}$.

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1 Introduction

The CPLEAR experiment has successfully developed a method [1], using tagged K^0 and $\overline{\mathrm{K}}^0$, for measuring the interference between the $\mathrm{K_L}$ and $\mathrm{K_S}$ amplitudes in the main neutral-kaon decay channels. The parameters obtained from these measurements test, with high precision, discrete symmetries in the neutral-kaon system. Among these, the phase ϕ_{+-} of η_{+-}, when it is compared with the superweak phase ϕ_{sw}, provides a significant input to a test of CPT invariance [2]. Moreover, limits on parameters describing the possible evolution of pure states into mixed states, sensitive to physics at ultra-high energies [3], are obtained.

In this paper we present precise measurements of $|\eta_{+-}|$ and ϕ_{+-} from the total data sample collected by the CPLEAR collaboration up to the end of 1996. Results based on data taken up to mid 1994, amounting to 30% of the total statistics, have already been published [4]. At that time, there were no measurements of the neutral-kaon forward-scattering amplitudes in the momentum range of the experiment and this lead to the largest source of systematic error on ϕ_{+-}. The present paper uses results from a dedicated run performed during 1996 to measure these amplitudes [5], enabling this source of error to be considerably reduced.

2 Experimental method

The neutral kaons are produced by antiproton annihilation at rest in gaseous hydrogen via the reactions:

$$\mathrm{p\overline{p}} \rightarrow \begin{array}{l} \mathrm{K^-}\pi^+\mathrm{K}^0 \\ \mathrm{K^+}\pi^-\overline{\mathrm{K}}^0 \end{array} \tag{1}$$

each with a branching ratio of $\approx 2\times 10^{-3}$. The neutral-kaon strangeness at production is tagged by the charge of the accompanying $\mathrm{K}^{\pm}$. The rates for an initial K^0 or $\overline{\mathrm{K}}^0$ decaying to $\pi^+\pi^-$, R and $\overline{R}$ respectively, can be expressed as a function of the decay time τ by

$$\begin{array}{c} R(\tau) \\ \overline{R}(\tau) \end{array} \propto (1 \mp 2\mathrm{Re}(\varepsilon_L))(\mathrm{e}^{-\Gamma_\mathrm{S}\tau} + |\eta_{+-}|^2 \mathrm{e}^{-\Gamma_\mathrm{L}\tau} \pm 2|\eta_{+-}|\mathrm{e}^{-\frac{1}{2}(\Gamma_\mathrm{S}+\Gamma_\mathrm{L})\tau}\cos(\Delta m\tau - \phi_{+-})) \tag{2}$$

where Δm is the $\mathrm{K_L}-\mathrm{K_S}$ mass difference, $\Gamma_\mathrm{L}(\Gamma_\mathrm{S})$ the $\mathrm{K_L}(\mathrm{K_S})$ decay width, and ε_L describes the CP-even impurity in the $\mathrm{K_L}$ state. Since $R(\tau)$ and $\overline{R}(\tau)$ are the decay rates of CP conjugate processes, any difference between them is a direct proof of CP violation. The decay rates for initial K^0 and $\overline{\mathrm{K}}^0$ determined from our measurement are displayed separately in Fig. 1, and clearly show the expected CP violation effect ($\tau_\mathrm{S} \equiv \mathrm{K_S}$ mean lifetime).

The $\mathrm{K_L}-\mathrm{K_S}$ interference term in Eq. (2) is isolated by forming the asymmetry between the measured number of K^0 and $\overline{\mathrm{K}}^0$ decaying to $\pi^+\pi^-$, $N(\tau)$ and $\overline{N}(\tau)$ respectively, as a function of decay time:

$$A_{+-}(\tau) = \frac{\overline{N}(\tau) - \alpha N(\tau)}{\overline{N}(\tau) + \alpha N(\tau)} \tag{3}$$

$$= -2\frac{|\eta_{+-}|\mathrm{e}^{\frac{1}{2}(\Gamma_\mathrm{S}-\Gamma_\mathrm{L})\tau}\cos(\Delta m\tau - \phi_{+-})}{1 + |\eta_{+-}|^2\mathrm{e}^{(\Gamma_\mathrm{S}-\Gamma_\mathrm{L})\tau}} \tag{4}$$

The normalization factor, $\alpha = [1+4\mathrm{Re}(\varepsilon_L)]\times\xi$, corrects for the slight difference in the two decay rates due to the parameter ε_L, as well as for the tagging efficiency ξ of K^0 relative to $\overline{\mathrm{K}}^0$. The use of this asymmetry makes the measurement, to first order, independent of absolute acceptances and therefore of Monte Carlo simulation, thus reducing systematic uncertainties.

