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Measurement of the K_L–K_S mass difference using semileptonic decays of tagged neutral kaons

CPLEAR Collaboration

A. Angelopoulos [a], A. Apostolakis [a], E. Aslanides [k], G. Backenstoss [b], P. Bargassa [m], O. Behnke [q], A. Benelli [b], V. Bertin [k], F. Blanc [g], P. Bloch [d], P. Carlson [o], M. Carroll [i], E. Cawley [i], M.B. Chertok [c], M. Danielsson [o], M. Dejardin [n], J. Derre [n], A. Ealet [k], C. Eleftheriadis [p], L. Faravel [g], W. Fetscher [q], M. Fidecaro [d], A. Filipčič [j], D. Francis [c], J. Fry [i], E. Gabathuler [i], R. Gamet [i], H.-J. Gerber [q], A. Go [d], A. Haselden [i], P.J. Hayman [i], F. Henry-Couannier [k], R.W. Hollander [f], K. Jon-And [o], P.-R. Kettle [m], P. Kokkas [d], R. Kreuger [f], R. Le Gac [k], F. Leimgruber [b], I. Mandić [j], N. Manthos [h], G. Marel [n], M. Mikuž [j], J. Miller [c], F. Montanet [k], A. Muller [n], T. Nakada [m], B. Pagels [q], I. Papadopoulos [p], P. Pavlopoulos [b], G. Polivka [b], R. Rickenbach [b], B.L. Roberts [c], T. Ruf [d], M. Schäfer [q], L.A. Schaller [g], T. Schietinger [b], A. Schopper [d], L. Tauscher [b], C. Thibault [l], F. Touchard [k], C. Touramanis [i], C.W.E. Van Eijk [f], S. Vlachos [b], P. Weber [q], O. Wigger [m], M. Wolter [q], D. Zavrtanik [j], D. Zimmerman [c]

[a] *University of Athens, Greece*
[b] *University of Basle, Switzerland*
[c] *Boston University, USA*
[d] *CERN, Geneva, Switzerland*
[e] *LIP and University of Coimbra, Portugal*
[f] *Delft University of Technology, Netherlands*
[g] *University of Fribourg, Switzerland*
[h] *University of Ioannina, Greece*
[i] *University of Liverpool, UK*
[j] *J. Stefan Inst. and Phys. Dep., University of Ljubljana, Slovenia*
[k] *CPPM, IN2P3-CNRS et Université d'Aix-Marseille II, France*
[l] *CSNSM, IN2P3-CNRS, Orsay, France*
[m] *Paul Scherrer Institut (PSI), Switzerland*
[n] *CEA, DSM / DAPNIA, CE-Saclay, France*
[o] *Royal Institute of Technology, Stockholm, Sweden*
[p] *University of Thessaloniki, Greece*
[q] *ETH-IPP Zürich, Switzerland*

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Abstract

We report on a new measurement of the K_L–K_S mass difference Δm using the CPLEAR full data sample of neutral-kaon decays to $e\pi\nu$. The result is $\Delta m = (0.5295 \pm 0.0020_{stat} \pm 0.0003_{syst}) \times 10^{10}\ \hbar/s$. It includes earlier data reported in R. Adler et al., CPLEAR Collaboration, Phys. Lett. B 363 (1995) 237. A measurement of the $\Delta S = \Delta Q$ violating parameter Re(x) is also obtained.

1. Introduction

We present the final measurement of the mass difference $\Delta m = m(K_L) - m(K_S)$ in the CPLEAR experiment, using neutral kaons of initially defined strangeness decaying to $e\pi\nu$. With respect to the previous measurement [1] we have improved the statistics by about a factor of two and reduced the systematic errors by 60% (mainly owing to a better background rejection).

