New Measurements of the Neutral Kaon Parameters Δm, τ_S, $\Phi_{00}-\Phi_{+-}$, and Φ_{+-}

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The full E731 data set is used to provide precise determinations of several parameters of the neutral kaon. We find the K_S lifetime $\tau_S=(0.8929\pm0.0016)\times10^{-10}$ s, the K_L-K_S mass difference $\Delta m=(0.5286\pm0.0028)\times10^{10}\hbar\ \mathrm{s}^{-1}$ the phase of η_{+-}, $\Phi_{+-}=42.2°\pm1.4°$, and the phase difference between Φ_{00} and Φ_{+-}, $\Delta\Phi=-1.6°\pm1.2°$. Comparisons with previous experiments and with *CPT* symmetry are given.

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This paper presents new determinations of the K_S lifetime, the mass difference between the K_S and K_L, the difference in the phases of η_{00} and η_{+-}, and the phase of η_{+-} itself. The following paper [1] in this issue presents the result for ε'/ε from the same data set.

CPT symmetry is a cornerstone of local quantum field theory and hence is worth probing, particularly given the nonlocal character of candidate (string) theories. In the neutral kaon system, *CPT* symmetry coupled with unitarity [2] leads to the curious fact that the K_S and K_L lifetimes and the K_S-K_L mass difference Δm are related to the phases of the *CP*-violating $\pi\pi$ decay amplitudes η_{+-} and η_{00} via

$$\Phi_{+-}\approx\Phi_{00}\approx\tan^{-1}[2\Delta m/(\Gamma_S-\Gamma_L)]\,, \qquad (1)$$

where $\Gamma_{S(L)}$ is the $K_{S(L)}$ decay rate, $\Phi_{+-}\equiv\arg(\eta_{+-})$, and $\Phi_{00}\equiv\arg(\eta_{00})$. The right-hand expression gives what is known as the superweak phase (Φ_{SW}). Discrepancies in (1) from possible direct *CP* violation (ε'/ε) can be limited to a fraction of a degree. Larger deviations of Φ_{+-} and Φ_{00} from Φ_{SW} could signal a violation of *CPT*, but may also arise from unexpectedly large *CP*-violating contributions from non-$\pi\pi$ decay modes to K-$\bar{K}$ mixing. The phase difference $\Delta\Phi\equiv\Phi_{00}-\Phi_{+-}$ is immune to the latter, giving a stringent test of *CPT* symmetry.

Verification of (1) requires accurate determinations of τ_S and Δm to determine Φ_{SW}, but more importantly to experimentally extract Φ_{+-} and Φ_{00}. Recent determinations [3,4] of $\Delta\Phi$ are consistent with zero, with the average having an error of $\pm2.0°$. The average value [5] of Φ_{+-} is $46.5°\pm1.2°$, higher than the expected value from (1) of $43.7°\pm0.2°$.

In this experiment, decays from two neutral kaon beams were simultaneously collected. One beam was pure K_L, while the other struck a regenerator to provide a coherent mixture of K_S and K_L. The results presented here were derived from the time dependence of the two-pion decays downstream of the regenerator where the interference effects could be measured. The flux on the regenerator was normalized using the decays from the other (vacuum) beam. We can fit for τ_S and Δm separately in the $\pi^+\pi^-$ and $2\pi^0$ data, while we use a combined fit to both modes to determine $\Delta\Phi$ and Φ_{+-}.

The data for this analysis were collected at Fermilab during the 1987-88 fixed target run. Full details of the experiment will be given in a future publication [6]. The two neutral kaon beams were produced by a beam of 800 GeV protons incident at 5 mrad on a beryllium target located upstream of a two-hole collimator. Coherent regeneration was provided by two interaction lengths of B_4C located 123 m downstream of the target. The regenerator alternated between the two beams once every minute, and was instrumented to reject inelastic scatters. In addition to the 2π modes, a large number of $\pi^{\pm}e^{\mp}\nu$ ($Ke3$), $\pi^+\pi^-\pi^0$, and $\pi^0\pi^0\pi^0$ decays were collected for studying the detector.

