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Measurement of K_L-K_S mass difference using semileptonic decays of tagged neutral kaons.

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Abstract

We present a new measurement of the K_L-K_S mass difference (Δm) using semileptonic decays of neutral kaons. The measurement yields $\Delta m = (0.5274 \pm 0.0029_{\mathrm{stat.}} \pm 0.0005_{\mathrm{syst.}}) \times 10^{10}\hbar/\mathrm{s}$.

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1 Introduction

We present a measurement of the mass difference $\Delta m = m(\mathrm{K_L}) - m(\mathrm{K_S})$, using the decay of neutral kaons of initially defined strangeness into the $\pi e \nu$ final state. A precise measurement of Δm, apart from its general interest, is important since the uncertainty of its value is a major source of systematic error in the measurement of ϕ_{+-}, the phase of the CP violation parameter η_{+-}[1, 2, 3]. With semileptonic decays, the measurement does not depend on the value of ϕ_{+-}.

We define four decay rates R, as a function of the decay eigentime τ of the kaon, depending on the strangeness of the neutral kaon ($\mathrm{K^0}$ or $\overline{\mathrm{K}}{}^0$) at the production time, $\tau = 0$, and on the charge of the decay lepton (e^+ or e^-):

$$R^+(\tau) \equiv R[\mathrm{K^0}_{(\tau=0)} \rightarrow \ e^+\pi^-\nu](\tau) \qquad \overline{R}^-(\tau) \equiv R[\overline{\mathrm{K}}{}^0_{(\tau=0)} \rightarrow e^-\pi^+\overline{\nu}](\tau) \tag{1}$$

$$R^-(\tau) \equiv R[\mathrm{K^0}_{(\tau=0)} \rightarrow \ e^-\pi^+\overline{\nu}](\tau) \qquad \overline{R}^+(\tau) \equiv R[\overline{\mathrm{K}}{}^0_{(\tau=0)} \rightarrow e^+\pi^-\nu](\tau) \tag{2}$$

If one assumes the validity of the $\Delta S = \Delta Q$ rule, then the first two processes (R^+ and $\overline{R}^-$) are directly allowed, while the other two (R^- and $\overline{R}^+$) occur only after a $\Delta S = 2$ transition.

The mass difference Δm is obtained from the asymmetry

$$\begin{aligned} A_{\Delta m}(\tau) &= \frac{[R^+(\tau) + \overline{R}^-(\tau)] - [\overline{R}^+(\tau) + R^-(\tau)]}{[R^+(\tau) + \overline{R}^-(\tau)] + [\overline{R}^+(\tau) + R^-(\tau)]} \\ &= \frac{2\cos(\Delta m \tau) e^{-\frac{1}{2}(\tau/\tau_\mathrm{L} + \tau/\tau_\mathrm{S})}}{(1 + 2\mathrm{Re}(x))e^{-\tau/\tau_\mathrm{S}} + (1 - 2\mathrm{Re}(x))e^{-\tau/\tau_\mathrm{L}}}\,, \end{aligned} \tag{3}$$

where a possible violation of the $\Delta S = \Delta Q$ rule is taken into account by the parameter $\mathrm{Re}(x)$[4], and τ_S (τ_L) denotes the mean life of $\mathrm{K_S}$ ($\mathrm{K_L}$).

2 The detector

The CPLEAR experiment uses initially pure $\mathrm{K^0}$ and $\overline{\mathrm{K}}{}^0$ states produced in the $p\overline{p}$ annihilation channels $\mathrm{K^+}\pi^-\overline{\mathrm{K}}{}^0$ and $\mathrm{K^-}\pi^+\mathrm{K^0}$, each with a branching ratio of 0.2%. The initial strangeness of the neutral kaon is tagged by the charge of the accompanying kaon ($\mathrm{K^+}$ for $\overline{\mathrm{K}}{}^0$, $\mathrm{K^-}$ for $\mathrm{K^0}$). Antiprotons provided by the Low Energy Antiproton Ring (LEAR) at CERN annihilate at rest in a 16 bar hydrogen target with a rate of $\approx 10^6 \mathrm{s}^{-1}$. In the CPLEAR detector[5], the tracking is performed with two layers of proportional chambers, six layers of drift chambers and two layers of streamer tubes. The charged particle identification ($\mathrm{K^\pm}$, $\pi^\pm$, $e^\pm$) is achieved with a sandwich of scintillator-Čerenkov-scintillator counters (S1-CE-S2). The whole apparatus, including