From the CPLEAR sample of neutral kaons decaying to $e\pi\nu$ we extract four decay rates R as a function of the decay eigentime τ of the kaon, depending on the strangeness of the neutral kaon (K^0 or $\overline{K}^0$) at the production time and on the charge of the decay lepton (e^+ or e^-):

$$\begin{aligned}
R_+(\tau) &\equiv R\left(K^0_{t=0} \to e^+\pi^-\nu_{t=\tau}\right),\\
\overline{R}_-(\tau) &\equiv R\left(\overline{K}^0_{t=0} \to e^-\pi^+\overline{\nu}_{t=\tau}\right),\\
R_-(\tau) &\equiv R\left(K^0_{t=0} \to e^-\pi^+\overline{\nu}_{t=\tau}\right),\\
\overline{R}_+(\tau) &\equiv R\left(\overline{K}^0_{t=0} \to e^+\pi^-\nu_{t=\tau}\right).
\end{aligned} \tag{1}$$

The mass difference Δm is obtained from the asymmetry

$$\begin{aligned}
A_{\Delta m}(\tau) &= \frac{\left[R_+(\tau) + \overline{R}_-(\tau)\right] - \left[\overline{R}_+(\tau) + R_-(\tau)\right]}{\left[R_+(\tau) + \overline{R}_-(\tau)\right] + \left[\overline{R}_+(\tau) + R_-(\tau)\right]}\\
&= \frac{2\cos(\Delta m\tau)e^{-\frac{\Gamma_L+\Gamma_S}{2}\tau}}{(1+2\mathrm{Re}(x))e^{-\Gamma_S\tau} + (1-2\mathrm{Re}(x))e^{-\Gamma_L\tau}},
\end{aligned} \tag{2}$$

where a possible violation of the $\Delta S = \Delta Q$ rule is taken into account by the parameter Re(x) [2], and where Γ_S and Γ_L denote the decay widths of K_S and K_L respectively. This formalism is only valid if there is no CPT violation in the $\Delta S = -\Delta Q$ transitions. This determination of Δm does not depend on the phase of the CP-violation parameter η_{+-}.

2. The detector

The CPLEAR experiment used initially pure K^0 and $\overline{K}^0$ states produced in the $p\overline{p}$ annihilation channels $K^+\pi^-\overline{K}^0$ and $K^-\pi^+K^0$, each with a branching ratio of 0.2%. The initial strangeness of the neutral kaon was tagged by the charge of the accompanying charged kaon. Antiprotons provided by the Low Energy Antiproton Ring (LEAR) at CERN annihilated at rest in a 16 bar hydrogen gas target (a sphere of 7 cm radius) with a rate of $\approx 10^6\ s^{-1}$. In the CPLEAR detector [3], the tracking was performed with two layers of proportional chambers, six layers of drift chambers and two layers of streamer tubes. The charged particle identification ($K^\pm$, $\pi^\pm$, $e^\pm$) was achieved with a sandwich of scintillator–Cherenkov–scintillator counters (S1–CE–S2). The whole apparatus, including a lead/gas sampling electromagnetic calorimeter, was located inside a solenoidal magnet ($B = 0.44$ T). The online event selection was performed by hardwired processors, which provided a complete topological and kinematic event reconstruction.

For the second-half of the data-taking the apparatus was upgraded, by introducing a new proportional chamber around a smaller, cylindrical target (1.1 cm radius, 27 bar hydrogen pressure) in order to get, at the first trigger level, a fast counting of charged tracks arising from annihilation. This upgrade allowed some of the trigger conditions to be relaxed by accepting only neutral kaons decaying after the chamber, thus removing annihilation pionic background.

3. Analysis method

A detailed description of the event selection can be found in [1]. The main tools used to select the events are kinematic constrained fits and particle identification techniques based on measurements of energy loss in scintillator counters, number of photons in Cherenkov counters, and time of flight [4]. The total sample contains 1.2×10^6 semileptonic decays in the decay time interval between 1 and 20 τ_S. Before entering the data in the asymmetry (2), experimental acceptances (normalization) and background need to be considered.

Most of the experimental acceptance factors are common to the four rates and cancel in (2). We corrected for any residual difference between the rate acceptances by introducing three normalization factors, defined as

- $\xi = \epsilon(K^+\pi^-)/\epsilon(K^-\pi^+)$, where the efficiencies involved, $\epsilon(K,\pi)$, are those of the charged particles at the production vertex (primary vertex normalization);
- $\eta = \epsilon(e^-\pi^+)/\epsilon(e^+\pi^-)$, which takes into account the different detection efficiencies, $\epsilon(e\pi)$ for the particles in the two final states (secondary vertex normalization);
- $\omega = \epsilon(K^{\pm}e^{\mp})/\epsilon(K^{\pm}e^{\pm})$, which is the ratio of the efficiencies for detecting an event with equal and opposite curvature sign for the primary charged kaon and the decay lepton (curvature correlation).

