Measurement of the τ Lifetime

G. J. Feldman, G. H. Trilling, G. S. Abrams, D. Amidei, A. Bäcker,[a] C. A. Blocker, A. Blondel,[b] A. M. Boyarski, M. Breidenbach, D. L. Burke, W. Chinowsky, M. W. Coles,[c] G. von Dardel,[d] W. E. Dieterle, J. B. Dillon, J. Dorenbosch,[e] J. M. Dorfan, M. W. Eaton, M. E. B. Franklin, G. Gidal, L. Gladney, G. Goldhaber, L. J. Golding, G. Hanson, R. J. Hollebeek, W. R. Innes, J. A. Jaros, A. D. Johnson, J. A. Kadyk, A. J. Lankford, R. R. Larsen, B. LeClaire, M. Levi, N. Lockyer, B. Löhr,[f] V. Lüth, C. Matteuzzi, M. E. Nelson, J. F. Patrick, M. L. Perl, B. Richter, A. Roussarie,[g] D. L. Scharre, H. Schellman, D. Schlatter, R. F. Schwitters, J. L. Siegrist, J. Strait, R. A. Vidal, I. Videau,[b] Y. Wang,[h] J. M. Weiss, M. Werlen,[i] C. Zaiser, and G. Zhao[h]

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, and Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720, and Department of Physics, Harvard University, Cambridge, Massachusetts 02138

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With use of three-prong τ decays observed by the Mark II detector at the Stanford Linear Accelerator Center (PEP), the τ lifetime is measured to be $(4.6 \pm 1.9) \times 10^{-13}$ sec.

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A measurement of the τ-lepton lifetime provides a direct determination of the strength of the coupling of the τ to the charged weak current. In this Letter we present the first measurement of the τ lifetime which has a statistically significant nonzero value.[1]

The data for this measurement were collected by the Mark II detector at the e^+e^- storage ring PEP located at the Stanford Linear Accelerator Center. The data sample contains approximately 1500 $\tau^+\tau^-$ pairs produced at a center-of-mass energy ($E_{\text{c.m.}}$) of 29 GeV, corresponding to an integrated luminosity of 15 400 events/nb.

The Mark II detector at PEP is substantially the same as it was at SPEAR.[2] The only change that is significant for this measurement is the addition of two small hemicylindrical drift chambers around the beam pipe. Since the main purpose for adding these chambers was to improve the detector trigger, they are referred to collectively as the trigger chamber. Each hemicylinder contains four layers of 32 sense wires strung parallel to the incident e^+ and e^- beams. The trigger chamber is 86 cm long; the inner and outer sense-wire layers are at radii of 16.6 and 20.2 cm, respectively. The main drift chamber has sixteen cylindrical layers of sense wires at radii between 41 and 145 cm. Six layers are parallel to the incident beams and the other ten are $\pm 3°$ relative to the incident beams. Both the trigger chamber and the main drift chamber have inherent resolution of about 0.2 mm at each layer; for this measurement we analyzed the data as if the trigger chamber had a resolution of 0.3 mm to allow for possible small misalignments among the three chambers.

Both the trigger chamber and main drift chamber reside in a uniform 4.6-kG axial magnetic field. The rms momentum resolution of the trigger-chamber–drift-chamber combination, measured on 14.5 GeV/c muons, is constrained to pass through the luminous region. It increases to $0.008p^2$ if, as in this measurement, the constraint cannot be made. The addition of the trigger chamber improved the resolution for locating the τ vertex by between 30% and 50% over what it would have been with only the main drift chamber.

To measure the τ lifetime we reconstructed the vertex of three-prong τ decays and calculated the flight distance between the center of the luminous region (IP) and the vertex projected along the τ momentum. Since the expected mean τ flight distance (0.7 mm) is smaller than our resolution, this measurement requires statistical averaging and a good control of systematic errors to achieve the necessary precision.

The τ leptons that we wished to study were pair produced in the reaction

$$e^+e^- \to \tau^+\tau^- \quad (1)$$

and thus had an energy equal to the energy of the incident beams, in this case 14.5 GeV. To identify events from Reaction (1), we first selected events with either four or six charged particles. Each event was divided into two jets by the plane normal to the sphericity axis.[3] We required that at least one jet have exactly three charged particles with net charge ±1.

