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Precise measurement of the lifetime of the tau lepton*

H. R. Band, M. Bosman,[a] T. Camporesi,[b] G. B. Chadwick, M. C. Delfino,[c] R. De Sangro, W. T. Ford, M. W. Gettner, G. P. Goderre,[d] G. L. Godfrey, D. E. Groom, R. B. Hurst, J. R. Johnson, T. L. Lavine, R. E. Leedy, I. Lippi,[e] T. Maruyama, R. L. Messner, L. J. Moss, F. Muller,[f] H. N. Nelson, I. Peruzzi, M. Piccolo, R. Prepost, J. Pyrlik, N. Qi, A. L. Read, Jr.,[g] D. M. Ritson, L. J. Rosenberg,[h] J. C. Sleeman, J. G. Smith, J. P. Venuti, P. G. Verdini, E. von Goeler, Roy Weinstein, D. E. Wiser, and R. W. Zdarko

(MAC Collaboration)

Department of Physics, University of Colorado, Boulder, Colorado 80309, and
I. N. F. N., Laboratori Nazionali di Frascati, Frascati, Italy, and
Department of Physics, University of Houston, Houston, Texas 77004, and
Department of Physics, Northeastern University, Boston, Massachusetts 02115, and
Department of Physics and Stanford Linear Accelerator Center,
Stanford University, Stanford, California 94305, and
Department of Physics, University of Utah, Salt Lake City, Utah 84112, and
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706

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ABSTRACT

Data accumulated with a high-precision vertex drift chamber operating in the PEP detector MAC are used for a precise measurement of the lifetime of the τ lepton. Results from a decay-length analysis of a sample in which one τ decays into one charged particle and the other to three charged particles are combined with those from an impact-parameter analysis of an independent sample of events that includes both one- and three-prong tau decays. We find $\tau_\tau = 0.309 \pm 0.019$ ps, in agreement with the prediction from the measured leptonic branching ratio and τ-μ universality.

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Measurements of the tau-lepton lifetime and leptonic branching fractions test lepton universality, the prediction of the standard electroweak theory that all leptons have the same coupling to the charged weak current. Certain grand unified theory models[1] predict the existence of massive neutral leptons which can mix with the known neutrinos. An observable conseqence of mixing with ν_τ would be a larger tau lifetime than that predicted by universality. Recent measurements of tau leptonic branching ratios[2] with a precision of $\sim 3\%$ permit more accurate tests if the τ lifetime can be measured with similar precision. The best published τ lifetime measurements[3,4] have an uncertainty of 15-20%. In this Letter we present a measurement of the τ lifetime with an uncertainty of 6%, obtained with the MAC detector operating at a center-of-mass energy of 29 GeV at the PEP storage ring of the Stanford Linear Accelerator Center. The data sample used in this measurement corresponds to an integrated luminosity of 94 pb^{-1} with a high-precision vertex drift chamber installed near the interaction point of the MAC detector.

Since a complete description of the MAC detector can be found elsewhere,[5] we describe in detail only the components crucial to the present measurement. The central drift chamber (CD) has ten cylindrical layers of wires, six of which are oriented at $\pm 3°$ to the beam axis, embedded in a 0.57-T, axial magnetic field. The radii of the first and last layers are 12 and 45 cm, respectively. A high-precision vertex drift chamber[6] (VC) with an inner radius of 4.6 cm, was installed within the CD by considerably reducing the beam-pipe radius and augmenting the radiation shielding. The VC consists of 324 thin-walled drift tubes arranged axially in three double layers. Typical spatial resolutions of 160 μm

(CD) and 50 μm (VC) provide an impact parameter resolution of 90 μm in the plane perpendicular to the beam, as measured with Bhabha scattering events. Multiple scattering in the beam pipe and VC walls (a total of 0.008 radiation lengths) typically adds 65 μm/p(GeV/c) to the impact parameter resolution.