Owing to the form of the asymmetry (2), only the last normalization factor, ω, is important in this measurement of Δm. The other two factors, ξ and η, enter in the asymmetry as $(1-\xi)$ and $(1-\eta)$, and only to second order, since both sides of the asymmetry contain K^0 and $\overline{K}^0$, and e^+ and e^-. They were handled in the same way as in the time-reversal analysis [5], leading to a neglible contribution to systematic errors.

Special care was taken to minimize any detection efficiency correlation between tracks, and track isolation criteria were applied to avoid such correlations both at the online selection and in the offline analysis. We have ensured with a high statistics Monte Carlo simulation that the normalization factor ω was equal to unity (with an error of $\pm 4 \times 10^{-4}$) for the data sample taken with the less restrictive trigger in the upgraded apparatus. For earlier data samples, taken with a more restrictive trigger, a small bias ($\omega = 0.9957 \pm 0.0009$) was observed and corrected. This bias was calibrated by simulating the restrictive trigger decision on the unbiased sample. The overall correction is small compared to the statistical error of the measurement ($\delta(\Delta m) = (+0.0006 \pm 0.0001) \times 10^{10}\ \hbar/\mathrm{s}$).

An important point in this analysis is the accuracy with which we can determine the background con-

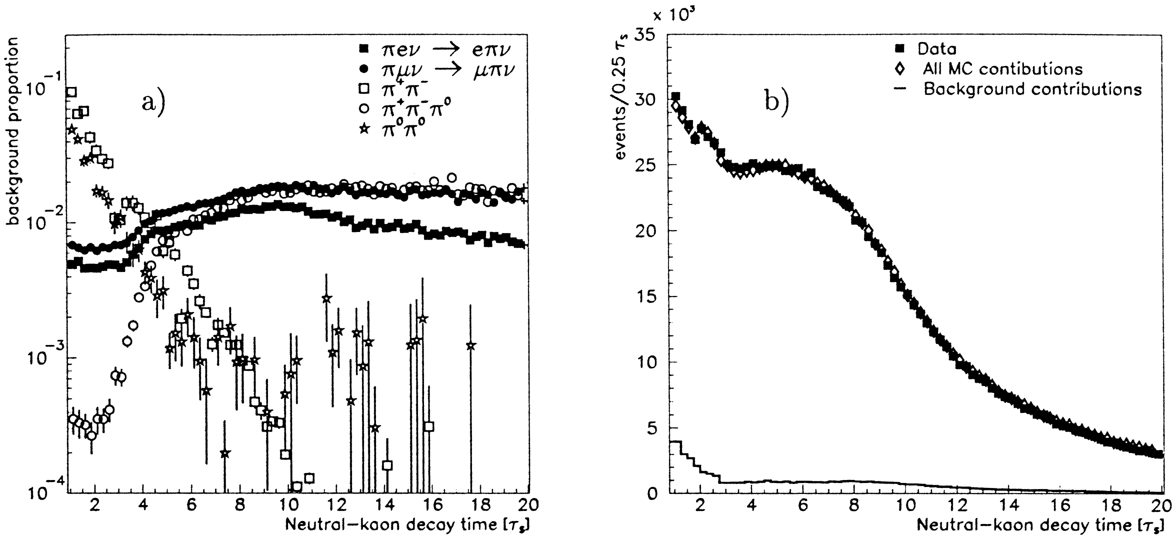

Fig. 1. a) Proportion of different background channels relative to the semileptonic signal. b) Decay-time distribution for real data (squares) and simulated data (open diamonds). The expected background contribution is shown by the solid line.

Table 1
Systematic errors

Source	$\Delta(\Delta m)$ $[10^{10}\ \hbar/\mathrm{s}]$	$\Delta(\mathrm{Re}(x))$ $[10^{-3}]$
background level	± 0.0002	4.4
normalization	± 0.0001	0.1
decay-time resolution	± 0.0001	0.3
absolute time-scale	± 0.0001	0.3
Γ_S	± 0.0001	0.7
Total	± 0.0003	4.5

tamination in the final data sample. With respect to Ref. [1], by refining the selection criteria we have reduced the amount of background by a factor of three at small decay times, with only a small loss in signal, and the corresponding systematic error by a factor of two.