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an electromagnetic calorimeter, is located inside a solenoidal magnet (B = 0.44 T). The online event selection is performed by hardwired processors, which provide a complete topological and kinematical reconstruction of the event.

3 Event selection

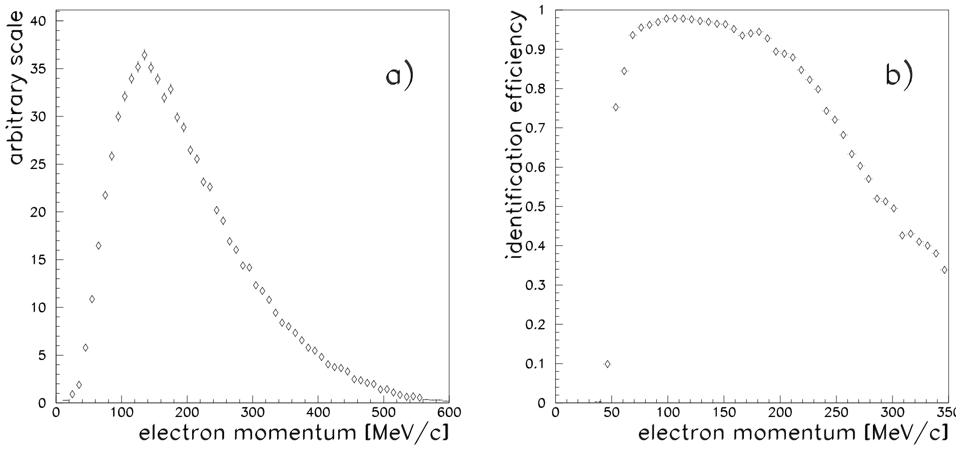

Figure 1: a) Expected electron momentum spectrum in semileptonic decays of neutral kaons. b) Electron identification efficiency versus momentum when 2% of pions fake electrons.

A first selection requires four tracks with zero total charge, good track quality and at least one charged kaon candidate. The annihilation vertex (primary vertex) must lie within the beam stopping distribution and a separate vertex for the decay of the neutral kaon (secondary vertex) is required. A cut on the minimum distance between the two vertices (1 cm in the transverse plane) is applied to remove ambiguities on the track assignment to either vertex, and to reduce the background from other $\mathrm{p\overline{p}}$ annihilation channels to less than 1% for decay times greater than 1 τ_S. A kinematical fit requiring the $\mathrm{K^0}$ missing mass at the primary vertex is performed to validate the hypothesis of the $(\mathrm{K}^{\pm}\pi^{\mp}\mathrm{K}^0)$ channel.

The semileptonic decay channel is selected by identifying one of the secondary tracks as an electron or a positron. Electron-pion separation is based on the energy loss in S1 and S2, the number of photo-electrons per unit path length in CE and the time of flight of the particle from the decay vertex to S1[6]. The selection has been optimized using electron data from converted photons and pions from decays of neutral kaons into $\pi^+\pi^-$. The expected electron momentum spectrum obtained from Monte Carlo is shown in Fig. 1 a). The electron identification efficiency versus momentum is shown in Fig. 1 b). This efficiency is obtained requiring that less than 2% of pions are misidentified as electrons, independently of the momentum. Under these conditions, muons have an average probability of $\approx 15\%$ to be misidentified as electrons. A constrained fit requiring energy-momentum conservation under the assumption of a missing neutrino and the alignment of the $\mathrm{K^0}$ momentum vector with the line joining the two vertices is performed. This fit also improves the resolution of the decay time and fixes the absolute time scale of the neutral kaon with a precision better than 2×10^{-4}. Simulation studies show that the decay time resolution varies from 5 ps to 15 ps as a function of the neutral kaon decay radius. Finally, events which fit to the $(\mathrm{K}\pi\mathrm{K}^0,\ \mathrm{K}^0\rightarrow\pi^+\pi^-)$ hypothesis with high probability are removed in order to reduce the $\pi^+\pi^-$background which is dominant at short decay times. The final sample contains $\approx 700,000$ $(\mathrm{K}^0,\ \overline{\mathrm{K}}^0\rightarrow\pi e\nu)$ events collected up to mid 1994.