Hexagonal barrel and planar end-cap electromagnetic and hadronic calorimeters surround the inner detectors, covering 98% of the full solid angle. The calorimeters are surrounded by drift chambers to detect muons. Scintillators, placed immediately inside the barrel hadron calorimeter and in the end caps, provide trigger and time-of-flight information.

The trigger for the experiment and the tau sample selection criteria have been described previously. The selection of events from the process $e^+e^- \rightarrow \tau^+\tau^-$ begins by dividing an event into two hemispheres with respect to the charged-particle thrust axis. Events are rejected if they do not satisfy $|\cos\theta_T| < 0.9$, where θ_T is the angle of the thrust axis with respect to the beam. Events are required to have a single charged track in one hemisphere and no more than three in the other, all of which must be separated from the isolated track by an angle of more than 120°. Two-track (1-1) events are rejected if both tracks are identified as muons or both as electrons. The total calorimetric energy is required to be greater than 6 GeV and the electromagnetic shower energy to be less than 23 GeV. The sphericity of the event is required to be greater than 0.05 and in four-track (1-3) events the charged-track (calorimetric) mass of the 3-prong hemisphere must be less than 2.0 (5.1) GeV/c^2. A variety of other cuts effectively reduce the background from all processes except $e^+e^- \rightarrow e^+e^-\tau^+\tau^-$ and $e^+e^- \rightarrow$ hadrons to negligible levels. Poorly measured events are removed by requiring at least two "quality" tracks which have: ≥ 3 VC hits, ≥ 7 CD hits, $p > 0.5$ GeV/c, and a satisfactory χ^2 for a fit to a vertex originating at the interaction point (primary vertex).[9] The selected sample contains 3788 events, of which 2409 have 1-1 topology.

The dominant backgrounds are estimated with the Monte Carlo programs of the Lund group[10] (hadronic) and Vermaseren *et al.*[11] ($ee\tau\tau$), processed through a detailed detector simulation.[5] The hadronic background is also estimated from a sample of hadronic data for which one hemisphere has three tracks and the other more than three. The amount of background in the samples is discussed below.

We form two subsamples to measure the tau lifetime. A sample of events with 1-3 topology is selected for a measurement of the decay length (DL) between the production point and the vertex of the 3-prong tau decay. In a second method, applicable also to events with 1-1 topology, we determine the lifetime from the impact parameters of the individual tracks.

The 590 events selected for the decay-length measurement satisfy the additional requirements that all four tracks are compatible with the primary vertex[9] and the 3-prong has at least two tracks with four or more VC hits (hits cannot be shared between tracks) and a net charge of ± 1. The 3-prong vertex is refit (omitting the opposing track and the beam constraint) to establish the decay point and its error ellipse. The decay length is the distance parallel to the 3-prong momentum vector that maximizes the likelihood for the production and decay points to lie within their respective error ellipses.[12] Projections of the vectors onto a plane perpendicular to the beam are used to exploit the precise tracking information in this view. The full decay length is then computed by dividing the projected length by $\sin\theta$, where θ is the polar angle of the 3-prong momentum vector.

The distribution of decay lengths is shown in Fig. 1 (in the figure and in the fit, we include only the 532 events having assigned DL error less than 3 mm and DL between -2 mm and $+4$ mm). The mean decay length is obtained from a maximum-likelihood fit to the data of a convolution of the decay exponential with a sum of Gaussian resolution functions having width parameters that come from the individual track reconstruction error matrices. Additional terms are included to account for backgrounds, which are estimated to be $(2.7\pm1.0)\%$, nearly equally divided between hadronic and $ee\tau\tau$ events. The result is $\langle DL\rangle = 777\pm61$ μm. A similar fit to Monte Carlo samples with a range of assumed lifetimes serves to calibrate the decay length to the lifetime. We estimate the systematic uncertainties in the lifetime from uncertainties in this calibration and the tracking resolution to be 3% and in the number and decay lengths of background events in the sample to be 1%. From the decay length-measurement we find $\tau_\tau = 0.316\pm0.026\pm0.010$ ps, where the first error is statistical and the second is systematic.

