



New Measurements of the Neutral Kaon Parameters  
 $\Delta m$ ,  $\tau_S$ ,  $\Phi_{00} - \Phi_{+-}$ , and  $\Phi_{+--}$

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Abstract

The full E731 data set is used to provide precise determinations of several parameters of the neutral kaon. We find the  $K_S$  lifetime  $\tau_S = (0.8929 \pm 0.0016) \times 10^{-10}$  s, the  $K_L$ - $K_S$  mass difference  $\Delta m = (0.5286 \pm 0.0028) \times 10^{10} \text{ } \hbar\text{s}^{-1}$ ; the phase of  $\eta_{+-}$ ,  $\Phi_{+-} = 42.2^\circ \pm 1.4^\circ$ ; and the phase difference between  $\Phi_{00}$  and  $\Phi_{+-}$ ,  $\Delta\Phi = -1.6^\circ \pm 1.2^\circ$ . 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  $\eta_{00}$  and  $\eta_{+-}$ , and the phase of  $\eta_{+-}$  itself. The following paper<sup>1</sup> in this issue presents the result for  $\epsilon'/\epsilon$  from the same data set.

Both  $\tau_S$  and  $\Delta m$  are primary parameters of the neutral kaon system. Their interest lies primarily in the curious fact that one can relate them to the phases of the CP violating  $\pi\pi$  decay amplitudes,  $\eta_{+-}$  and  $\eta_{00}$ . CPT symmetry and Unitarity<sup>2</sup> imply

$$\Phi_{+-} = \Phi_{00} = \tan^{-1} \frac{2\Delta m}{(\Gamma_S - \Gamma_L)}, \quad (1)$$

where  $\Gamma_{S(L)}$  is the  $K_{S(L)}$  decay rate,  $\Phi_{+-} \equiv \arg(\eta_{+-})$  and  $\Phi_{00} \equiv \arg(\eta_{00})$ . The righthand expression gives what is known as the superweak phase ( $\Phi_{SW}$ ). Beyond this relation, there is the additional importance that the experimental extraction of  $\Phi_{+-}$  and  $\Phi_{00}$  depends upon accurate determinations of  $\tau_S$  and  $\Delta m$ .

CPT symmetry is a cornerstone of local quantum field theory and hence is worth probing, particularly given the non-local character of candidate (string) theories. The neutral kaon system is one of the most sensitive arenas for a study of CPT symmetry, which requires that the charged and neutral phases be equal within a fraction of a degree ( $\Delta\Phi \equiv \Phi_{00} - \Phi_{+-} = 0$ ) and that they obey (1). Recent  $\Delta\Phi$  determinations<sup>3,4</sup> are consistent with zero, with the average having an error of  $\pm 2.0^\circ$ . The average value<sup>5</sup> of  $\Phi_{+-}$  is  $46.5^\circ \pm 1.2^\circ$ , higher than the expected value from (1) of  $43.7^\circ \pm 0.2^\circ$ .

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  $\tau_S$  and  $\Delta m$  separately in the  $\pi^+\pi^-$  and  $2\pi^0$  data, while we use a combined fit to both modes to determine  $\Delta\Phi$  and  $\Phi_{+-}$ .

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<sup>6</sup>. 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 123m 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  $2\pi$  modes, a large number of  $\pi^+e^+\nu$  (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 figure 1. Electrons and photons were detected in an 804 block lead glass calorimeter 18.7 radiation lengths deep located 181m downstream of the target. Its resolution was  $1.5\%(2.5\%)+5\%/\sqrt{E}$  for electrons (photons), and its average response was understood to  $\pm 0.1\%$ . 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 (6 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 0.5mm Pb sheet was present 137.8m from the target in early subsets of the neutral sample. Previous experiments<sup>7</sup> 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 2  $\pi^0$ 's decaying from a common vertex. This pairing used the known  $\pi^0$  mass as a constraint. The  $2\pi^0$  mass could then be reconstructed with an average mass resolution of 5.5 MeV. Events within  $\pm 24$  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 GeV and 60 GeV were accepted. When the lead sheet was in place, kaons reconstructing within 1 cm of the sheet were rejected.

