Measurement of the τ-Lepton Lifetime

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We report a new and precise measurement of the lifetime of the τ lepton. The data were taken with the High Resolution Spectrometer at the SLAC e^+e^- colliding-beam facility PEP operating at 29 GeV center-of-mass energy. The flight distances of 1311 τ decays to three charged particles were measured with a four-layer tubular-cell vertex chamber in conjunction with the main drift chamber. The resulting lifetime of the τ lepton is $\tau_\tau = (2.99 \pm 0.15 \pm 0.10) \times 10^{-13}$ sec.

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All known properties of the τ lepton are consistent with its being the sequential lepton of the third generation.[1] Lepton universality leads to the prediction for the τ lifetime given by the relation[2]

$$\tau_\tau = \tau_\mu (m_\mu/m_\tau)^5 B_e = (2.86 \pm 0.06) \times 10^{-13}\,\text{sec},$$

where τ_μ and m_μ are the muon lifetime and mass, and the τ branching ratio to $e\nu\bar{\nu}$ is taken[3] as $B_e = 0.179 \pm 0.004$. A precise measurement of the τ lifetime thus allows an important check of e-μ-τ universality. Conversely, with the assumption of lepton universality, the τ lifetime provides an independent measurement of the electron branching ratio. Such a check is of particular interest in view of the discrepancy between the topological decay branching ratio of the τ to a single charged particle and the sum of the individual one-prong modes.[1,4]

The lifetime of the τ lepton has been measured by several groups working at e^+e^- storage rings.[5-9] We report in this Letter a new and very precise measurement of this fundamental quantity. The result is based on τ decays to three charged prongs, utilizing a determination of the separation between the three-track secondary vertex and the mean e^+e^- interaction point. Systematic error has been significantly reduced as a result of the superior tracking capabilities of the High Resolution Spectrometer, enhanced by a precision Mylar straw tube vertex chamber.[10] The vertex chamber consisted of two double layers of aluminized Mylar tubes arranged in coaxial cylinders with the axis along the beam direction.[11] The inner (outer) layer of the vertex chamber was approximately 0.09 (0.11) m from the interaction point. The chamber had a total of 352 tubes, each with an intrinsic resolution of 100 μm in the xy plane perpendicular to the beam direction. The charged-particle tracking was done in a 1.62-T field over a radial length from 0.09 to 1.03 m in the vertex chamber and the central drift chamber of the High Resolution Spectrometer. The outer drift chamber, which was located at a mean radius of 1.89 m, was not used in the track reconstruction to avoid alignment problems and scattering in the Čerenkov counters, which were located between the central and outer drift chambers.

This technique of measuring the decay distance requires that the production and decay points of the τ leptons be known. The decay vertex was determined for each event, while the production point was evaluated statistically. The average beam position was located for each data set (equivalent to about 100 nb^{-1} of luminosity) by combining the tracks in all of the wide-angle Bhabha events contained in that set. The resulting typical statistical error in the average beam position was 50 μm horizontally (x) and 20 μm vertically (y). The size of the beam was determined by use of the impact parameter distributions for the subset of Bhabha tracks within 100 mrad of the horizontal and vertical directions. The result of $\sigma_x = 385$ μm, $\sigma_y = 95$ μm included effects due to movements of the beam center during the run and small misalignments between the drift chambers, in addition to the true beam size.

The τ pair events used for this lifetime measurement were characterized by one τ decaying to one charged particle while the other τ decayed to three charged particles. These events were selected from a data sample with a total integrated luminosity of 200 pb^{-1} with criteria similar to those previously described.[12] These event selections yielded 2866 candidates. Several additional cuts were imposed to ensure good track quality and to remove systematic bias. In particular, each of the tracks on the three-prong side was required to have at least two hits in the vertex chamber. Events were removed if any of these tracks shared one or more hits in the vertex chamber with any other reconstructed track. This restriction eliminated the confusion within a single vertex-chamber cell which would result in a systematic bias toward a longer apparent lifetime. The additional cuts reduced the sample to 1852 events, with a background contamination estimated to be $(6.1 \pm 1.0)\%$, mainly (5.1%) due to misidentified multihadron events.[13]