Using a Monte Carlo simulation, we have determined the relative background contributions from various neutral-kaon decays, namely $\pi e \nu$ and $\pi \mu \nu$ (when the electron, or muon, and pion assignement are exchanged), $\pi^+\pi^-$, $\pi^+\pi^-\pi^0$ and $\pi^0\pi^0$ (with one Dalitz decay or one converted photon), as shown in Fig. 1a. The agreement between the observed decay-time distribution and the simulated one is very good (Fig. 1b). By changing the analysis cuts, on both real and simulated data, we estimated that we control the contributions of all background channels to better than $\pm 10\%$.

4. Fit and systematic errors

A fit of Eq. (2) to the data was performed letting Δm and $\mathrm{Re}(x)$ free. The dilution in the asymmetry caused by the background (see Section 3) was taken into account as in Ref. [1]. The starting point of the fit was fixed at 1 τ_S to avoid any possible residual annihilation background.

The systematic errors were evaluated by letting the variable describing the error source to vary during the fit procedure within its uncertainty. The systematic errors related to normalization and background were already mentioned in Section 3. We discuss now the regeneration effects and the precision of the decay-time measurement.

Since in the construction of $A_{\Delta m}$ all terms linear in the regeneration amplitudes cancel, corrections for regeneration effects are not essential for this measurement of Δm.

Extensive studies have shown that after the kinematic constrained fits, the absolute time-scale is known with a precision of $\pm 2 \times 10^{-4}$ [3,6]. The decay-time resolution was computed using simulated

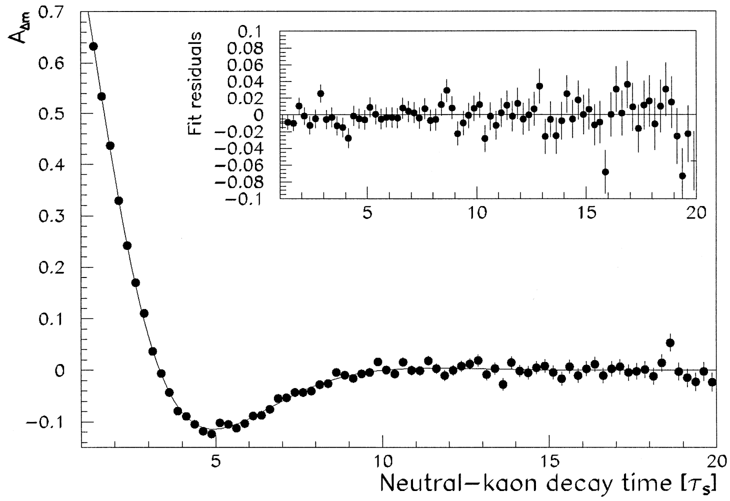

Fig. 2. The asymmetry $A_{\Delta m}$ versus the neutral-kaon decay time (in unit of τ_S). The solid line represents the result of the fit.

data, and found to vary from 0.05 τ_S to 0.20 τ_S as a function of the neutral-kaon decay time. Folding the resolution distributions to the $A_{\Delta m}$ asymmetry results in a shift of $+0.0013 \times 10^{10}$ $\hbar/s$ for the value of Δm and -2.9×10^{-3} for the value of Re(x). The uncertainty of this correction was estimated to be $\pm 10\%$. Finally, the uncertainty on Γ_S [2] was also considered.

The systematic errors of Δm and Re(x) are summarized in Table 1.

5. Results

The measured asymmetry, together with the fitted function, is plotted in Fig. 2. Fit residuals are shown in the inset. Our final results are the following:

$$\Delta m = \left(0.5295 \pm 0.0020_{\rm stat} \pm 0.0003_{\rm syst}\right) \times 10^{10}\,\hbar/{\rm s}\,, \tag{3}$$

$$\mathrm{Re}(x) = \left(-1.8 \pm 4.1_{\rm stat} \pm 4.5_{\rm syst}\right) \times 10^{-3}\,, \tag{4}$$

$$\chi^2/\,\mathrm{d.o.f.} = 0.94\,. \tag{5}$$

The correlation coefficient between Δm and Re(x) is equal to 0.40.

Our Δm measurement is the single most accurate value and has the same error as the present world average. The Re(x) measurement improves the present limit on possible $\Delta S = \Delta Q$ rule violation by a factor of three.

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