Charged final states, including  $\pi^+\pi^-$ ,  $\pi^+\pi^-\pi^0$ , and  $\pi^+e^+\nu$  (Ke3), were triggered by requiring a two track signature using hodoscopes at 137.8 m 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  $\mu\text{m}$ , the average momentum resolution was 0.7%, and the K mass resolution was 3.5 MeV. Those  $\pi^+\pi^-$  events which reconstructed within  $\pm 14$  MeV of the nominal K mass were accepted.

The treatment of backgrounds in the charged and neutral modes is discussed in the following paper.<sup>1</sup>

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

$$\frac{dN}{dpdz} = aF(p)\rho(p)e^{-z/2\gamma\tau_s + i\Delta m z/\gamma} + \eta e^{-z/2\gamma\tau_L} \epsilon(p,z),$$

where F is the kaon flux,  $\tau_L$  is the  $K_L$  lifetime,  $\epsilon$  is the (Monte Carlo determined) acceptance,  $a$  is the kaon transmission relative to the vacuum beam,  $\gamma$  is the Lorentz boost, and  $c$  is the speed of light. The transmission was measured to be  $0.0635 \pm 0.0003$  using the  $\pi^0\pi^0\pi^0$  and  $\pi^+\pi^-\pi^0$

samples. The regeneration amplitude  $\rho$  follows a power-law behavior<sup>8</sup> in kaon momentum,  $\rho(p) \propto p^\alpha$ .

We will first discuss the determination of  $\tau_S$  and  $\Delta m$  in the charged and neutral modes.

In the fits used to extract  $\tau_S$  and  $\Delta m$ , the parameters simultaneously varied were  $\tau_S$ ,  $\Delta m$ ,  $\rho(70\text{GeV}/c)$ ,  $\alpha$  (the power-law exponent), and normalization parameters. It is important that we assumed CPT symmetry by fixing  $\Phi_{+-}(00)$  to  $\Phi_{SW}$  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<sup>9</sup> (the  $\omega$ ) which yields a pure power law behaviour and hence a phase determined by analyticity:

$$\rho(p) \propto p^\alpha \exp(-i\frac{\pi}{2}(2+\alpha)). \quad (2)$$

(Later we present a check of this relation.) At momenta higher than about 20 GeV/c where nuclear absorption is nearly constant<sup>10</sup>, 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 GeV/c to 160 GeV/c. The fit was performed to the number of events in each 10 GeV/c by 2m (p,z) bin. Using events either upstream of 124.5 m, where the turn-on in the regeneration rate is rapid, or downstream of 135m, 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:  $(\tau_S)_{+-} = (0.8952 \pm 0.0015 \pm 0.0020) \times 10^{-10}$  s;  $(\Delta m)_{+-} = (0.5311 \pm 0.0044 \pm 0.0020) \times 10^{10}$   $h s^{-1}$ ;  $\chi^2 = 92$  for 90 degrees of freedom (dof), 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  $\alpha$  is 0.003, corresponding (eqn. 2) to an error on the regeneration phase of  $0.3^\circ$ . 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  $0.5^\circ$  shift in quadrature for the possibility of a non-pure power law behavior<sup>11</sup>. This is consistent with the observed change of 0.004 in  $\alpha$  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 Figure 2.

In the neutral mode fits, the momentum range used was 40 - 160 GeV/c, the z-range was between 125 m 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:  $(\tau_S)_{NPB} = (0.8920 \pm 0.0025) \times 10^{-10}$  s,  $(\Delta m)_{NPB} = (0.5251 \pm 0.0047) \times 10^{10}$   $\hbar s^{-1}$ ,  $\chi^2 = 100$  for 99 dof;  $(\tau_S)_{PB} = (0.8904 \pm 0.0022) \times 10^{-10}$  s,  $(\Delta m)_{PB} = (0.5289 \pm 0.0039) \times 10^{10}$   $\hbar s^{-1}$ ,  $\chi^2 = 118$  for 99 dof. A combined fit to both the PB and NPB data sets gives:  $(\tau_S)_{00} = (0.8912 \pm 0.0017 \pm 0.0012) \times 10^{-10}$  s,  $(\Delta m)_{00} = (0.5274 \pm 0.0030 \pm 0.0017) \times 10^{10}$   $\hbar s^{-1}$ ,  $\chi^2 = 221$  for 203 dof, 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<sup>1</sup>. The smaller range in 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 behaviour are expected to be smaller. Because the error on the power  $\alpha$  for the combined fit already corresponds to a  $0.7^\circ$  error in the regeneration phase, no additional contribution to the systematic uncertainty in this quantity was necessary.