4 Rate normalizations

Due to the different strong interaction cross-sections of K^+ and K^-, as well as of π^+ and π^-, the detection efficiencies of a $(\mathrm{K}^+\pi^-)$ pair and a $(\mathrm{K}^-\pi^+)$ pair are not identical. The difference of the overall ($K^+\pi^-$) and ($K^-\pi^+$) efficiencies is of the order of 15%. To restore the initial K^0-$\overline{K}^0$ production symmetry, we have to correct for this difference in the tagging efficiencies. Let ξ denote the ratio of the two efficiencies, $\xi = \epsilon(K^+\pi^-)/\epsilon(K^-\pi^+)$, which depends on the momenta of the primary pion and kaon [$\xi(\vec{p}_K, \vec{p}_\pi)$]. This ratio is independent of the decay mode and is determined from the decay rates of neutral kaons into $\pi^+\pi^-$. The weight ξ is then applied event by event to the semileptonic data. The error on Δm due to the uncertainty of this procedure is smaller than $0.00002 \times 10^{10}\hbar/s$.

We have also studied the difference in the detection efficiencies of the two possible final states ($\pi^+e^-\overline{\nu}$) and ($\pi^-e^+\nu$). Using data from photon conversions, we have not observed any difference in the detection of $e^+$and e^-. On the other hand, the difference between the $\pi^+$and π^-cross-sections with matter leads to the detection of a small excess of π^+. We define the parameter η as the ratio of the two detection efficiencies $\epsilon(\pi^+)$ and $\epsilon(\pi^-)$. This ratio is measured as a function of the transverse and longitudinal momentum of the pion by selecting kinematically, in minimum bias events, the annihilation pionic channel and applying subsequently all the online and offline pion selection criteria. We find that η never deviates from unity by more than 2.5%, inducing, at the present stage of the analysis, an uncertainty on Δm of $0.0001 \times 10^{10}\hbar/s$.

The effect of these corrections is particularly small due to the manner of construction of the asymmetry $A_{\Delta m}$ (Eq. 3) which compares two sets of data containing both $K^0$and $\overline{K}^0$and also $e^+$and e^-.

5 Results

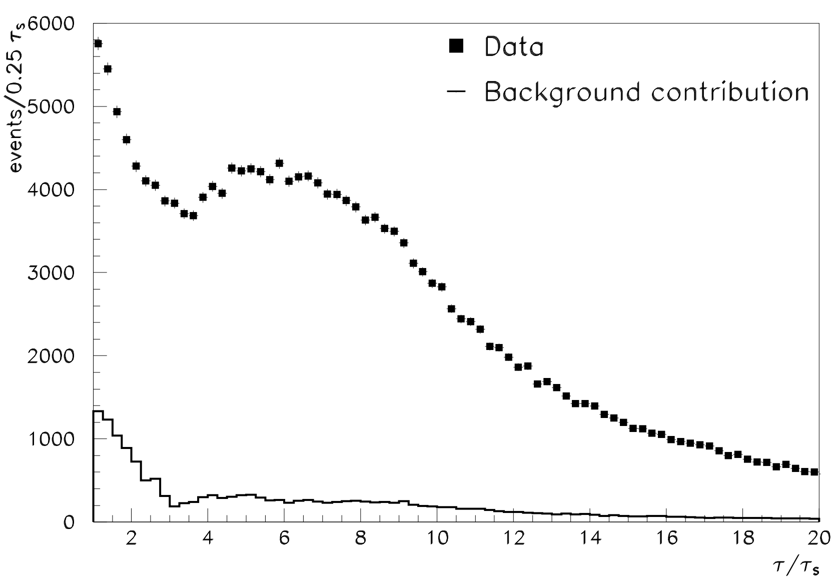

Figure 2: Decay time distribution for real data (squares) and expected background contribution obtained from simulation (solid line).