3 The detector

The CPLEAR detector has been described elsewhere [6]. It had a cylindrical geometry and was mounted inside a solenoid of length 3.6 m and internal radius 1 m, which produced a magnetic field of 0.44 T parallel to the $\overline{\mathrm{p}}$ beam. The beam, extracted from the Low Energy Antiproton Ring (LEAR) at CERN, had a momentum of 200 MeV/c and stopped in the target at the centre of the detector. The target,

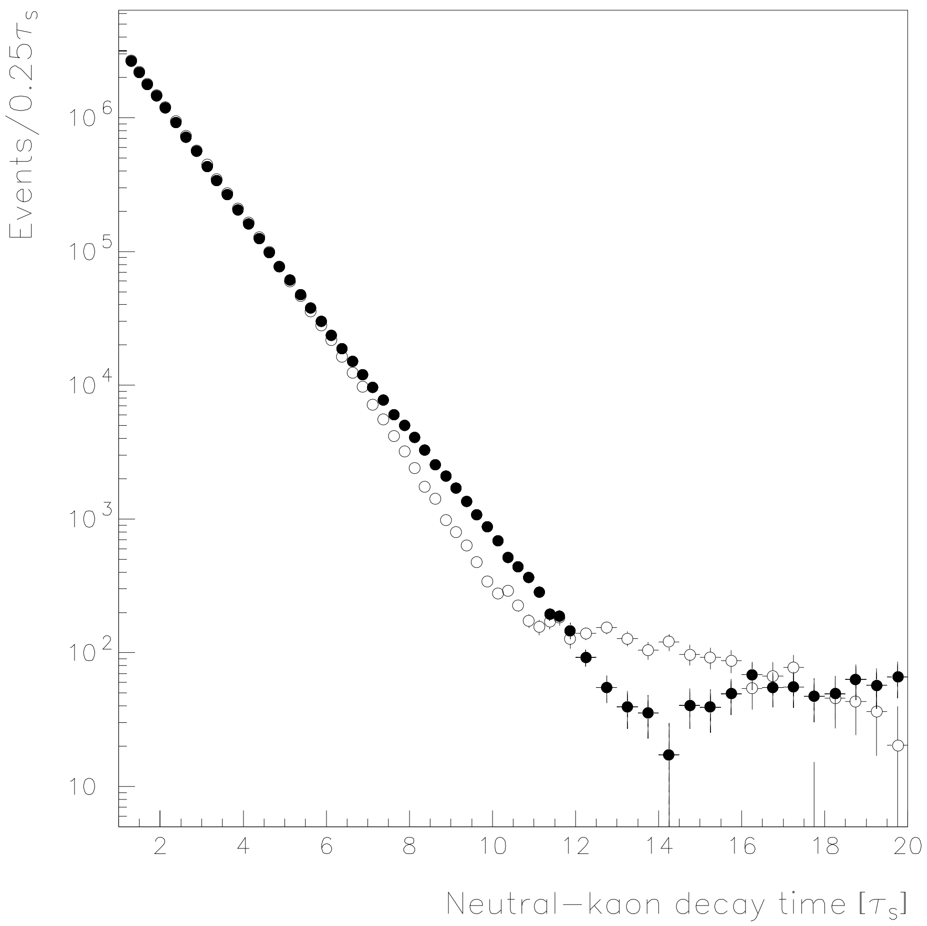

Figure 1: The measured decay rates for K^0 (open circles) and $\overline{K}^0$ (solid circles) after acceptance correction and background subtraction.

consisting of a 7 cm radius sphere filled with gaseous hydrogen at 16 bar pressure, was replaced in mid 1994 by a 1.1 cm radius, 27 bar, cylindrical target surrounded by a 1.5 cm radius, cylindrical proportional chamber (PC0).

Tracking of the annihilation products was performed by two layers of proportional chambers, six layers of drift chambers and two layers of streamer tubes. Kaon, pion and electron identification (Cherenkov light, time of flight and energy loss) was provided by a threshold Cherenkov counter sandwiched between two layers of plastic scintillator. An 18-layer, lead/gas-sampling electromagnetic calorimeter completed the detector.