Combining errors in quadrature, we find:  $(\tau_S)_{00} = (0.8912 \pm 0.0021) \times 10^{-10}$  s,  $(\Delta m)_{00} = (0.5274 \pm 0.0034) \times 10^{10}$   $\hbar s^{-1}$ . The extracted exponential and interference terms together with the superposed best fits are shown in Figure 3. The extended vertex range in this sample allows for the more accurate determination of  $\Delta m$  here relative to the charged mode.

The values for  $\tau_S$  and  $\Delta m$  obtained from the two modes agree, and combining them we have  $\tau_S = (0.8929 \pm 0.0016) \times 10^{-10}$  s, and  $\Delta m = (0.5286 \pm 0.0028) \times 10^{10}$   $\hbar s^{-1}$ .  $\tau_S$  is in good agreement with the world average of  $(0.8922 \pm 0.0022) \times 10^{-10}$  s, while  $\Delta m$  is about 2 standard deviations lower than the world average of  $(0.5351 \pm 0.0024) \times 10^{10}$   $\hbar s^{-1}$ . Precise values for  $\Delta m$  have not been reported for nearly 20 years.

To check the analyticity relation, we fit all data for  $\alpha$  and the regeneration phase, assuming CPT symmetry. Using the PDG value for  $\Delta m$ , the phase predicted using analyticity and the measured phase agree within an error of  $0.8^\circ$ . With  $\Delta m$  floating, they agree within an error of  $1.3^\circ$ .

To extract  $\Delta\Phi$ , a simultaneous fit to the charged and neutral mode data is done.  $\text{Re}(\epsilon'/\epsilon)$ ,  $\Phi_{+-}$ , and  $\Delta\Phi$  are floated, but we cannot report  $\Phi_{+-}$  in this fit as we use our own values for  $\tau_S$  and  $\Delta m$  where CPT symmetry was assumed through the use of (1). The fit gives  $\Delta\Phi = -1.6^\circ \pm 1.0^\circ \pm$

0.7<sup>0</sup> with a  $\chi^2$  of 318 for 297 dof.  $\text{Re}(\epsilon'/\epsilon)$  is consistent with that reported in the next paper<sup>1</sup>. The systematic error results from uncertainties in the background (0.2<sup>0</sup>), photon energy reconstruction (0.5<sup>0</sup>), and acceptance (0.4<sup>0</sup>). Combining the errors in quadrature, the result becomes  $\Delta\Phi = -1.6^0 \pm 1.2^0$

$$+190^0 \left( \frac{\tau_S \times 10^{10} \text{ s}^{-1} - 0.8929}{0.8929} \right) + 32^0 \left( \frac{\Delta m \times 10^{-10} \text{ h}^{-1} \text{ s} - 0.5286}{0.5286} \right),$$

where we have given the dependences upon  $\tau_S$  and  $\Delta m$ . This is more precise than the PDG<sup>5</sup> average of  $-0.1^0 \pm 2.0^0$  and further constrains CPT violating terms in the neutral kaon system.

To extract  $\Phi_{+-}$ , we performed a similar fit with  $\Delta m$  floating. The best previous experiments with their sensitivities to  $\Delta m$  and our own result are shown in Table 1. Our result includes a statistical error of 1.3<sup>0</sup> and a systematic error of 0.5<sup>0</sup> from possible uncertainties in the regeneration phase. (In this fit we find a consistent value for  $\Delta m$  with about twice the error.)

Experiment	$\Phi_{+-}$ (degrees)	Internal Error (degrees)	Assumed $\Delta m$ ( $10^{10} \text{ h} \text{ s}^{-1}$ )	$\frac{\Delta\Phi_{+-}}{0.01\Delta m}$ (degrees)	$\Phi_{+-}$ (our $\Delta m$ )
C. Geweniger et. al. <sup>12</sup>	49.4	1.0	0.5400	+3.05	43.0
W.C.Carithers et al. <sup>13</sup>	45.5	2.8	0.5348	+1.20	44.1
R.Carosi et al. <sup>3</sup>	46.9	1.6	0.5351	+3.10	43.4
This result	42.2	1.4	floated	-	42.2

Table 1: Our result and the best previous measurements of the phase  $\Phi_{+-}$  of the CP-violating parameter  $\eta_{+-}$ . Using the reported dependences upon the  $K_L$ - $K_S$  mass difference  $\Delta m$ , the measured phases have been corrected using the value of  $\Delta m$  measured in this experiment.