A schematic of the detector is shown in Fig. 1. Electrons and photons were detected in an 804 block lead-glass calorimeter 18.7 radiation lengths deep located 181 m downstream of the target. Its resolution was 1.5% (2.5%) + $5\%/\sqrt{E}$ for electrons (photons), and its average response was understood to ±0.1%. The neutral trigger required an energy deposit of at least 28 GeV and either four or six isolated showers. The $\pi^0\pi^0\pi^0$ sample (six showers) was used to study the detector acceptance and to monitor the calorimeter. Eleven planes of anticounters rejected events with escaping photons to reduce the $3\pi^0$ background in the $\pi^0\pi^0$ sample. A 0.5 mm Pb sheet was present 137.8 m from the target in early subsets of the neutral sample. Previous experiments [7] required a conversion in this sheet; during the run studies indicated that the unconverted events would yield better results, so it was removed.

Neutral events were reconstructed by pairing the photons such that they were consistent with two π^0's decaying from a common vertex. The $2\pi^0$ mass could then be reconstructed with an average mass resolution of 5.5 meV. Events within ±24 MeV of the nominal K mass were accepted. The center of energy of the reconstructed photons was used to distinguish between decays in the vacuum and regenerator beams. Events with all photon energies between 1.5 and 60 GeV were accepted. When the lead sheet was in place, kaons reconstructing within ±1 m of the sheet were rejected.

Charged final states, including $\pi^+\pi^-$, $\pi^+\pi^-\pi^0$, and $\pi^{\pm}e^{\mp}\nu$ ($Ke3$), were triggered by requiring a two-track signature using hodoscopes at 137.8 and 179.5 m from the target. Particle momenta and trajectories were reconstructed with a four drift chamber magnetic spectrometer. Each chamber had two orthogonal pairs of offset planes transverse to the beam. The resolution of each plane was 100 μm, the average momentum resolution was 0.7%, and the K mass resolution was 3.5 MeV. Those $\pi^+\pi^-$ events which reconstructed within ±14 MeV of the nominal K mass were accepted.

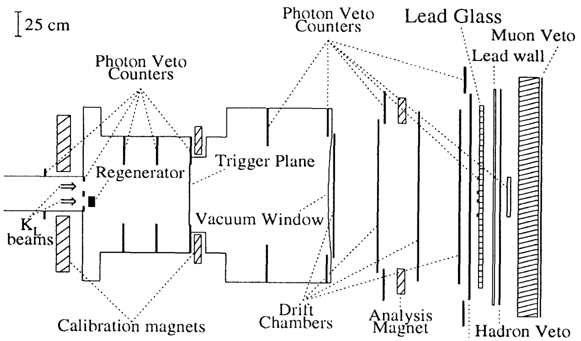

FIG. 1. Schematic of the E731 detector.

The treatment of backgrounds in the charged and neutral modes is discussed in the following paper [1].

For fitting, the data were divided into bins of momentum (p) and decay position (z). The event rate downstream of the regenerator is given by

$$\frac{dN}{dp\,dz}=aF(p)|\rho(p)e^{-z/2\gamma c\tau_S+i\Delta m z/\gamma c}+\eta e^{-z/2\gamma c\tau_L}|^2\varepsilon(p,z)\,,$$

where F is the kaon flux, τ_L is the K_L lifetime, ε is the (Monte Carlo determined) acceptance, a is the kaon transmission relative to the vacuum beam, γ is the Lorentz boost, and c is the speed of light. The transmission was measured to be 0.0635 ± 0.003 using the $\pi^0\pi^0\pi^0$ and $\pi^+\pi^-\pi^0$ samples. The regeneration amplitude ρ follows a power-law behavior [8] in kaon momentum, $\rho(p)\propto p^{\alpha}$.