Four potential sources of background events in this data sample are beam-gas interactions; two-photon τ pair production,

$$e^+e^- \to e^+e^-\tau^+\tau^-; \tag{2}$$

hadron production,

$$e^+e^- \to \text{hadrons}; \tag{3}$$

and radiative Bhabha scattering,

$$e^+e^- \to e^+e^-\gamma \atop \quad\quad\quad\;\; \llcorner\!\to e^+e^-, \tag{4}$$

where the photon conversion either was internal or occurred in the 0.09 radiation length of material between the IP and the main drift chamber. To reduce backgrounds from beam-gas interactions and two-photon τ production, we required that the visible energy in charged particles be greater than $0.125E_{\text{c.m.}}$ and that either there be an electron or muon identified in the event or the visible energy in all particles be greater than $0.25E_{\text{c.m.}}$ To reduce backgrounds from hadron production we required the visible invariant mass of each jet to be less than 1.6 GeV/c^2 calculated from the charged particles and less than 1.8 GeV/c^2 calculated from all detected particles. Finally, to reduce background from radiative Bhabha scattering, we required the invariant mass of each three-prong jet calculated assuming that each prong is an electron to be greater than 0.3 GeV/c^2. We also required the total energy measured by either the tracking system or the lead-liquid-argon calorimeters to be less than $0.9E_{\text{c.m.}}$.

After these cuts, 284 events containing 306 three-prong τ decays remained. The number of these events and their properties, such as total visible energies, transverse momenta between the two jets, jet masses, and the ratio of four- to six-prong events, are all consistent with the events coming entirely from Reaction (1). We will estimate the number of residual background events in the final data sample later in this Letter.

From this point on in the analysis, each three-prong τ decay was treated as an independent event. To reduce the probability that any of the tracks in an event scattered or were mismeasured, we applied the following additional cuts: Each track was required to have signals from at least ten drift-chamber layers, a χ^2 from a fit to its trajectory of less than 40, a distance of closest approach to the IP transverse to its trajectory of less than 5 mm,[4] and a measured momentum of greater than 500 MeV/c. We also required the three tracks from a single decay to appear to originate from a common point along the direction of the incident beams to within 5 cm. These cuts left 126 three-prong τ decays.

We found a vertex position for each of the remaining decays by varying the parameters of the particle trajectories in a least-squares manner so that the three tracks intersected at a common point. We eliminated eight events because the χ^2 of the vertex fit was greater than 15 for three degrees of freedom. An uncertainty in the position of the vertex along the τ direction of flight was calculated for each event and is displayed in Fig. 1.[5] For future use, the data are divided into two data sets, one with vertex uncertainties less than 4 mm, and the other with vertex uncertainties between 4 and 8 mm. The sixteen events with vertex uncertainties greater than 8 mm contain negligible information on the τ lifetime and are not used any further.

The τ flight distance was calculated as the distance between the vertex and the IP projected on the direction of the τ momentum. The location of the IP was determined by measuring the intersection point of Bhabha scattering events in large blocks of experimental runs. We found that its location was quite stable within a block of runs. The rms beam spreads were measured to be 0.30 mm in the vertical direction and 0.76 mm in the horizontal direction; these values are dominated by experimental resolution and the physical size of the beam, respectively.

Figure 2 shows the τ flight distance for (a) all data with vertex uncertainties less than 8 mm and for (b) the higher-resolution data set alone. Evidence for a nonzero τ lifetime can be seen at this point. In the full data sample there are 35 events with negative flight distances and 67 events with positive flight distances. In the ab-

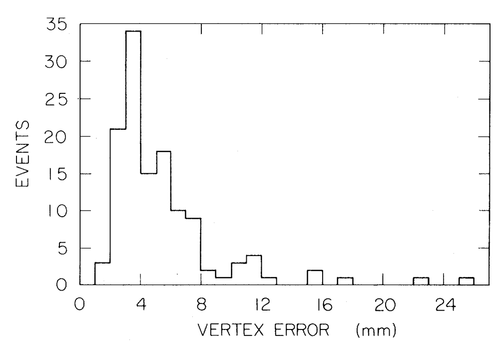

FIG. 1. Distribution of vertex uncertainties in the direction of the τ momentum.