The average, using our  $\Delta m$  value and including correlated systematic errors<sup>14</sup>, is  $\Phi_{+-} = 42.8^\circ \pm 1.1^\circ$  in agreement with  $43.7^\circ$  ( $43.4^\circ$ ) expected from CPT symmetry (1), using PDG<sup>5</sup> (our) values for  $\Delta m$  and  $\tau_S$ .

In summary, we have reported new precise determinations of  $\tau_S$ ,  $\Delta m$ ,  $\Phi_{+-}$ , 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  $\epsilon'/\epsilon$  is given in the following paper<sup>1</sup>.

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<sup>1</sup>L.K.Gibbons et al., following paper.

<sup>2</sup>See, for example, The Physics of Time Reversal, R.G.Sachs, U of C Press (1987)

<sup>3</sup>R. Carosi et al., Phys. Lett. B237, 303 (1990)

<sup>4</sup>M. Karlsson et al., Phys. Rev. Lett. 64, 2976 (1990). This result is superceded by the current analysis.

<sup>5</sup>Particle Data Group, Review of Particle Properties, Phys. Rev. D 45 (1992)

<sup>6</sup>See also L.K. Gibbons, U. of Chicago Ph.D. thesis (1993), in preparation.

<sup>7</sup>M. Woods et al., Phys. Rev. Lett. 60, 1695 (1988).

<sup>8</sup>J. Roehrig et al., Phys. Rev. Lett. 38, 1116 (1977).

<sup>9</sup>F.J. Gilman, Phys. Rev. 171, 1453 (1968), and ref. [7].

<sup>10</sup>A. Gsponer et al., Phys. Rev. Lett. 42, 13 (1979).

<sup>11</sup>This would arise from an additional trajectory, in this case the Pomeron. The Pomeron is pure imaginary and doesn't 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  $0.4^\circ$ .

<sup>12</sup>C. Geweniger et al., Phys. Lett. 52B, 119 (1974)

<sup>13</sup>W. C. Carithers et al., Phys. Rev. Lett. 34, 1244 (1975)

<sup>14</sup>H. Wahl, Rare Decay Symposium, Vancouver, Canada, Dec. 1988, World Scientific, p. 281, Eds. D. Bryman, J. Ng, T. Numao, J.-M. Poutissou.

#### FIGURE CAPTIONS

Figure 1. Schematic of the E731 detector.

Figure 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.

Figure 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 charged mode.