In the second method, all events in the sample can be used to determine the impact parameter (IP), in the plane perpendicular to the beam, of each track with respect to the estimated τ production point. This production point is calculated by taking the weighted average of the beam centroid, determined from Bhabha scattering events at frequent intervals, and information from the other tracks in the event.[13] In order not to dilute the result with tracks having little sensitivity, only "quality" tracks (see above) with an angle with respect to

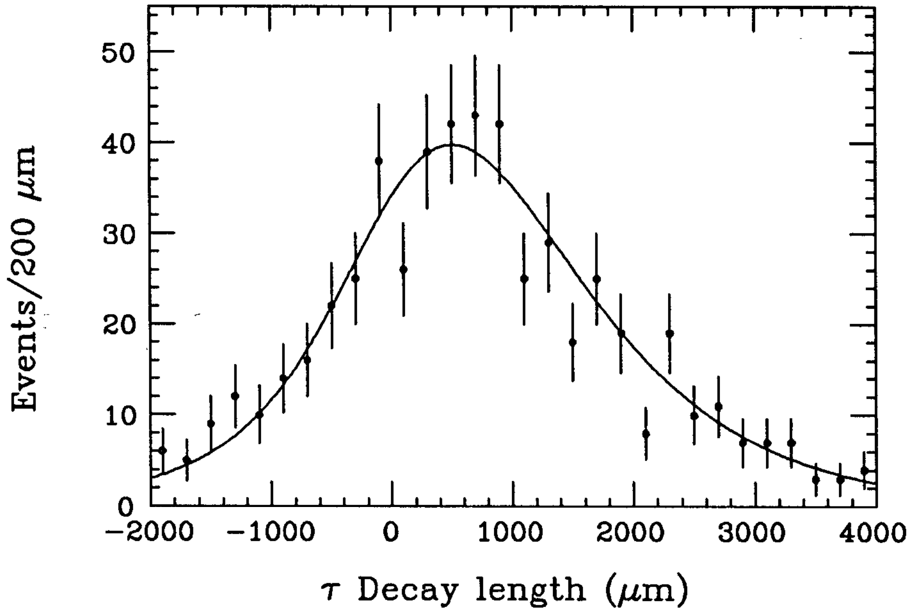

FIGURE 1. Distribution of measured 3-prong decay lengths for the 532 1-3 events in the decay-length sample. The curve is the result of the maximum-likelihood fit described in the text.

the thrust axis of more than 2.6° are included in the analysis. The sign of the impact parameter is taken to be positive (negative) when the track appears to travel forward (backward) relative to the apparent τ direction as estimated by the thrust axis. The average uncertainty in the impact parameter is 155 μm (270 μm) with (without) the improvement of the beam position from the other tracks in the event. Fig. 2a shows the impact parameter distributions for the 4065 tracks which remain after the events used in the DL analysis, discussed above, are excluded. We estimate that $(5.1 \pm 1.6)\%$ of these tracks are due to backgrounds, half from hadronic events and the rest from $ee\tau\tau$ and other events.[7]

The DL measurement described above makes no use of the lifetime information contained in the impact parameter of the isolated track opposite the 3-prong vertex. To exploit this information, for each event in the DL sample, we