Because of the small branching ratio of the desired annihilation channels, Eq. (1), and the high beam-intensity ($\approx 10^6$ $\overline{\mathrm{p}}/s$), a multi-level trigger system [6], based on custom-made hardwired processors, was used to provide fast and efficient background rejection. The PC0 information was incorporated into the trigger for all data taken during 1995 and 1996. Not more than two hits in this chamber were required, thus ensuring that the neutral kaon decayed outside PC0. This eliminated a large number of unwanted, very short lifetime K_S decays as well as background multikaon and multipion annihilations, allowing the rate of useful recorded events to be significantly increased.

4 Data analysis

Events corresponding to the desired annihilation channels, followed by the decay of the neutral kaon to $\pi^+\pi^-$, are selected by demanding four charged tracks with zero total charge. In order to be well above the pion threshold in the Cherenkov detector, the charged kaon is required to have a momentum of at least 350 MeV/c. Furthermore, to be consistent with the trigger requirements, a momentum component in the plane transverse to the beam axis of at least 300 MeV/c is demanded. The events are then passed through a geometrical and kinematical constrained fit, with a total of nine constraints. These are:

- overall conservation of energy and momentum (4C),
- missing mass at the annihilation vertex equal to the K^0 mass (1C),
- at each vertex, corresponding to the intersection in the transverse plane of two tracks, same coordinate along the beam axis for both tracks (2C),
- neutral-kaon momentum colinear with the line joining the two vertices in both the transverse and longitudinal planes (2C).

Events are required to have a probability from the 9C fit of at least 5%. At lifetimes beyond $11\ \tau_{\mathrm{S}}$ tighter probability cuts are applied to reduce the residual background, such that the signal-to-background ratio always exceeds unity. The dependence of the residual background on the neutral-kaon decay time is determined by acceptance studies using simulated semileptonic and $\pi^+\pi^-$ events. The absolute level of the background at any decay time is then determined by three independent methods:

- from a fit to the experimental decay rate for the sum of K^0 plus $\overline{\mathrm{K}}^0$ after acceptance correction.
- from the relative acceptance of semileptonic and $\pi^+\pi^-$ data and the known branching ratios for neutral kaons decaying to these final states.
- by modifying Eq. (4) to include a background term and leaving the absolute level as a free parameter in the fit to the asymmetry $A_{+-}(\tau)$.

These three methods yield values in good agreement with each other. The magnitude of the background depends only weakly on the neutral-kaon decay time and, between 15 and 20 τ_{S}, its mean value is about the same as the level of CP violating $\mathrm{K_L} \to \pi^+\pi^-$ decays, with an uncertainty of 6%.

A total of 7×10^7 events having a measured decay time above 1 τ_{S} survive this selection. The neutral-kaon decay time is calculated from its momentum component and the separation of its production and decay vertices in the plane transverse to the beam axis. A simulation study of the detector shows that, after the 9C fit, the neutral-kaon decay time resolution varies from 0.05 τ_{S} to 0.11 τ_{S} as the lifetime increases, leading to very small corrections to the results (see Section 8).

5 Normalization of K^0 and $\overline{\mathrm{K}}^0$ rates

The detection efficiencies of $(\mathrm{K}^+\pi^-)$ and $(\mathrm{K}^-\pi^+)$ pairs, used to tag $\overline{\mathrm{K}}^0$ and K^0 production respectively, are different. This difference arises partly from slight geometrical imperfections in the detector, which cause the detection efficiency to depend on the curvature sign of a track, and partly from the differences in the strong interaction probabilities of opposite-charge pions and kaons with the detector material (mainly in the scintillators and the Cherenkov counter).

In order to eliminate biases caused by geometrical imperfections, the magnetic field polarity was reversed three times per day. Figure 2 shows the tagged $\overline{\mathrm{K}}^0/\mathrm{K}^0$ ratio as a function of the neutral-kaon transverse momentum component for each curvature sign of the charged kaon, i.e. $\overline{\mathrm{K}}^0$ for one field polarity divided by K^0 for the other. It can be seen that the two ratios are identical to within a few parts per mil over the whole range of neutral-kaon transverse momentum. This shows that the geometrical biases are the same for K^0 and $\overline{\mathrm{K}}^0$ and cancel in the ratio. Studies using high statistics simulated data have shown that such biases can be completely eliminated by adding the data from the two field polarities.