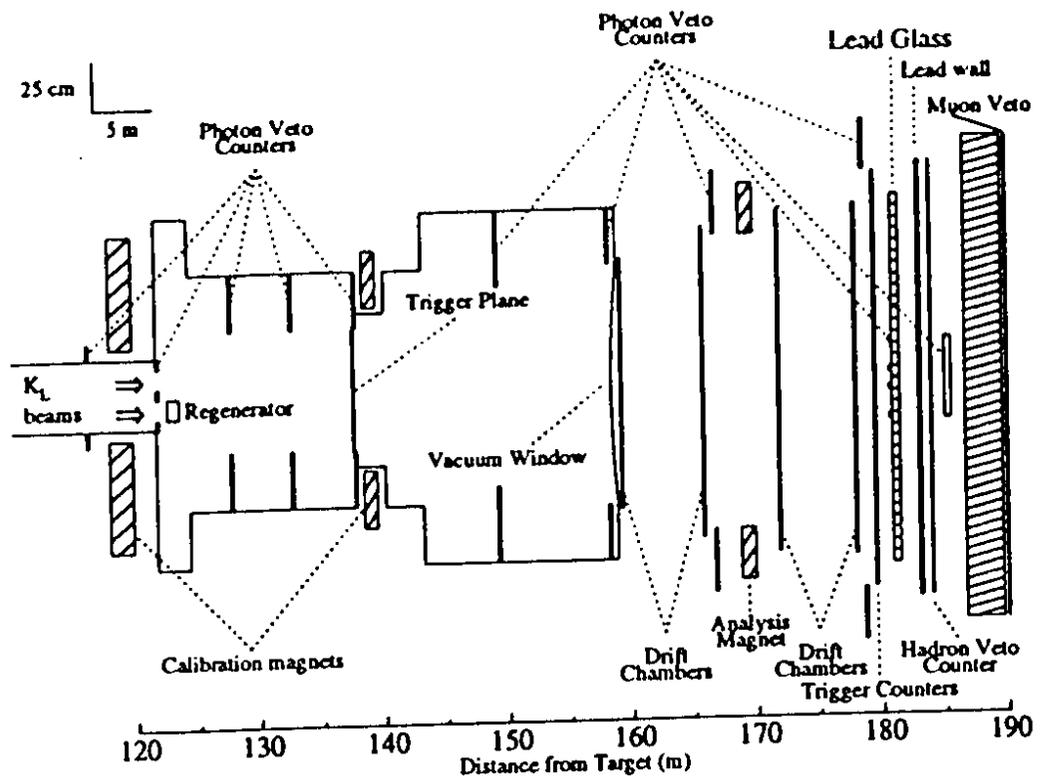


Figure 1

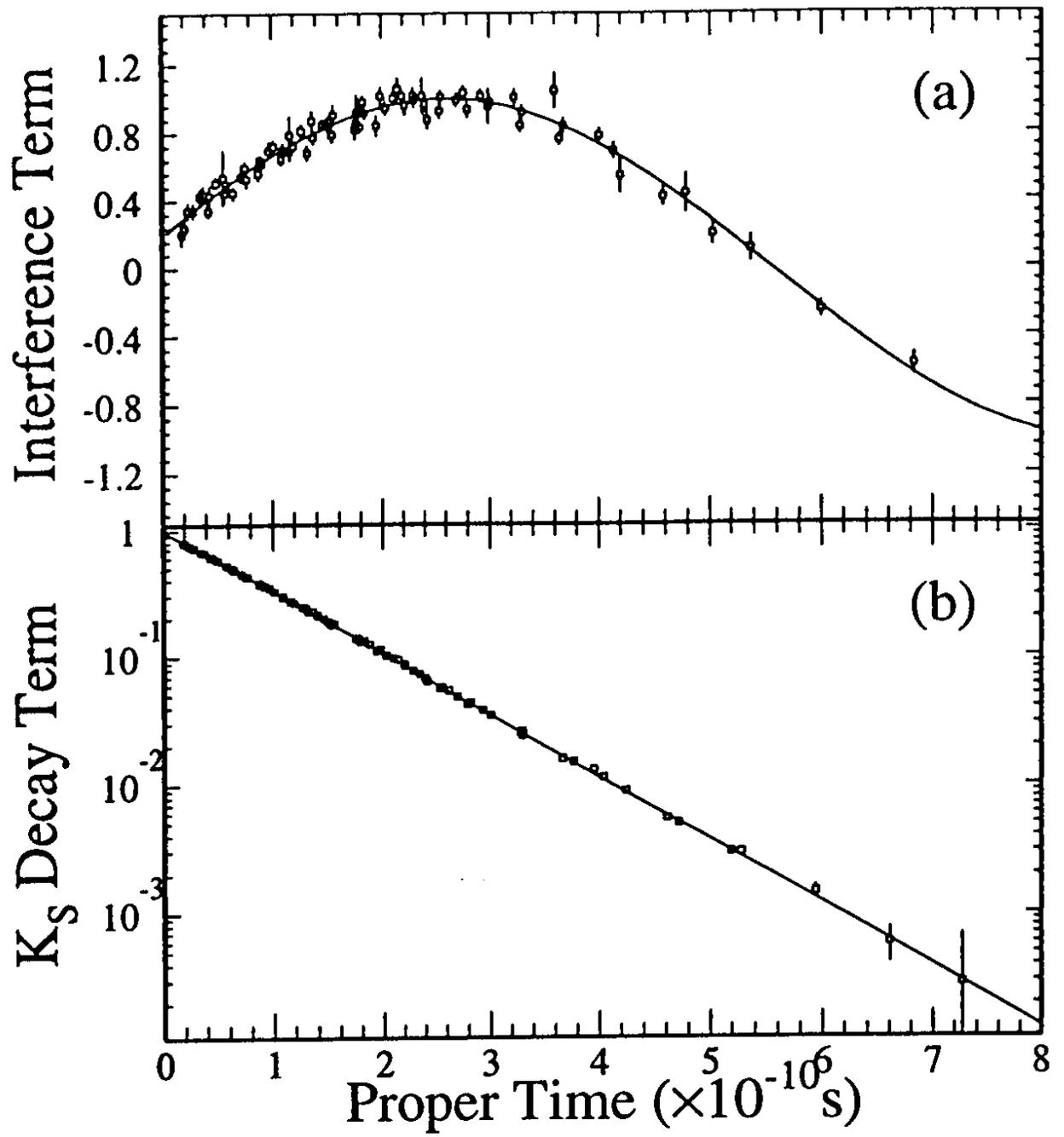