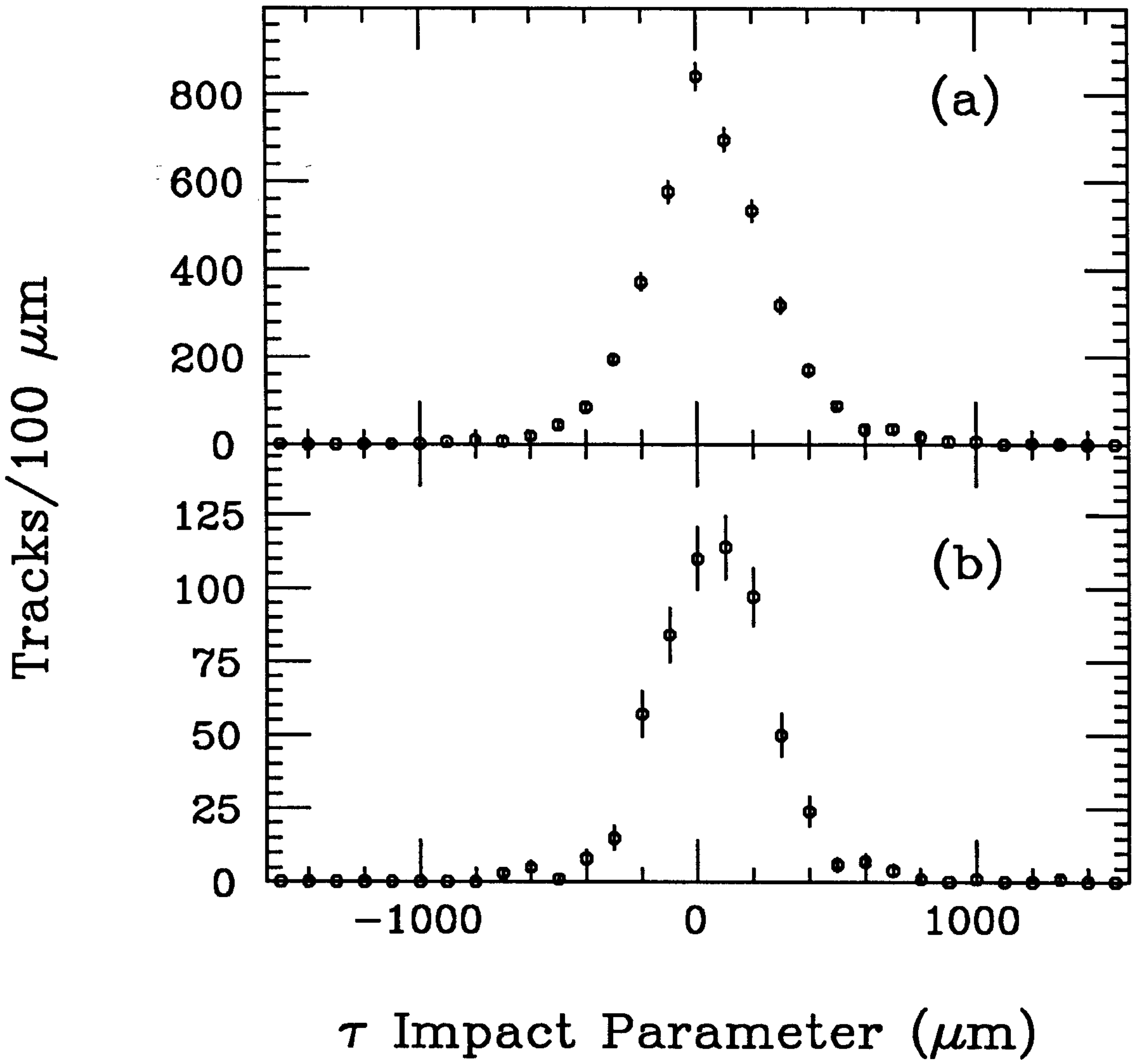

FIGURE 2. Impact parameter distributions for: a) the 4065 tracks from the IP sample with the events used in the decay-length method removed, and b) the isolated tracks from the 590 events in the DL sample.

project the fitted 3-prong momentum vector to the beam ellipse to find the most probable production point and its uncertainty.[14] The impact parameter of the isolated track is then measured with respect to this point. The IP so defined is independent of the decay length measured above since the 3-prong vertex fit contributes here through the projection component *transverse* to the line of flight. The resulting distribution is shown in Fig. 2b.