For each event the three tracks were refitted subject to the constraint that each track traverse a common point. This least-squares fit was performed in the plane transverse to the beam line since the vertex chamber provided no information in the z direction. Events with a decay-vertex error along the τ flight direction of more than 1.5 mm were rejected. In addition, a χ^2 cut of 5 per degree of freedom was imposed on the vertex fit. This selection further reduced the sample to 1311 events. The most probable decay distance in the xy plane was then determined.[14] This distance was projected to three dimensions by use of an accurate determination of the τ polar angle derived from the combined three-prong momentum vector. The proper decay time and its error were calculated for each event with the radiatively corrected average τ-lepton momentum of 13.88 GeV/c. The distributions of the proper time and its error are shown in Figs. 1 and 2.

The lifetime of hadronic background events was also measured. The standard hadronic event sample was searched for events that satisfied the same selection criteria as the τ events. Similar track and vertex quality cuts were applied to the background events as were used in the selection of the signal events. The background events were distinguished from the signal events by imposition of a constraint that the mass of the three-prong jet exceed 2.2 GeV/c^2; the signal events possessed a jet mass of less than 1.6 GeV/c^2. A total of 61 such background events were obtained. The analysis procedure yielded a Gaussian decay-time distribution which was offset from zero by only $(0.01 \pm 0.24) \times 10^{-13}$ sec.

The best determination of the lifetime of the τ was obtained by fitting of the proper time distribution with a maximum likelihood technique. The probability density function was taken to be the convolution of an exponential decay function with characteristic lifetime τ_τ and a Gaussian resolution function with $\sigma = R\delta\tau$, where R is a scaling factor on the calculated error in the value of the proper lifetime $\delta\tau$. The effect of the background was included by addition of a simple Gaussian function with a weight of 6.1% displaced from zero lifetime by 0.01×10^{-13} sec. The background function was also convoluted with the experimental resolution function.

The scale factor R was needed since the single-track χ^2 distributions are broader than those predicted from the measured drift-chamber resolution. The latter was evaluated from a sample of very high-quality tracks and does not completely represent the normal data. The χ^2 per degree of freedom distribution for the τ decay tracks is displayed in Fig. 3. The dashed line, which is a good representation of the data, was obtained with a weighted mixture of tracks with two different resolution functions. A fraction of the tracks, F_1, was assigned the calculated error ($R_1 = 1.0$), and a second fraction, $F_2 = 1 - F_1$, was assigned an error scaled by R_2.[15] The maximum likelihood fit for the lifetime allowed these parameters to vary

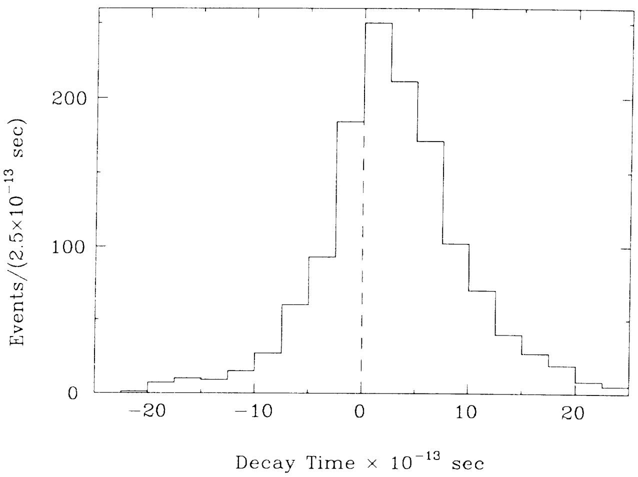

FIG. 1. Proper-time distribution for the τ-lepton decays.