As a result of the finite decay volume of the detector, there is a correlation between the neutral-kaon kinematics and its decay time. This, in conjuction with the momentum dependence of the relative tagging efficiency, Fig. 2, due to particles' strong interactions with the detector material, leads to a dependence of the relative tagging efficiency on the neutral-kaon decay time. This dependence is removed by constructing a multi-dimensional table of event weights in the relevant variables of the primary $\mathrm{K}^\pm\pi^\mp$ kinematics [4]. Figure 3 shows, after event weighting, the ratio of the number of $\overline{\mathrm{K}}^0$ to K^0 events, for the sum of the two field polarities, as a function of the neutral-kaon transverse momentum component and of

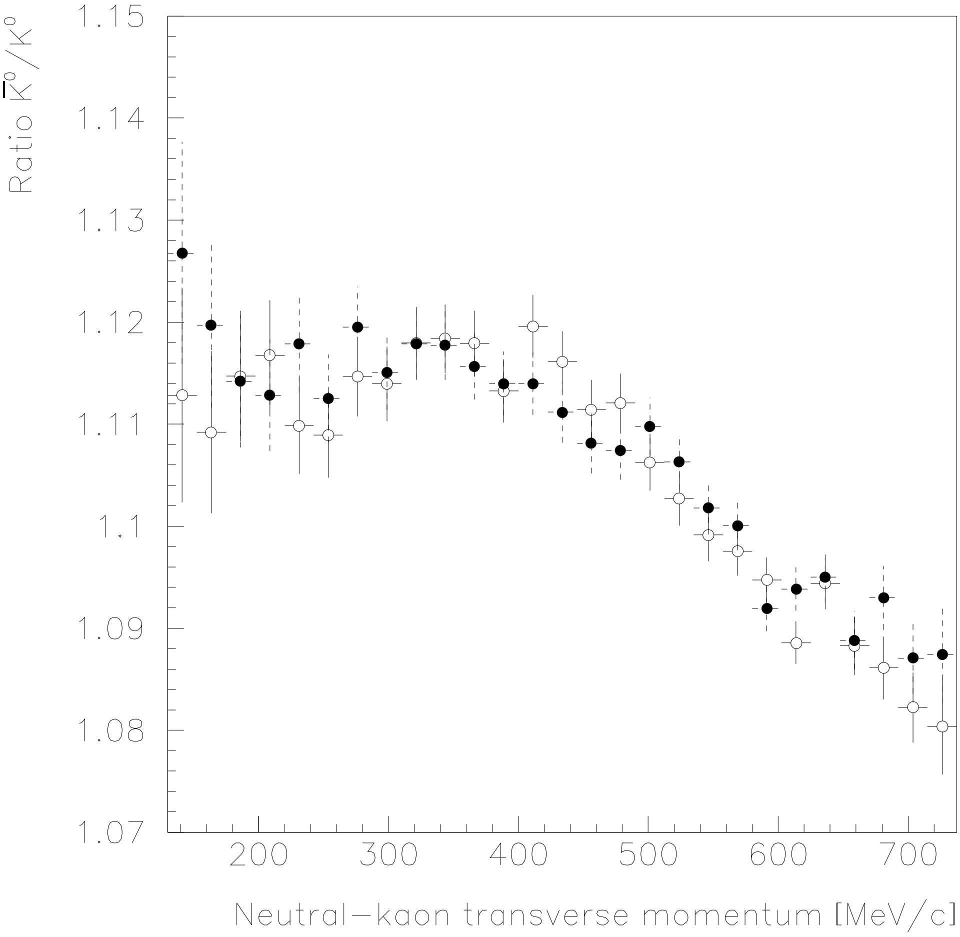

Figure 2: Ratio $\overline{\mathrm{K}}^0/\mathrm{K}^0$ vs neutral-kaon transverse momentum component for events in which the $\mathrm{K}^{\pm}$ has positive (open circles) and negative (solid circles) curvature.

the separation, in the transverse plane, of the production and decay vertices (these are the two variables used in the calculation of the decay time).

The table of event weights is constructed using events at short decay times where high statistics are available and CP-violation effects are small. Following this weighting procedure, the residual normalization factor, α (Eq. (3)), is expected to be equal to unity when CP-violation at short decay times is correctly taken into account. The value of α is left free in the fit of Eq. (3) to the data over the whole measured decay time range; the value returned by the fit is 0.9997 ± 0.0004.

