Measurement of the Lifetime of K_S^0 Mesons in the Momentum Range 100 to 350 GeV/c

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In an experiment at Fermilab we have measured the lifetime of K_S^0 mesons produced by 800-GeV/c protons on tungsten. $K_S^0 \rightarrow \pi^+\pi^-$ decays from 100 to 350 GeV/c, between 9.3 and 25.3 m from production, were selected for the measurement. The result was $(0.8920 \pm 0.0044) \times 10^{-10}$ sec, in excellent agreement with measurements performed for 2–5-GeV/c K_S^0. The lifetime was also calculated for seven momentum bins. The results were completely consistent with Lorentz invariance. No evidence was found for the momentum dependence suggested by the intermediate-range "fifth-force" hypothesis.

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In this Letter we report high-precision measurements of the K_S^0 lifetime (τ_S) made over a wide range of kaon momenta. While it is intrinsically important to measure the basic parameters of the K^0-$\bar{K}^0$ system, our τ_S measurement was also motivated by recent speculation[1] about the existence of a fifth force that couples to hypercharge. The data were collected during Fermilab experiment 621 to search for CP-symmetry nonconservation in $K_S^0 \rightarrow \pi^+\pi^-\pi^0$ decays.

In a reanalysis of three K_S^0 regeneration experiments at Fermilab, Aronson, Bock, Chen, and Fischbach[2] (ABCF) found evidence that the values of four K^0-$\bar{K}^0$ parameters changed with the kaon's momentum over the range 30–110 GeV/c. These were Δm, the mass difference of $K_L^0 - K_S^0$; $|\eta_{+-}|$, the magnitude of the CP-nonconservation parameter in $K_L^0 \rightarrow \pi^+\pi^-$ decay; ϕ_{+-}, the phase of η_{+-}; and τ_S. In these experiments a K_L^0 beam strikes a target, and the number of $\pi^+\pi^-$ decays in the forward direction, per unit proper time t, dN_R/dt, is

$$\frac{dN_R}{dt} = B_{+-}\frac{N_L}{\tau_S}\left\{|\rho|^2\exp\left(\frac{-t}{\tau_S}\right) + |\eta_{+-}|^2\exp\left(\frac{-t}{\tau_L}\right) + 2|\rho|\,|\eta_{+-}|\cos(\Delta m\,t + \phi_\rho - \phi_{+-})\exp\left[-\frac{t}{2}\left(\frac{1}{\tau_S}+\frac{1}{\tau_L}\right)\right]\right\}, \quad (1)$$

where B_{+-} is the $K_S^0 \rightarrow \pi^+\pi^-$ branching ratio, N_L is the number of K_L^0 in the beam, τ_L is the K_L^0 lifetime, and ρ is the (complex) regeneration amplitude with phase ϕ_ρ. These experiments were designed to measure ρ (and extract the difference of K^0 and $\bar{K}^0$ forward scattering amplitudes), not to measure K^0-$\bar{K}^0$ decay parameters. As ABCF point out, with so many parameters affecting proper time dependence, it is not easy to isolate the effect of any one parameter by fitting Eq. (1) to regeneration data.

We avoid this problem in our experiment by studying decays of K_S^0 made in proton-tungsten collisions, rather than by regeneration, and by choosing a proper time range where the contribution of CP nonconservation is insignificant. A proton beam of momentum 800 GeV/c struck a tungsten target, 9.6 cm long and 3.5 mm in diameter, located at the entrance to the Fermilab Proton Center Hyperon Magnet, which is 7.3 m long, weighs 400 tons, and has a 3.5-T field. A collimator was located in the magnet with a defining aperture 3.2 mm in diameter 4.0 m from the target. It allowed only neutral particles to pass through the magnet and enter our detector, a pair spectrometer. Figure 1 shows the target, magnet, collimator, and detector. Two 1-mm-thick scintillation counters V1 and S1, located inside an evacuated pipe, defined a decay region between 8.1 and 26.7 m from the target. Six multiwire proportional chambers (MWPC's), and an analysis magnet with transverse momentum bend of 1.6 GeV/c were used to reconstruct

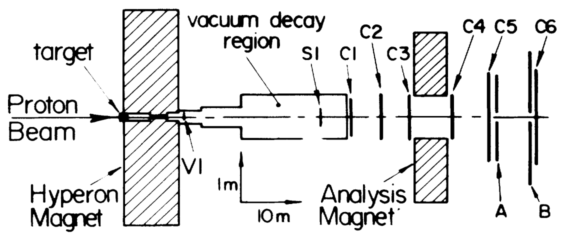

FIG. 1. Plan view of the apparatus showing the 800-GeV/c proton beam, K^0 production target, Hyperon magnet and collimator, evacuated decay region with scintillation counters V1 and S1, multiwire proportional chambers C1–C6 with the Analysis magnet between C3 and C4, and the A and B hodoscopes of scintillation counters.

the vector momenta of the π^+ and π^-. Two hodoscopes of scintillation counters, A and B, were used in forming the trigger. The list of hit MWPC wires and scintillation counters was generated and written on magnetic tape whenever the following trigger conditions were satisfied: A $\overline{\mathrm{V1}}\cdot\mathrm{S1}$ coincidence occurred, signaling the decay of a neutral particle in the decay region; and one counter was hit in the left half and one in the right half of each of the A and B hodoscopes. In addition the hits in the A and B hodoscopes were examined by a trigger processor that chose those decays where the momentum ratio of the π^+ and π^- was between $\frac{1}{3}$ and 3. This eliminated the copious background of $\Lambda^0 \to p\pi^-$ decays.