Figure 2

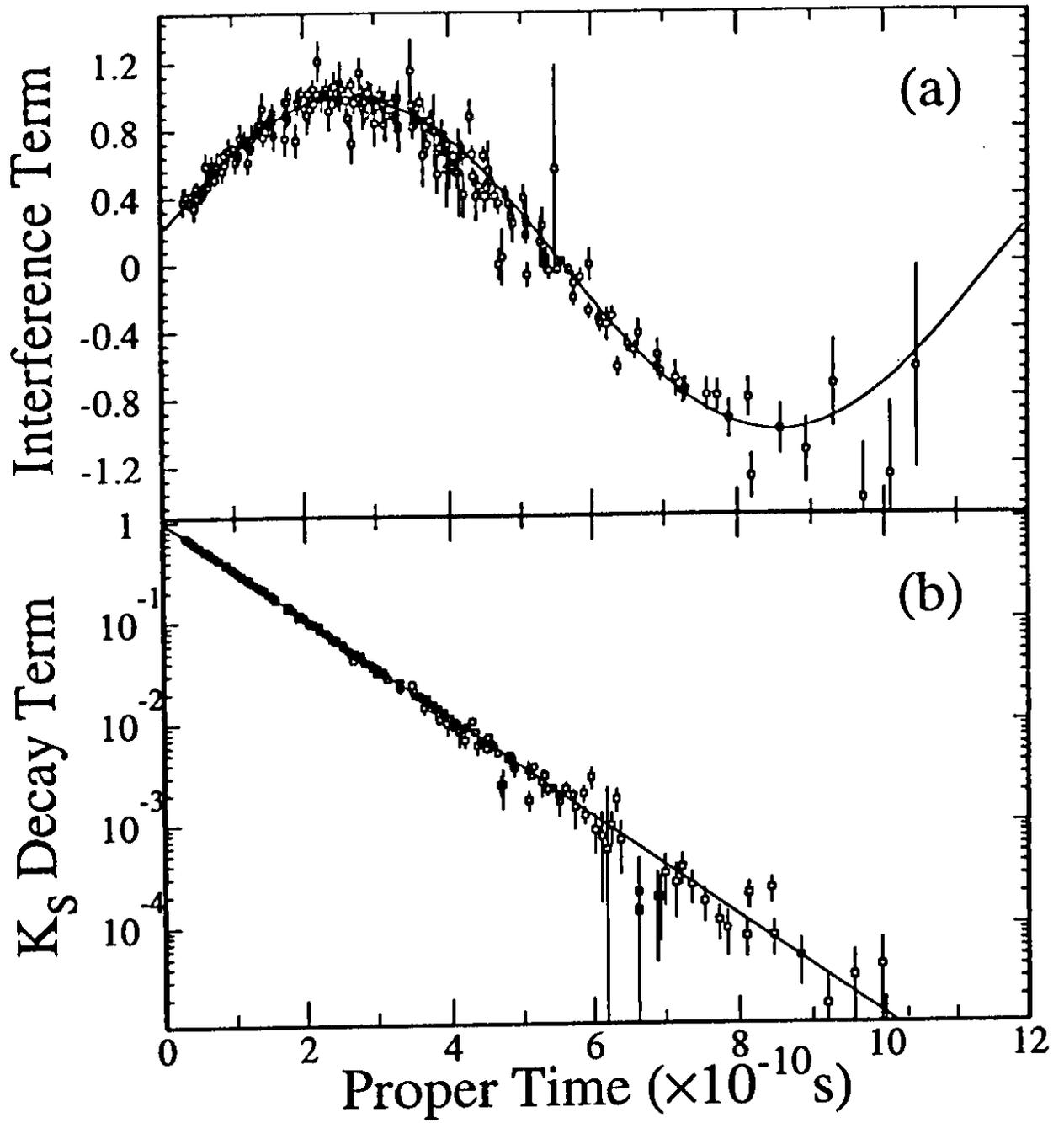


Figure 3