Figure 2 shows the decay time distribution of the selected events weighted by ξ and η, above 1 τ_S. The signal consists of correctly reconstructed $\pi e\nu$ events and of $\pi\mu\nu$ events seen as $\pi e\nu$ ($\approx 10\%$ of the signal). The background is determined from a Monte Carlo simulation. The main background source consists of residual neutral kaon decays to $\pi^+\pi^-$and is concentrated at short decay times. At large decay times there are contributions from $\pi^+\pi^-\pi^0$ decays and from $\pi l\nu$ decays where the pion and the lepton assignments are exchanged. In the simulation, each channel is scaled to the same number of generated $p\overline{p}$ annihilations. The sum of the background contributions normalized by the weight ξ as the signal (since both the signal and the background result from neutral kaon decays) is displayed in Fig. 2 by the solid line. The background causes a dilution in the asymmetry $A_{\Delta m}$ of Eq. 3, which is accounted for by the factor $f_b(\tau)$:

$$f_b(\tau) = \frac{1 + \frac{B^+(\tau)+\overline{B}^-(\tau)-B^-(\tau)-\overline{B}^+(\tau)}{R^+(\tau)+\overline{R}^-(\tau)-R^-(\tau)-\overline{R}^+(\tau)}}{1 + \frac{B^+(\tau)+\overline{B}^-(\tau)+B^-(\tau)+\overline{B}^+(\tau)}{R^+(\tau)+\overline{R}^-(\tau)+R^-(\tau)+\overline{R}^+(\tau)}} \;, \tag{4}$$

computed by simulation of the background rates $\overset{(-)}{B}{}^{\pm}(\tau)$, and the associated signal rates $\overset{(-)}{R}{}^{\pm}(\tau)$ (Eqs. 1 and 2).

The diluted asymmetry $A_{\Delta m}(\tau) \times f_b(\tau)$, folded with the decay time resolution, is fitted to the real data asymmetry $A_{obs}(\tau)$ leaving Δm and $\mathrm{Re}(x)$ as free parameters:

$$A_{\Delta m}(\tau) \times f_b(\tau) = A_{obs}(\tau) \;. \tag{5}$$

In order to reduce the systematic error related to the background knowledge, and to minimize the correlation between Δm and $\mathrm{Re}(x)$, the fit is performed above $2\,\tau_\mathrm{S}$. The value of $\mathrm{Re}(x)$ resulting from the fit is compatible with zero and we obtain $\Delta m = (0.5274 \pm 0.0029_{\mathrm{stat.}}) \times 10^{10}\hbar/\mathrm{s}$. The correlation coefficient between Δm and $\mathrm{Re}(x)$ is 0.068, and the value and the error of Δm do not change by fixing the value of $\mathrm{Re}(x)$ to zero. The asymmetry $A_{\Delta m}$ is plotted in Fig. 3, using the value of Δm found by the fit, together with the data points corrected for $f_b(\tau)$.