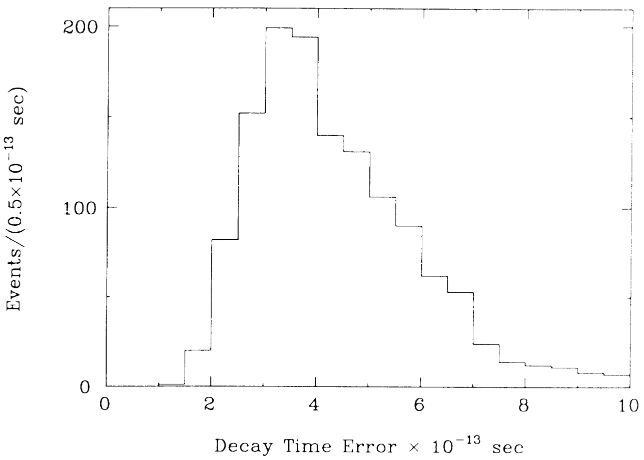

FIG. 2. The distribution of calculated error on the proper decay time of the τ lepton.

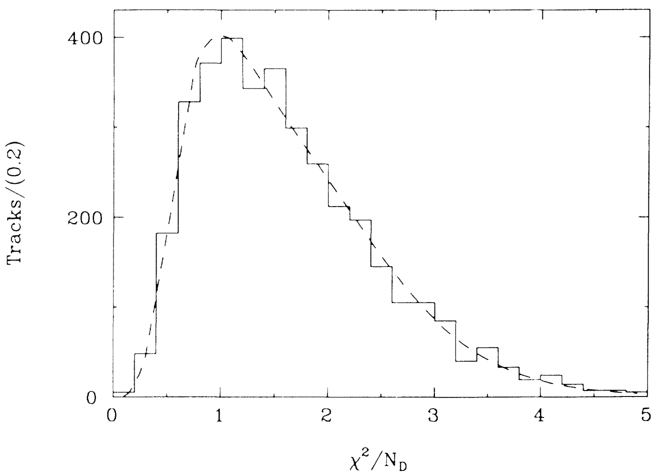

FIG. 3. The single-track χ^2 per degree of freedom distribution for the three-prong τ decay tracks used in the final data sample. The dashed curve, which is explained in the text, represents the best fit to these data.

subject to the combined constraints of the measured lifetime and single-track χ^2 distributions. This fit yielded a value for the lifetime of $(2.99 \pm 0.15) \times 10^{-13}$ sec, where the error indicated the statistical uncertainty. This result has been corrected for the spread of the τ-lepton momentum by variation of the τ momentum directly in the maximum likelihood fit, according to the expected radiative distribution. The combined fit resulted in the values $F_1 = 0.45 \pm 0.04$ and $R_2 = 1.50 \pm 0.03$. In order to study the sensitivity of this result to variations in the parameters F_1 and R_2, an alternative maximum likelihood fit was performed in which the values obtained from the fit to Fig. 3 were used to define the form of the overall resolution function. The result was $\tau_\tau = (3.03 \pm 0.15) \times 10^{-13}$ sec. Systematic errors are discussed below.

Monte Carlo studies were conducted to check that this analysis technique reproduced the assumed τ lifetime within the statistical uncertainties. Simulated τ pair events with a lifetime of 3.40×10^{-13} sec were generated and propagated through a full detector simulation program. The resulting events were then analyzed in a manner completely analogous to that performed on the data sample. After cuts the remaining 9204-event Monte Carlo sample gave a fitted lifetime of $(3.40 \pm 0.06) \times 10^{-13}$ sec, when the fit utilized constraints from both the measured lifetime and single-track χ^2 distributions. The combined fit resulted in the values $F_1 = 0.58 \pm 0.02$ and $R_2 = 1.45 \pm 0.01$. Other correlated choices of F_1 and R_2 might be made, for instance, by allowing them to vary freely in the lifetime fit. The range of values that we have explored exceeds the size of the statistical errors obtained by several fitting schemes. The fitted lifetime varied from $(3.33 \pm 0.06) \times 10^{-13}$ sec to $(3.50 \pm 0.06) \times 10^{-13}$ sec, depending on whether the track resolution parameters F_1 and R_2 were allowed to vary freely in the lifetime fit, or fixed at values determined by the single-track χ^2 distributions.[16] These results indicate reasonable agreement with the input lifetime value, despite a systematic uncertainty somewhat larger than the statistical error. Additional tests of similar analysis techniques using other Monte Carlo data samples have been carried out for charmed-meson decays, such as $D_s(F)^{\pm} \rightarrow \phi\pi^{\pm}$, with $\phi \rightarrow K^+K^-$.[17] In these studies it was confirmed that within statistics the fitted lifetimes agreed with the generated values for several samples with different assumed lifetimes. In particular, we observed no significant lifetime offset.