We will first discuss the determination of τ_S and Δm in the charged and neutral modes.

In the fits used to extract τ_S and Δm, the parameters simultaneously varied were τ_S, Δm, ρ(70 GeV/c), α (the power-law exponent), and normalization parameters. It is important that we used (1) in these fits by fixing $\Phi_{+-(00)}$ to $\Phi_{\rm SW}$ in the charged (neutral) data fits.

The treatment of the phase of the regeneration amplitude deserves special mention. The regeneration amplitude at our energies is dominated by a single Regge trajectory [9] (the ω) which yields a pure power-law behavior and hence a phase determined by analyticity:

$$\rho(p)\propto p^{\alpha}\exp[-i\tfrac{1}{2}\pi(2+\alpha)]\,. \tag{2}$$

(Later we present a check of this relation.) At momenta higher than about 20 GeV/c where nuclear absorption is nearly constant [10], the uncertainties in the regeneration phase as deduced from the momentum dependence are relatively small.

In the charged fits, the range in z vertex in the regenerator beam was 124.5–135 m and the range in momentum was 20 to 160 GeV/c. The fit was performed to the number of events in each 10 GeV/c by 2 m (p,z) bin. Using events either upstream of 124.5 m, where the turn-on in the regeneration rate is rapid, or downstream of 135 m, where the convolution of the acceptance, incident flux, and decay rate is changing rapidly, would have increased the systematic error beyond the small gain in statistics. The results of the charged-mode fit are $(\tau_S)_{+-}=(0.8952\pm0.0015\pm0.0020)\times10^{-10}$ s, $(\Delta m)_{+-}=(0.5311\pm0.0044\pm0.0020)\times10^{10}\hbar$ s^{-1}, with $\chi^2=92$ for 90 degrees of freedom (d.o.f.), where the first (second) errors are statistical (systematic).

The systematic error in the lifetime is dominated by uncertainties in the detector acceptance. The error on the parameter α is 0.003, corresponding [Eq. (2)] to an error on the regeneration phase of 0.3°. Because of the analyticity constraint in the fit, the statistical errors already include the contribution from this uncertainty. We add the uncertainty from an additional 0.5° shift in quadrature for the possibility of a nonpure power-law behavior [11]. This is consistent with the observed change of 0.004 in α if the fit begins at 40 GeV/c rather than 20 GeV/c.

Combining statistical and systematic errors in quadrature, we have $(\tau_S)_{+-} = (0.8952 \pm 0.0025) \times 10^{-10}$ s, $(\Delta m)_{+-} = (0.5311 \pm 0.0048) \times 10^{10} \hbar$ s^{-1}. The extracted exponential and interference terms together with the superposed best fits are shown in Fig. 2.

In the neutral-mode fits, the momentum range used was 40–160 GeV/c, the z range was between 125 and 152 m, and the bin size was 10 GeV/c by 3 m. Fits were performed separately to data without the lead sheet (NPB) from those with it (PB). The results (statistical errors) of the neutral-mode fits are $(\tau_S)_{\rm NPB} = (0.8920 \pm 0.0025) \times 10^{-10}$ s, $(\Delta m)_{\rm NPB} = (0.5251 \pm 0.0047) \times 10^{10} \hbar$ s^{-1}, $\chi^2 = 100$ for 99 d.o.f.; $(\tau_S)_{\rm PB} = (0.8904 \pm 0.0022) \times 10^{-10}$ s, $(\Delta m)_{\rm PB} = (0.5289 \pm 0.0039) \times 10^{10} \hbar$ s^{-1}, $\chi^2 = 118$ for 99 d.o.f. A combined fit to both the PB and NPB data sets gives

$$(\tau_S)_{00} = (0.8912 \pm 0.0017 \pm 0.0012) \times 10^{-10}\,\text{s},$$

$$(\Delta m)_{00} = (0.5274 \pm 0.0030 \pm 0.0017) \times 10^{10} \hbar\,\text{s}^{-1},$$

$\chi^2 = 221$ for 203 d.o.f., where the first (second) errors are statistical (systematic).