The trajectories of the two charged particles were reconstructed from the MWPC hits, and the following criteria were used to select events: (1) Under the assumption that both tracks were pions, the $\pi^+\pi^-$ invariant mass was within three σ of the K^0 mass, (2) the reconstructed vertex was within the decay region, and (3) the kaon lay within the volume of phase space occupied by the beam. These criteria eliminated backgrounds and kaons from sources other than the production target. 80% of triggers reconstructed to a "V" topology and 54% of V's satisfied the three criteria.

In Fig. 2(a) we show the $\pi^+\pi^-$ invariant mass for events satisfying criteria 2 and 3. In Fig. 2(b), for events satisfying all three criteria, we show the p_T^2 distribution, where p_T is the momentum component measured by the spectrometer that is transverse to the (known) kaon direction. The Monte Carlo simulation agrees with the data very closely.

We then divided the data into bins 10 GeV/c wide in momentum and 0.5 m long in longitudinal decay vertex position. We binned the Monte Carlo events in the same way, and in each bin calculated the acceptance of the detector. We then fitted the acceptance-corrected data to the hypothesis of the known proper-time evolution of $K^0 \to \pi^+\pi^-$, dN_p/dt:

$$\frac{dN_p}{dt} = \frac{N_s B_{+-}}{\tau_S}\left\{\exp\left(\frac{-t}{\tau_S}\right) + |\eta_{+-}|^2 \exp\left(\frac{-t}{\tau_L}\right) + 2D|\eta_{+-}|\cos(\Delta m\, t - \phi_{+-})\exp\left[-\frac{t}{2}\left(\frac{1}{\tau_S}+\frac{1}{\tau_L}\right)\right]\right\}. \quad (2)$$

Here D is the dilution factor $[D=(K^0-\bar{K}^0)/(K^0+\bar{K}^0)]$. To eliminate possible correlations among the parameters in the fit, we chose only events of momentum greater than 100 GeV/c, for which CP nonconservation contributes $<1.6\%$,

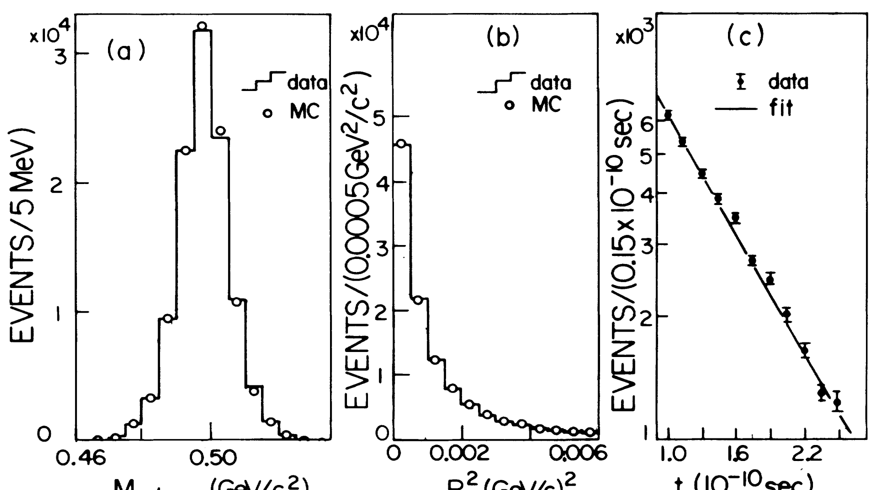

FIG. 2. (a) Histogram of invariant mass of $\pi^+\pi^-$ pairs, showing the K^0 peak. (b) Histogram of transverse momentum squared of reconstructed $K^0 \to \pi^+\pi^-$ events. In (a) and (b) the results of the Monte Carlo simulation of the experiment are also plotted. (c) Proper time histogram of data corrected for acceptance, for kaon momenta between 160 and 170 GeV/c, shown on a semilogarithmic plot. The fit to Eq. (2) with $\tau_s = 0.8920\times10^{-10}$ sec is also shown.