The systematic uncertainty was estimated to be 0.10×10^{-13} sec, on the basis of a variational study of the cuts and tracking errors. We considered several independent contributions and added them in quadrature to obtain this systematic error:

(i) Allowing for reasonable variation in the scaling of tracking errors yielded a contribution to the error in the lifetime of 0.08×10^{-13} sec. This uncertainty stemmed from the determination of the parameters F_1 and R_2 used to represent the overall experimental resolution function. These parameters are strongly correlated: The maximum likelihood fit yielded a stable value for the τ lifetime when the input parameters F_1 and R_2 were varied over a large range of the correlated values. However, varying these parameters by two standard deviations in a direction normal to that of their correlation gave an uncertainty in the lifetime of 0.06×10^{-13} sec. Furthermore, allowing these parameters to vary freely within the maximum likelihood fit caused a lifetime shift of only 0.04×10^{-13} sec. The Monte Carlo sample seemed to be more sensitive to these effects than the data. On the basis of this additional information, we have increased the estimate of the systematic error contribution in the lifetime to 0.08×10^{-13} sec.

(ii) Varying the background fraction by one standard deviation gave a systematic change of 0.03×10^{-13} sec. Independent variation of the background lifetime between zero and 1.0×10^{-13} sec yielded a similar lifetime uncertainty of 0.03×10^{-13} sec.

(iii) Variations in both of the cuts on the vertex χ^2 and path length error gave an overall contribution to the systematic error of 0.03×10^{-13} sec.

(iv) Finally, the beam-size uncertainty gave a contribution of 0.02×10^{-13} sec. Shifts in the average beam position were negligible since they effectively added in quadrature to a much larger decay length.

In conclusion, we have measured the τ-lepton lifetime to be

$$\tau_\tau = (2.99 \pm 0.15 \pm 0.10) \times 10^{-13} \text{ sec.}$$

This result agrees well with previous measurements and with lifetime calculations based on e-μ-τ universality.

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[13] For details see Ref. 12 and K. K. Gan, Ph.D. thesis, Purdue University, 1985 (unpublished).

[14] The most probable decay distance between the vertex and the average beam center is given by the formula

$$l=\frac{x_v B_{xx} t_x + y_v B_{yy} t_y - B_{xy}(x_v t_y + y_v t_x)}{B_{xx} t_x^2 + B_{yy} t_y^2 - 2B_{xy} t_x t_y},$$

where (x_v, y_v) is the vertex point, B is the matrix formed by taking the inverse of the sum of the error matrices associated with both the vertex point and the mean interaction point, and (t_x, t_y) is the unit tangent vector of the three-decay-track combination in the xy plane. More details can be found in Ref. 7; D. Amidei, Ph.D. thesis, University of California, Berkeley, 1984 (unpublished); R. Ong and K. Riles, MARK II/SLC Note No. 166, 1986 (unpublished).

[15] The fit to the track χ^2 distributions resulted in the values $F_1=0.39\pm0.03$ and $R_2=1.43\pm0.03$.

[16] For the simulated events it was necessary to refit the corresponding single-track χ^2 distributions since the observed resolution differed from that of the tracks in the experimental data sample. The fit to the track χ^2 distributions resulted in the values $F_1=0.66\pm0.01$ and $R_2=1.37\pm0.01$.

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