6 Regeneration

Coherent and incoherent regeneration arises from the interference between the inherent $\mathrm{K_S}$ amplitude of the neutral kaon and that regenerated from the $\mathrm{K_L}$ amplitude by scattering in the material of the detector. In our earlier paper [4], we used the forward-scattering amplitudes of K^0 and $\overline{\mathrm{K}}^0$ calculated by Eberhard and Uchiyama [7] because of the lack of experimental data in the momentum range of our experiment (< 800 MeV/c). During the dedicated data-taking in 1996 a carbon regenerator was inserted into the detector, enabling us to measure the forward kaon scattering amplitudes [5] from which the regeneration corrections to the fitted values of $|\eta_{+-}|$ and ϕ_{+-} were deduced. The results were in good agreement with the predictions of Eberhard and Uchiyama and enabled us to reduce the systematic uncertainties on the sizes of these corrections by more than a factor of three. Regeneration corrections

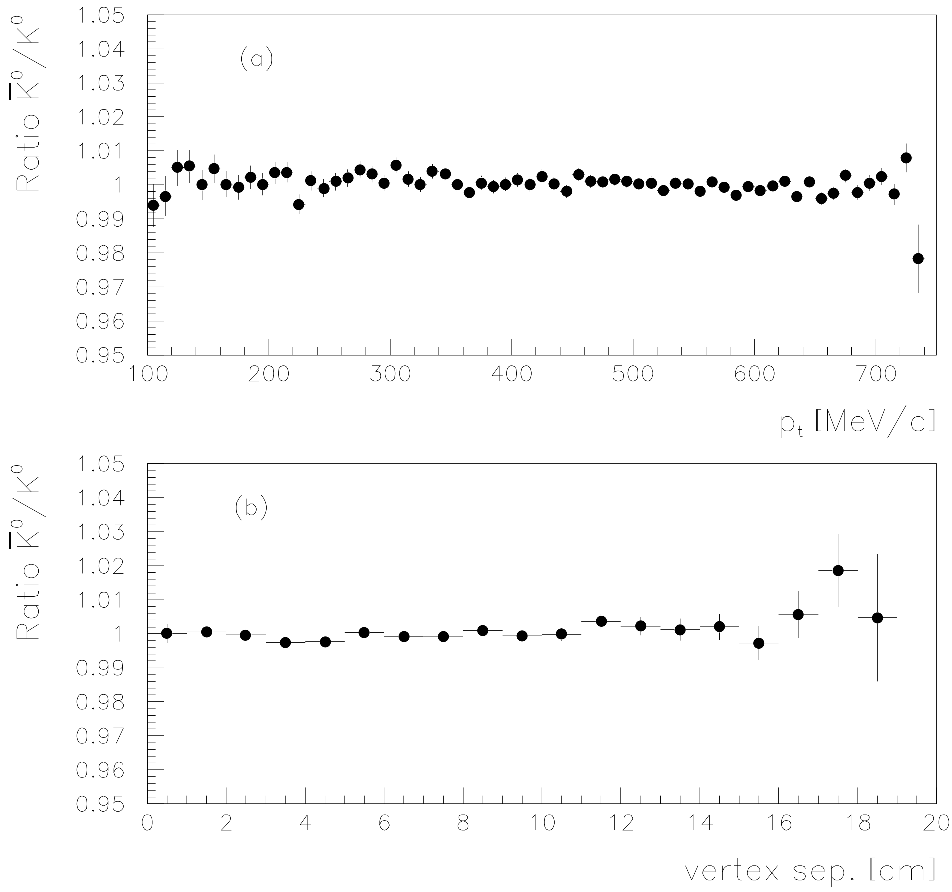

Figure 3: $\overline{\mathrm{K}}^0/\mathrm{K}^0$ ratio vs (a), neutral-kaon transverse momentum, and (b), vertex separation, after event weighting.

are calculated on an event-by-event basis, depending on the magnitude and direction of the neutral kaon momentum and on the positions of its production and decay vertices.

For data taken with the original, 16 bar target, the effect of the coherent regeneration correction is to increase the value of ϕ_{+-} by 3.5° and to reduce the value of $|\eta_{+-}|$ by 0.08×10^{-3}. For data taken with the 27 bar target the corrections are smaller due to the smaller distance of the target wall from the production vertex, ϕ_{+-} being increased by 2.6° and $|\eta_{+-}|$ reduced by 0.05×10^{-3}. The effects of incoherent regeneration are much smaller, reducing ϕ_{+-} by 0.11° and $|\eta_{+-}|$ by 0.003×10^{-3}. The errors on the sizes of these corrections are discussed in Section 8.