The trimmed-mean technique[15] is used to determine the τ lifetime from the impact-parameter distributions. A fraction of the tracks are removed symmetrically from the tails of the distributions. The best statistical precision is achieved when 10% of the tracks are removed. We find the trimmed means of the full IP sample and the samples shown in Figs. 2a and 2b to be 51.0 ± 2.9 μm, 39.6 ± 3.3 μm, and 58.5 ± 8.3 μm, respectively. The second result is smaller since about one-half of the 1-3 events have been removed (1-3 events have a considerably larger mean impact parameter than 1-1 events). We extract a value of the τ lifetime by comparing these results with results from complete detector Monte Carlo (MC) simulations for a range of τ lifetimes. Corrections are made for the number of 1-1, 1-2, and 1-3 events actually observed in the data and the expected amount of backgrounds. The systematic error for the impact parameter measurement, estimated to be 4.8%, is composed of the following uncertainties: calibration of lifetime *vs* IP (3.5%), biases not modeled by the MC (2.0%), backgrounds (1.6%), relative amounts of various event topologies (1.7%), rejection of tracks at a small angle to the thrust axis (1.0%), and triming procedure (0.6%). From the trimmed mean results given above, we find $\tau_\tau = 0.297 \pm 0.026 \pm 0.014$ ps and $0.323 \pm 0.053 \pm 0.018$ ps for the DL excluded and 1-prong DL samples, respectively. All tau lifetime results are summarized in Table 1. As checks, especially of systematic errors not common to the two analysis methods, we also include in Table 1 results of the IP method applied to the full and the DL samples.

TABLE 1. Summary of tau lifetime measurements from the various samples and techniques discussed in the text. Both statistical and systematic errors are included except as noted. The two lines below the combined result represent checks which are not included in the final measurement.

Sample	Method	τ_τ (ps)
DL	3-prong DL	$0.316 \pm 0.026 \pm 0.010$
DL	1-prong IP	$0.323 \pm 0.053 \pm 0.018$
DL excluded	IP	$0.297 \pm 0.026 \pm 0.014$
Combined	-	0.309 ± 0.019
Full	IP	0.307 ± 0.019 (stat. only)
DL	IP	0.327 ± 0.022 (stat. only)

The results of the two methods used to determine the lifetime of the τ lepton are in good agreement with each other. When the values for the DL sample are combined with those of the IP sample from which the DL events have been removed, and all statistical and systematic errors combined in quadrature, we find τ_τ =0.309 $\pm$ 0.019 ps. This result is in agreement with our previous result from an independent sample[4] and with the world-average value, τ_τ =0.330$\pm$0.035

ps.[16] From τ-μ universality as expected in the standard electroweak theory, the τ and μ lifetimes are related by

$$\tau_\tau = B_e (m_\mu / m_\tau)^5 \tau_\mu$$

where B_e is the branching fraction for the decay $\tau \to \nu_\tau e \bar{\nu}_e$. With $B_e = 0.179 \pm 0.004$,[17] the above formula predicts $\tau_\tau = 0.286 \pm 0.006$ ps. Thus our results are in agreement with the universality predictions of the standard electroweak theory. From the ratio of the measured and predicted τ lifetimes, 1.08 ± 0.065, mixing of the tau neutrino with a massive neutral lepton[1] must be less than 21% at the 98% confidence level (2σ).

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(a) Present address: Max-Planck-Institut, Munich, Federal Republic of Germany.

(b) Present Address: CERN, Geneva, Switzerland.

(c) Present address: Universidad Autónoma de Barcelona, Barcelona, Spain.

(d) Present Address: Texas Accelerator Center, The Woodlands, Texas 77380.

(e) Permanent address: Physics Department, University of Padua, Padua, Italy.

(f) Permanent address: CERN, Geneva, Switzerland.

(g) Present address: University of Oslo, N-0316 Oslo 3, Norway.

(h) Present Address: Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637.

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