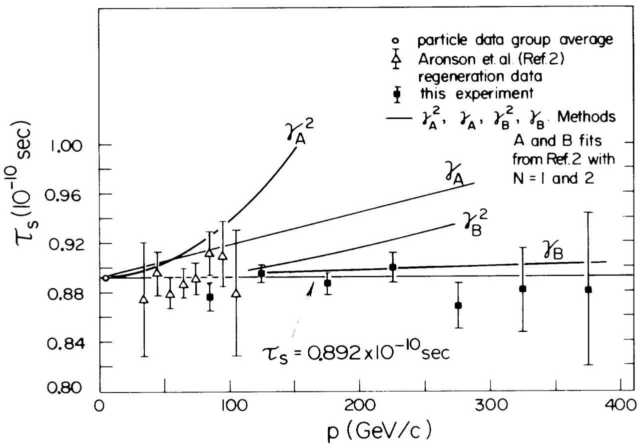

FIG. 3. Measurements of τ_s vs kaon momentum. The results of this experiment, the weighted averages of carbon and hydrogen regeneration results of Aronson *et al.* (Ref. 2), and the Particle Data Group compilation of low-energy experiments are shown. Fits from Ref. 2, discussed in the text, are also plotted.

as calculated from Eq. (2). The fit with Eq. (2) is sensitive only to τ_S. Figure 2(c) shows the acceptance-corrected data for $160 < p < 170$ GeV/c, plotted versus proper time.

ABCF performed their fits either for all of their data at once ("method A") or for independent momentum intervals ("method B"), and we have done the same. Our "method A" fit used 213967 events with $100 < p < 350$ GeV/c and $9.3 < z < 25.3$ m, and assumed that τ_S is independent of momentum. The result was $\tau_S = (0.8920 \pm 0.0044) \times 10^{-10}$ sec, in good agreement with the Particle Data Group (PDG) value[3] of $(0.8923 \pm 0.0022) \times 10^{-10}$ sec. The χ^2 was 822 for 799 degrees of freedom. Equation (2) with $\tau_S = 0.8920 \times 10^{-10}$ sec is plotted in Fig. 2(c). The good χ^2 indicates no detectable deviation from the hypothesis of momentum independence.

The statistical uncertainty is what is quoted above. We have investigated two sources of systematic uncertainty. First, backgrounds of non-$K_{\pi 2}$ decays are less than 0.1%, and their effect on τ_S is smaller yet. Second, we have estimated the uncertainty of the acceptance calculation by varying selected Monte Carlo input parameters within statistical errors. The acceptance calculation was most sensitive to the A hodoscope x position and the target x position. We changed these parameters and generated samples of events with statistics equal to the data, and analyzed them as if they were data to see their effect on τ_S. They contributed an uncertainty of $\pm 0.2\%$ and $\pm 0.1\%$, respectively. We investigated the effects on our final results of varying τ_S in the Monte Carlo program, and found them negligible. Adding all sources together in quadrature results in an estimate of the systematic uncertainty of $\pm 0.24\%$, or $\pm 0.0022 \times 10^{-10}$ sec.

TABLE I. K_S^0 lifetime results.

Momentum range (GeV/c)	Average acceptance (%)	Fit results (10^{-10} sec)
70–100	15.3	0.878 ± 0.010
100–150	33.6	0.896 ± 0.007
150–200	42.5	0.887 ± 0.008
200–250	39.7	0.901 ± 0.011
250–300	29.7	0.869 ± 0.018
300–350	19.4	0.883 ± 0.033
350–400	11.7	0.883 ± 0.06
100–350	35.3	0.892 ± 0.004

In a more sensitive test of τ_S momentum dependence, we binned our data in five 50-GeV/c-wide momentum bins from 100 to 350 GeV/c and fitted each bin independently. The result is shown in Fig. 3 and the numbers are given in Table I. Also shown in Fig. 3 is the Particle Data Group result (plotted at 5 GeV/c) and the weighted average of carbon and hydrogen regeneration "method B" fits of ABCF. We interpret the data of this figure as showing no evidence for a change of τ_S with momentum. Two additional points from our data are plotted in Fig. 3: one from 70–100 GeV/c, which has larger contributions from *CP* nonconservation, and one from 350–400 GeV/c, which has large statistical uncertainties.

For comparison Fig. 3 shows four fits made by ABCF to the hypothesis that

$$\tau_S = \tau_0 (1 + b^{(N)} \gamma^N),$$

where τ_0 is the value at zero momentum, $b^{(N)}$ is a fitted constant, $\gamma = p/m\beta$, and N is 1 or 2. They performed γ and γ^2 fits for both method A and method B. Their γ_A, γ_A^2, and γ_B^2 results, considered as hypotheses to explain our data, have χ^2 values of 1346, 108, and 29, respectively, for five degrees of freedom. Their γ_B fit, consistent with zero momentum dependence, has a χ^2 of 4.3 when compared with our data.

Their method-A and method-B fits disagree with each other, even for their data. As ABCF point out, the main difference between their fitting methods is the handling of correlations among the parameters. There are two kinds of correlations to consider: First, τ_S, η_{+-}, etc., might really change with momentum in a correlated way and, second, artificial correlations not present in nature may be introduced by the fitting program. Our data have better statistical precision and cover a broader range with which to search for momentum dependence of τ_S. We see no such momentum dependence. In a publication by Coupal *et al.*,[4] $|\eta_{+-}|$ was measured, at a mean K_L^0 momentum of 65 GeV/c, to be equal to the average of previous experiments that studied K_L^0 of momenta less than 10 GeV/c. This lends weight to the present conclusions.

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