7 Results

The residual background level and decay-time dependence were determined, as indicated in Section 4. Equation (4), modified to allow for residual background, was then fitted to the data with ϕ_{+-} , $|\eta_{+-}|$ and α as free parameters (see Fig. 4). The value obtained for ϕ_{+-} depends on the value of Δm, varying as

$$\phi_{+-}^{\Delta m} = \phi_{+-}^{<\Delta m>} + 0.300(\Delta m - <\Delta m>),$$

with ϕ_{+-} in degrees and Δm in units of $10^7 \hbar s^{-1}$, but has negligible dependence on the value of τ_S. The value of $|\eta_{+-}|$ depends on the value of τ_S as

$$|\eta_{+-}|^{\tau_\mathrm{S}} = |\eta_{+-}|^{<\tau_\mathrm{S}>} + 0.091(\tau_\mathrm{S} - <\tau_\mathrm{S}>) \times 10^{-3},$$

where τ_S is in ps, and has negligible dependence on the value of Δm.

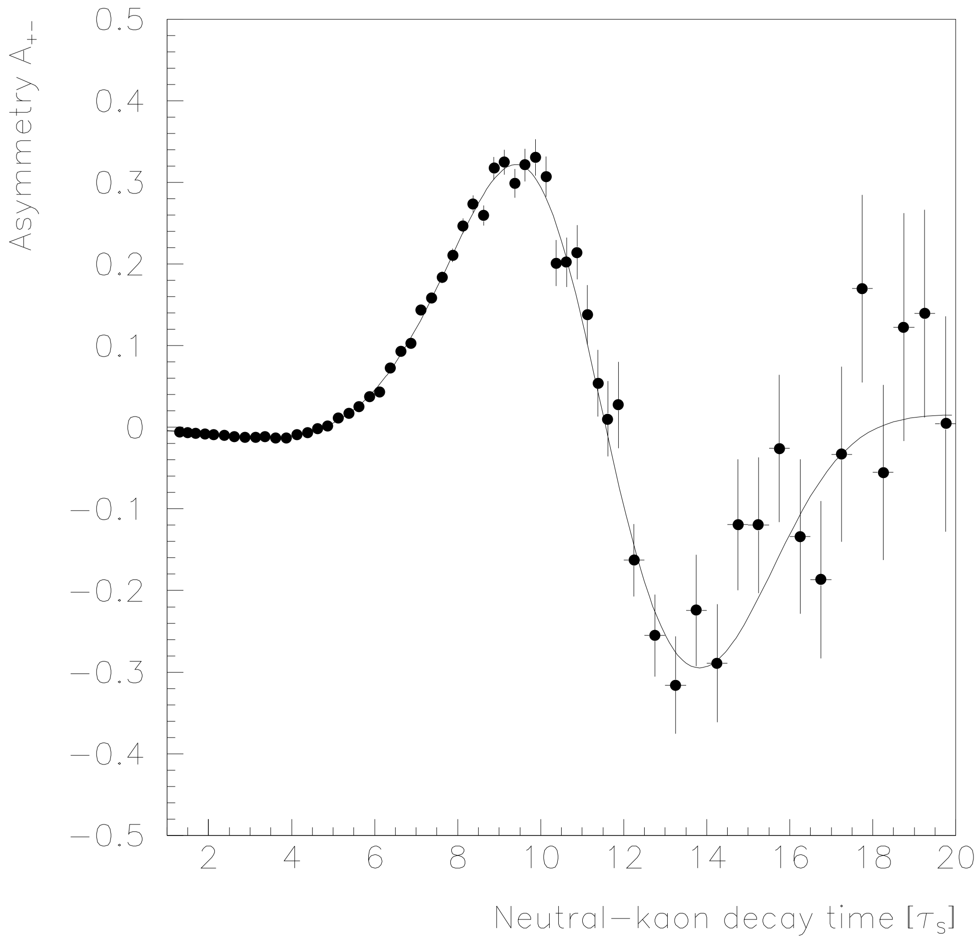

Figure 4: The time-dependent asymmetry A_{+-} vs the neutral-kaon decay time. The solid circles represent the data, including residual background, whereas the solid line is the result of our fit.

Using for $< \Delta m >$ and $< \tau_S >$ the world averages [8], $< \Delta m >= (530.1 \pm 1.4) \times 10^7 \hbar s^{-1}$ and $< \tau_S >= (89.32 \pm 0.08)$ ps, the results of the fit for ϕ_{+-} and $|\eta_{+-}|$ are:

$$|\eta_{+-}| = (2.264 \pm 0.023) \times 10^{-3}$$
$$\phi_{+-} = 43.19^\circ \pm 0.53^\circ,$$

where the errors are purely statistical and $\chi^2/d.o.f. = 1.2$. Table 1 shows the correlation coefficients between ϕ_{+-}, $|\eta_{+-}|$ and α , given by the fit.