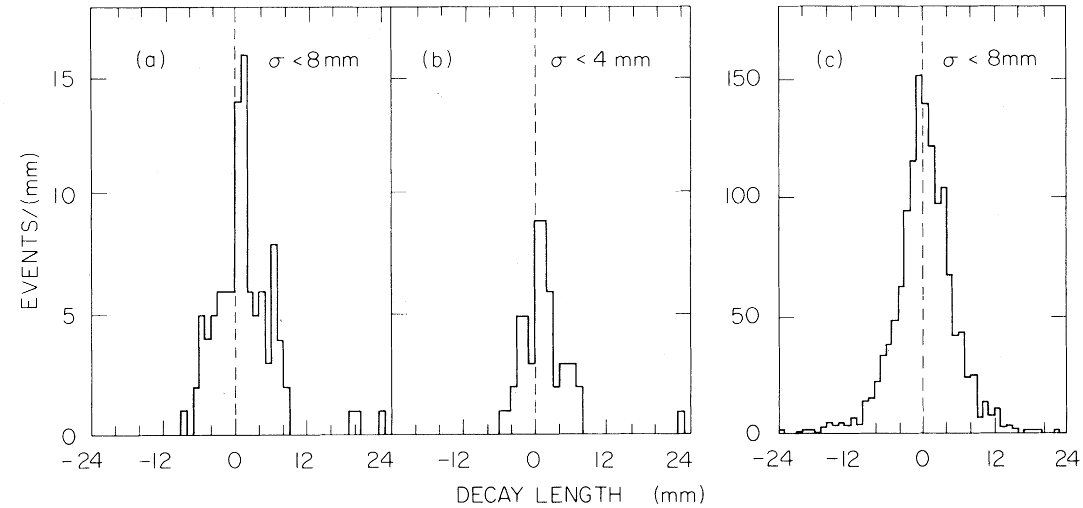

FIG. 2. Flight-distance distributions for τ events with vertex uncertainties less than (a) 8 mm and (b) 4 mm, and (c) for fake τ's made from hadronic events.

sence of systematic effects, the probability of a distribution this asymmetric occurring for a zero τ lifetime is about 0.2%.

To convert the distributions in Fig. 2 to a most probable mean flight distance, we performed a maximum-likelihood fit by the convolution of the flight-distance spectrum from a Monte Carlo simulation generated with zero τ lifetime and an exponential decay distribution. The Monte Carlo distribution was derived from a simulation which generated fake raw data. These data were then analyzed by the same analysis programs used to analyze the real data. The simulation included all important effects such as Coulomb and nuclear scattering.[6] The two data sets were fitted simultaneously with a common mean flight distance. The result for the mean flight distance is 1.07 $\pm$ 0.37 mm, where the error reflects statistical uncertainties only.

To check for biases in the vertexing and fitting procedures, we generated Monte Carlo simulations for the expected τ lifetime and for 4 times the expected τ lifetime, and analyzed them as if they were data. In both cases the analysis yielded the input mean flight distance within the statistical errors (less than 0.1 mm). To verify that the Monte Carlo programs can accurately simulate data, we created fake τ decays out of hadronic events. The fake decays were created by selecting the three most energetic tracks within a jet and analyzing them as if they were a τ decay. The fake τ's were required to have energy to mass ratios of greater than 5, so that they would resemble real τ's as closely as possible. The flight-distance distribution for the fake τ's is shown in Fig. 2(c). The resulting mean flight distance was 0.45 ± 0.11 mm compared to a Monte Carlo simulation result of 0.34 ± 0.11 mm. When the Monte Carlo simulation was run with zero K_S and D lifetimes, the resulting mean flight distance was 0.11 ± 0.13 mm. From these calculations we conclude that the Monte Carlo simulation agrees with measurements on the data to within 0.1 to 0.2 mm, and that it is likely that a substantial part of the positive mean flight distance seen in the hadronic data comes from the decay of short-lived particles.