The systematic errors include uncertainties in acceptance and backgrounds, but are dominated by uncertainties in the photon energy measurement. The energy scale error was estimated by varying the energy calibration within the allowed ranges, while the other uncertainties were obtained from a detailed Monte Carlo study. These are discussed in more detail in the following paper [1]. The 40 GeV/c minimum momentum for the neutral mode has two effects. The power law is determined less accurately than in charged mode, and deviations from a pure power-law behavior are expected to be smaller. Because the error on the power α for the combined fit already corresponds to a 0.7° error in the regeneration phase, no additional contribution to the systematic uncertainty in this quantity was necessary.

Combining errors in quadrature, we find

$$(\tau_S)_{00} = (0.8912 \pm 0.0021) \times 10^{-10}\,\text{s},$$

$$(\Delta m)_{00} = (0.5274 \pm 0.0034) \times 10^{10} \hbar\,\text{s}^{-1}.$$

The extracted exponential and interference terms together with the superposed best fits are shown in Fig. 3. The extended vertex range in this sample allows for the more accurate determination of Δm here relative to the charged mode.

The values for τ_S and Δm obtained from the two modes agree, and combining them we have $\tau_S = (0.8929 \pm 0.0016) \times 10^{-10}$ s, and $\Delta m = (0.5286 \pm 0.0028) \times 10^{10} \hbar$ s^{-1}. τ_S is in good agreement with the world average of $(0.8922 \pm 0.0022) \times 10^{-10}$ s, while Δm is about 2 standard deviations lower than the world average of $(0.5351 \pm 0.0024) \times 10^{10} \hbar$ s^{-1}. The results for Δm and τ_S would change by +0.58% and −0.09%, respectively, if we fixed both Φ_{00} and Φ_{+-} to a value 1° higher than in (1).

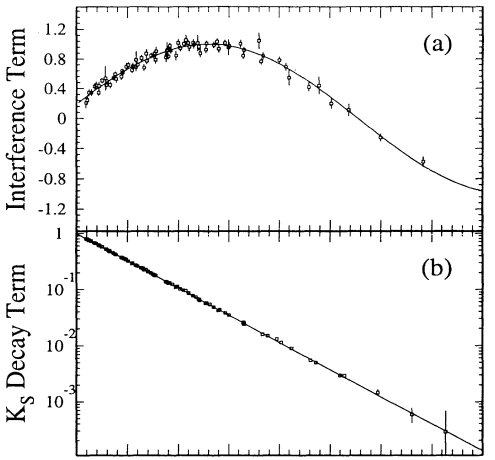

FIG. 2. Distributions in proper time for $\pi^+\pi^-$ decays for the sample $p_K < 90$ GeV/c. Each data point corresponds to a 1 m by 10 GeV/c bin. (a) The interference term; (b) the exponential term. Higher momentum data have not been plotted for clarity at small proper time. The lines are the best fit results described in the text.

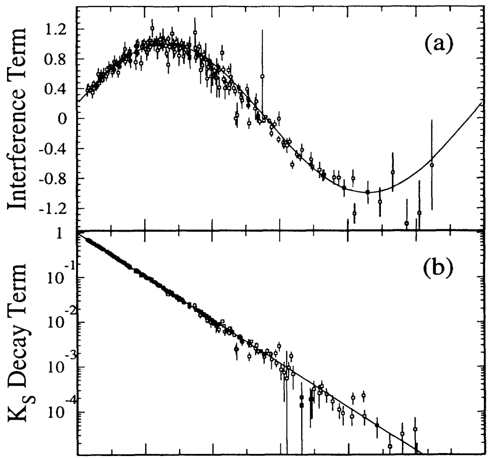

FIG. 3. Distributions in proper time for $2\pi^0$ decays for the sample $p_K < 90$ GeV/c. Each data point corresponds to a 1 m by 10 GeV/c bin. The lines are the best fit results described in the text. (a) The interference term; (b) the exponential term. Higher momentum data have not been plotted for clarity at small proper time. The longer decay region gives the increased reach in proper time compared to the charged mode.