	ϕ_{+-}	$\|\eta_{+-}\|$	α
ϕ_{+-}	1	0.17	0.37
$\|\eta_{+-}\|$	-	1	0.65
α		-	1

Table 1: Correlation coefficients for the fitted values in the case of fixed Δm

An alternative way of presenting the data is given by the 'reduced asymmetry' $A_{\rm red}(\tau) = A_{+-}(\tau) \times {\rm e}^{-\frac{1}{2}(\Gamma_S - \Gamma_L)\tau}$, as shown in Fig. 5. The physics content of this plot is identical to that of

Fig. 4, but it emphasizes the low/medium lifetime region where statistics are high and to which the fit is sensitive, at the expense of the high-lifetime region where statistics are low and to which the fit has little or no sensitivity.

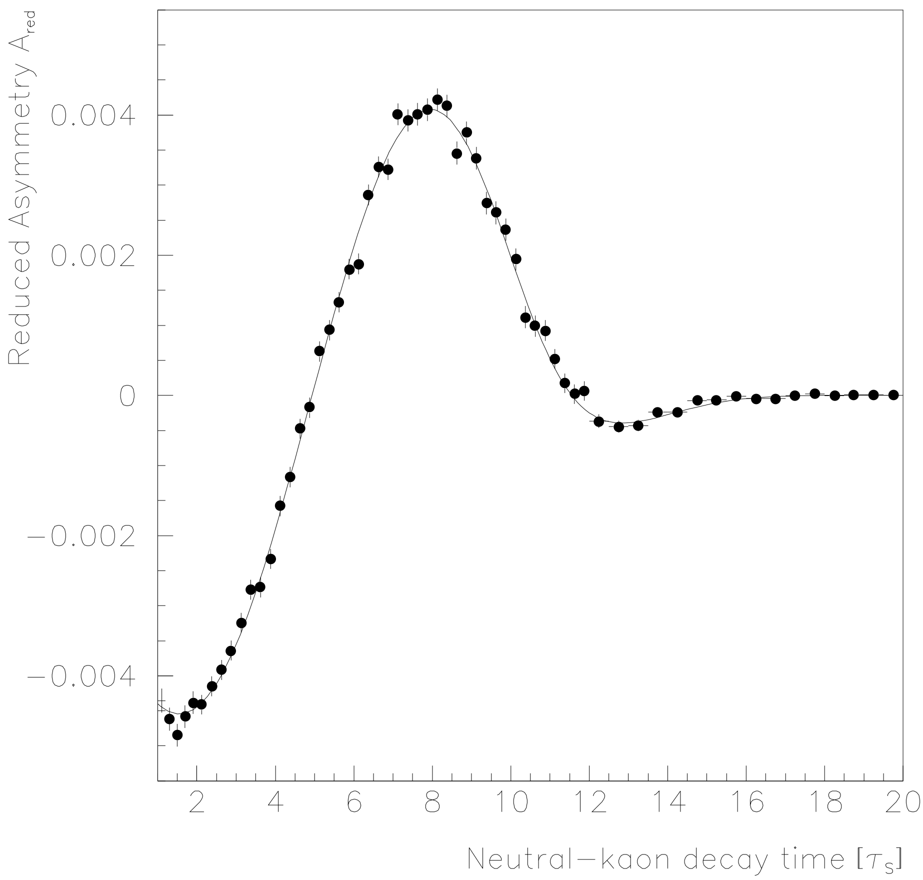

Figure 5: The 'reduced asymmetry' $A_{\rm red}(\tau)$ (see text) versus the neutral-kaon decay time. The solid line is the result of our fit.

If the value of Δm is left free in the fit of Eq. (4) to the data, the result is $\Delta m = (524.0 \pm 4.4_{\rm stat} \pm 3.3_{\rm syst}) \times 10^7 \hbar s^{-1}$, in agreement with the value $(529.5 \pm 2.0_{\rm stat} \pm 0.3_{\rm syst}) \times 10^7 \hbar s^{-1}$ obtained from the total sample of CPLEAR semileptonic data [9]; the correlation coefficient between Δm and ϕ_{+-} is 0.92. The systematic errors of this Δm measurement are discussed in Section 8.

8 Systematic errors

The following sources of systematic error have been investigated:

- level of background and its dependence (shape) as a function of decay time,
- changes in cut values,
- neutral-kaon decay time resolution,
- normalization procedure,
- absolute time measurement,
- regeneration correction.