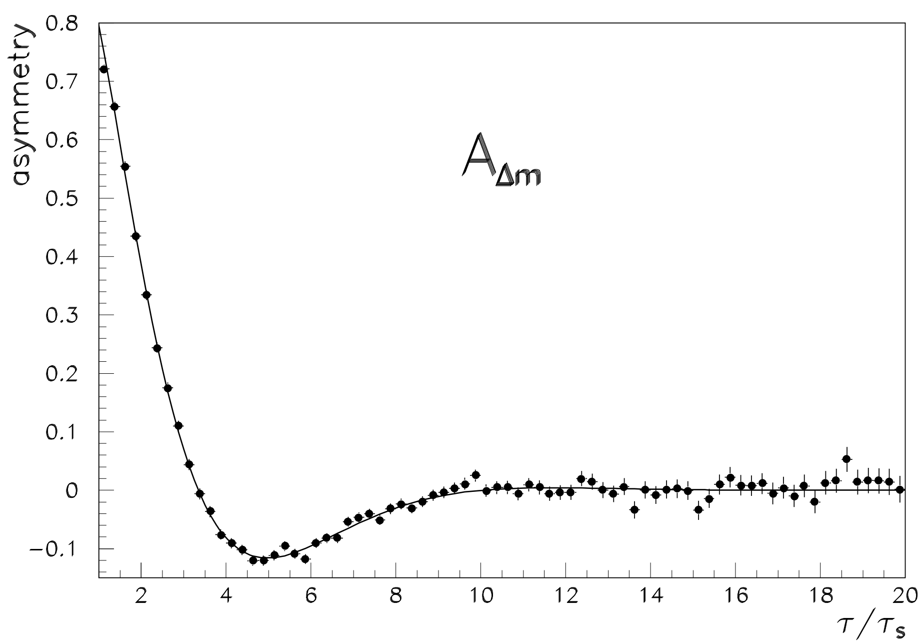

Figure 3: The asymmetry $A_{\Delta m}$ versus the decay time (in unit of τ_S). The solid line represents the result of the fit.

The systematic errors of the measurement are listed in Table 1. The main source of systematic uncertainty arises from the Monte Carlo estimation of the background, in particular at short decay times, where the $\pi^+\pi^-$final state has to be rejected by a large factor ($> 10^3$). The simulation shows that, for all the background channels, the misidentification of a pion as an electron results from a large error in the track momentum evaluation. To check our simulation, we have relaxed the cuts on the $\pi^+\pi^-$channel so that the background becomes comparable to the signal. The simulation still agrees with the data within 10%. We can thus assume a 10% accuracy on the estimation of the various types of background which are used to compute the background dilution factor $f_b(\tau)$.

Table 1: Systematic errors

Source of systematic error	Known precision	$\Delta(\Delta m)$ $[10^{10}\hbar/\mathrm{s}]$
background level	$\pm 10\%$	± 0.0004
background asymmetry	$\pm 1.0\%$	± 0.0001
decay time resolution	$\pm 10\%$	± 0.0001
η correction	$\pm 2.5\%$	± 0.0001
τ_{S} precision[4]	$\pm 0.0012 \times 10^{-10}\mathrm{s}$	± 0.0001
total		± 0.0005

A possible charge asymmetry in the remaining background has been studied with the pion data used to calibrate the e/π separation[6]. This sample shows a difference of $(3.0 \pm 1.0)\%$ between the number of π^+which are misidentified as positrons and the number of π^-which are misidentified as electrons. This asymmetry is taken into account in the fit and the corresponding uncertainty on Δm is $0.0001 \times 10^{10}\hbar/\mathrm{s}$.

Folding the decay time resolution in the $A_{\Delta m}$ asymmetry resulted in a shift of $+0.0009 \times 10^{10}\hbar/\mathrm{s}$ to the value of Δm. The uncertainty on this correction due to the Monte Carlo statistics is $\pm 0.0001 \times 10^{10}\hbar/\mathrm{s}$. In conclusion, our final result is

$$\Delta m = (0.5274 \pm 0.0029_{\mathrm{stat.}} \pm 0.0005_{\mathrm{syst.}}) \times 10^{10}\hbar/\mathrm{s}, \tag{6}$$

which does not depend on the value of ϕ_{+-}[1, 2] and is the most precise value obtained using semileptonic final states[4, 7]. Adding this new value and the most recent one[2] to the previous values used by the PDG[4], we obtain

$$\Delta m = (0.5310 \pm 0.0019) \times 10^{10}\hbar/\mathrm{s}, \tag{7}$$

where the error is scaled by a factor 1.2 following the PDG procedure.

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