TABLE I. Our result and the best previous measurements of the phase Φ_{+-} of the *CP*-violating parameter η_{+-}. Using the reported dependences upon the K_L-K_S mass difference Δm, the measured phases have been corrected using the value of Δm measured in this experiment.

Experiment	Φ_{+-} (deg)	Internal error (deg)	Assumed Δm ($10^{10}\hbar$ s^{-1})	$\frac{\Delta\Phi_{+-}}{0.01\Delta m}$ (deg)	Φ_{+-} (our Δm)
Geweniger *et al.* [12]	49.4	1.0	0.5400	+3.05	43.0
Carithers *et al.* [13]	45.5	2.8	0.5348	+1.20	44.1
Carosi *et al.* [3]	46.9	1.6	0.5351	+3.10	43.4
This result	42.2	1.4	Floated	⋯	42.2

To check the analyticity relation, we fitted all data for α and the regeneration phase and assumed (1). Using the Particle Data Group (PDG) value for Δm, the phase predicted using analyticity and the measured phase agree within an error of 0.8°. With Δm floating, they agree within an error of 1.3°.

To extract $\Delta\Phi$, a simultaneous fit to the charged and neutral-mode data is done. $\mathrm{Re}(\varepsilon'/\varepsilon)$, Φ_{+-}, and $\Delta\Phi$ are floated, but we cannot report Φ_{+-} in this fit as we use our own values for τ_S and Δm, derived assuming (1). The fit gives $\Delta\Phi = -1.6^\circ \pm 1.0^\circ \pm 0.7^\circ$ with a χ^2 of 318 for 297 d.o.f. $\mathrm{Re}(\varepsilon'/\varepsilon)$ is consistent with that reported in the next paper [1]. The systematic error results from uncertainties in the background (0.2°), photon energy reconstruction (0.5°), and acceptance (0.4°). Combining the errors in quadrature, the result becomes

$$\Delta\Phi = -1.6^\circ \pm 1.2^\circ + 190^\circ \left[\frac{\tau_S \times 10^{10}\,\mathrm{s}^{-1} - 0.8929}{0.8929}\right] + 32^\circ \left[\frac{\Delta m \times 10^{-10}\hbar^{-1}\,\mathrm{s} - 0.5286}{0.5286}\right],$$

where we have given the dependences upon τ_S and Δm. This is more precise than the PDG [5] average of $-0.1^\circ \pm 2.0^\circ$ and further constrains *CPT*-violating terms in the neutral kaon system.

To extract Φ_{+-}, we performed a similar fit with Δm floating. The best previous experiments with their sensitivities to Δm and our own result are shown in Table I. Our result includes a statistical error of 1.3° and a systematic error of 0.5° from possible uncertainties in the regeneration phase. (In this fit we find a consistent value for Δm with about twice the error.) The average, using our Δm value and including correlated systematic errors [14], is $\Phi_{+-} = 42.8^\circ \pm 1.1^\circ$ in agreement with 43.7° (43.4°) expected from (1), using PDG [5] (our) values for Δm and τ_S.

In summary, we have reported new precise determinations of τ_S, Δm, Φ_{+-}, and $\Delta\Phi$ in the neutral kaon system. Our results together with those of other experiments are now in excellent agreement with *CPT* symmetry. The result on the parameter ε'/ε is given in the following paper [1].

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[11] This would arise from an additional trajectory, in this case the Pomeron. The Pomeron is pure imaginary and does not affect the regeneration phase. The amplitude can differ from a perfect power law from logarithmic terms in the Pomeron. From the magnitude of the total cross-section rise, these terms can be estimated and they imply a phase change of no larger than about 0.4°.

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