By varying both the level and decay time dependence of the background within their estimated uncertainties, the corresponding systematic errors on the fitted parameters are determined.

The level and decay time dependence of the background at long lifetimes can be varied by changing the values of the 9C-fit probability cuts at these lifetimes (see Section 4). These changes in background level and shape lead to small variations in the values of the fitted parameters. This is particularly true for Δm which has much greater sensitivity than ϕ_{+-} or $|\eta_{+-}|$ to data beyond $10 - 12\ \tau_{\rm S}$. The values of other cuts have also been varied and found to give very small changes in the values of the fitted parameters. The magnitudes of the variations of the fitted parameter values due to changes in cuts are taken as additional sources of systematic error.

The values of ϕ_{+-}, $|\eta_{+-}|$ and Δm quoted in the previous section have already been corrected for the finite resolution of the neutral-kaon decay time. The sizes of these corrections, determined using high-statistics simulated data, are $-0.18°$, $+0.042 \times 10^{-3}$ and $+0.7 \times 10^7 \hbar s^{-1}$ respectively. The systematic errors due to these corrections are obtained by varying the resolution correction, as a function of decay time, by the uncertainty due to the finite statistics of the simulated data.

The normalization procedure of applying event weights changes the fitted value of ϕ_{+-} by $0.65°$, of $|\eta_{+-}|$ by 0.02×10^{-3} and of Δm by $-1.3 \times 10^7 \hbar s^{-1}$. To determine the systematic errors induced by the normalization procedure, a large number of different event-weight tables were constructed in which the correction factors were varied randomly within their statistical uncertainties. The systematic errors on the fitted parameters were then taken to be the standard deviations of the distributions of the corresponding changes in their values due to the different event weighting.

Extensive studies have shown that after the kinematic constrained fit, the absolute time scale is known with a precision of ± 0.2 parts per mil [6, 10]. Changing the absolute time scale by this factor, produces the shifts in the fitted parameters shown in Table 2.

The systematic uncertainties on the regeneration corrections have been determined by varying both the real and imaginary parts of the neutral kaon forward scattering amplitudes by their statistical uncertainties. Contributions to the systematic errors due to uncertainties in the positions, thicknesses and densities of the various elements of the detector traversed by the neutral kaons were found to be negligible.

The values of all sources of systematic error on ϕ_{+-} and $|\eta_{+-}|$ are shown in Table 2 for Δm fixed. The errors arising from $< \Delta m >$ and $< \tau_{\rm S} >$ are calculated from the quoted corresponding uncertainties [8]. Table 2 also shows the systematic errors on Δm for ϕ_{+-} fixed.

Source	ϕ_{+-} [°]	$\lvert\eta_{+-}\rvert \times 10^3$	Δm $[10^7 \hbar s^{-1}]$
Background level	0.09	0.010	0.9
Background shape	0.04	0.005	0.5
Changes in cuts	0.16	0.008	3.0
Decay time resolution	0.06	0.010	0.2
Normalization procedure	0.07	0.001	0.3
Absolute time scale	0.03	0.001	0.1
Regeneration	0.19	0.019	0.7
Total syst. error	**0.28**	**0.026**	**3.3**
$\sigma(\Delta m)$	0.42	0.001	
$\sigma(\tau_{\rm S})$	0.03	0.007	

Table 2: Systematic errors on the fitted values of ϕ_{+-}, $|\eta_{+-}|$ and Δm.

9 Final results and conclusions

Our final results for η_{+-}, with Δm and $\tau_{\rm S}$ fixed at the world average values from [8], are

$$\begin{aligned} |\eta_{+-}| &= (2.264 \pm 0.023_{\rm stat} \pm 0.026_{\rm syst} \pm 0.007_{\tau_{\rm S}}) \times 10^{-3} \\ \phi_{+-} &= 43.19° \pm 0.53°_{\rm stat} \pm 0.28°_{\rm syst} \pm 0.42°_{\Delta m} \end{aligned}$$

These results have approximately the same errors as the averages of all previous experiments [8], enabling the precision on the world average values to be increased by almost a factor of $\sqrt{2}$. Our value for

ϕ_{+-} is in good agreement with the superweak phase [8]

$$\phi_{\rm sw} \;=\; \arctan[\frac{2\Delta m}{\Delta\Gamma}] \;=\; 43.50^\circ \pm 0.08^\circ,$$

where $\Delta\Gamma = \Gamma_{\rm S} - \Gamma_{\rm L}$, and is hence consistent with CPT invariance.

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