The cylindrical symmetry of the detector eliminated many sources of systematic error. For example, a shift in the position of the IP would not create a net effect in the mean flight distance but would only increase the width of the distribution. For this reason, we made small global adjustments in the tracking to compensate for chamber misalignments so that there was no azimuthal angle dependence to the apparent IP location.

As a result of these and other studies of the magnitude of possible systematic errors, we estimate the uncertainty in the mean flight distance due to systematic effects to be 0.3 mm.

Backgrounds from beam-gas interactions and radiative Bhabha scattering, Reaction (4), were shown to be negligible, the former by an investigation of the vertex distribution along the direction of the incident beams, and the latter by relaxing the cuts against that process. From Monte Carlo simulations we estimated that the contamination from two-photon τ production, Reaction (2), was 2.5 events, and that the contamination from hadronic events, Reaction (3), was 5 events. These backgrounds require an upward correction of 4% in the mean flight distance.

Making this correction and combining the statistical and systematic errors in quadrature, we obtain a τ lifetime of

$$\tau_\tau = (4.6 \pm 1.9) \times 10^{-13} \text{ sec.} \qquad (5)$$

If the τ couples to the charged weak current with the same strength as the μ, then the τ lifetime will be

$$\tau_\tau = (m_\mu/m_\tau)^5 \tau_\mu B_e = (2.8 \pm 0.2) \times 10^{-13} \text{ sec,} \quad (6)$$

where B_e is the branching fraction for $\tau \to e\nu\bar{\nu}$, 0.176 ± 0.016.[7] Thus our result indicates that at the 1-standard-deviation level the τ coupling to the weak charged current is 0.66 to 1.02 times the expected value from τ-μ universality.

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[a]Present address: Universität Siegen, D-5900 Siegen 21, Federal Republic of Germany.

[b]Present address: Laboratoire de Physique Nucléaire et Hautes Energies, Ecole Polytechnique, F-91128 Palaiseau, France.

[c]Present address: Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213.

[d]Present address: University of Lund, S-22362 Lund, Sweden.

[e]Present address: CERN, CH-1211 Geneva 23, Switzerland.

[f]Present address: Universität Bonn, D-5300 Bonn, Federal Republic of Germany.

[g]Present address: Centre d'Etudes Nucléaires de Saclay, F-91190 Gif-sur-Yvette, France.

[h]Permanent address: Institute of High Energy Physics, Academia Sinica, Beijing, People's Republic of China.

[i]Present address: Université de Genève, CH-1211 Geneva 23, Switzerland.

[1]The TASSO experiment at PETRA has published a value for the τ lifetime of $(1.6 \pm 7.2) \times 10^{-13}$ sec corresponding to an upper limit of 14×10^{-13} sec at the 95% confidence level [R. Brandelik *et al.*, Phys. Lett. 92B, 199 (1980)]. Recently, the same experiment has reported an improved measurement of $(-0.25 \pm 3.5) \times 10^{-13}$ sec corresponding to an upper limit of 5.7×10^{-13} sec at the 95% confidence level [J. G. Branson, in Proceedings of the 1981 International Symposium on Lepton and Photon Interactions at High Energy, Bonn, Germany, 24–29 August 1981 (to be published)].

[2]R. H. Schindler *et al.*, Phys. Rev. D 24, 78 (1981), and references therein.

[3]G. Hanson *et al.*, Phys. Rev. Lett. 35, 1609 (1975).

[4]A τ decay with the expected lifetime will typically contribute only 0.1 mm to this quantity. Thus, this cut does not bias the lifetime measurement. Any substantial biases that are introduced by any of the selection procedures will be revealed by Monte Carlo simulations to be discussed later.

[5]Quantities such as the uncertainty in the vertex position and the flight path are measured in the plane perpendicular to the incident beams and scaled to three dimensions by multiplying by the ratio of the total momentum to the transverse momentum.

[6]The three events near +2 cm in Fig. 2(a) have a negligible effect on the fit because the fitting function is dominated by scattering in that region and is relatively flat.

[7]C. A. Blocker *et al.*, Stanford Linear Accelerator Center Report No. SLAC-PUB-2820, 1981 (unpublished).