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Measurement of the τ Lifetime*

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1. Introduction. If the tau lepton couples to the charged weak current with universal strength, its lifetime can be expressed in terms of the muon's lifetime, the ratio of the masses of the muon and the tau, and the tau's branching ratio[1] into $e\bar{\nu}_e\nu_\tau$ as

$$\tau_\tau = \tau_\mu \left(\frac{m_\mu}{m_\tau}\right)^5 B(\tau \to e\bar{\nu}_e\nu_\tau) = 2.8 \pm 0.2 \times 10^{-13} \text{ s.}$$

This paper describes the measurement of the tau lifetime made by the Mark II collaboration, using a new high precision drift chamber in conjunction with the Mark II detector at PEP. The results of other tau lifetime measurements are summarized.

2. Method. Tau leptons are pair-produced in e^+e^- annihilations, so each tau has the known beam energy. Thus we can measure the lifetime by determining the average decay length of the taus; at PEP energies, $E_{cm} = 29$ GeV, it is expected to be about 700 μ. The decay length can be measured when the tau decays in the three-charged-prong topology. It is simply the distance between the production point, i.e. the beam position, and the position of the decay vertex. This same technique has been exploited by several PEP and PETRA experiments.[2-5]

3. Apparatus. The measurement was performed with the Mark II vertex detector[6] in conjunction with the main drift chamber. The vertex detector is a high precision drift chamber designed to measure tracks as accurately as possible in the vicinity of the interaction point. The chamber captures a Beryllium beam pipe which is 0.6% of a radiation length thick. The chamber has seven axial layers in all, four just beyond the beam pipe about 12 cm from the beamline, and three additional layers at about 30 cm. The measurement accuracy is about 100 μ per layer. In practice, tracks which have been extrapolated to the interaction point are measured with 100 μ accuracy.

4. Event Selection. We select events in which (at least) one of the taus has decayed in the three-charged prong topology. Tau production at PEP/PETRA energies is distinctive: low multiplicity, low mass, back-to-back jets are produced, which are easily distinguished from higher multiplicity hadron production. We require the total charge to be zero and the three particle invariant mass to be in the range $0.7 < m_{3\pi} < 1.5$ GeV/c^2. To reject tau pairs produced by two-photon processes, we further require the total energy in the event to be at least a fourth the center of mass energy and the three-pion energy to exceed 3 GeV. We require all three of the tracks be well-measured in both the main drift chamber and the vertex detector.

5. Decay Length. The decay length is determined once we have measured the beam position, the decay vertex position, and the tau direction.

The rms beam size at PEP is 500 μ horizontally and about 50 μ vertically. The average beam position is remarkably stable from one fill to the next. Over the course of the entire experiment the horizontal beam position varied less than 2 mm and the vertical beam position, 0.5 mm. We measured it by finding the average intersection point for an ensemble of well-measured tracks. As a cross check, we have compared this determination of the beam position to the vertex position

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measured in hadronic events. Fig. 1 shows that these methods agree. The width of the Δx distribution is consistent with the known beam size, and the width of the Δy distribution is consistent with our vertex resolution. This demonstrates that the beams are stable.

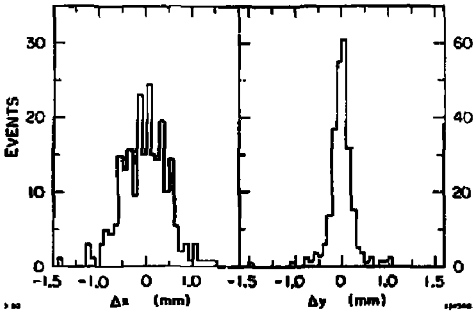

Fig. 1 : Horizontal and vertical hadronic vertex positions relative to the beam position. Only those runs with tau decays are shown.

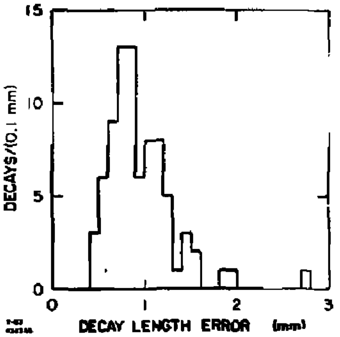

Fig. 2 : Calculated error in the decay length.

The decay vertex position and its error ellipse are determined from the three pion trajectories and their associated errors with a chi-square minimization procedure. We exclude events with a vertex chi-squared per degree of freedom greater than 6. The best estimate for the projected decay length is then given in terms of the decay vertex position relative to the beam position (x_v, y_v), the sum of the beam and vertex error matrices (σ_{ij}), and the τ direction cosines (t_x, t_y) by the following expression:

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

The tau direction is accurately approximated by the direction of the 3π system. Then the decay length is

$$\ell = \frac{|\vec{p}_{3\pi}|}{p^z_{3\pi}}\,\ell_p \quad ,$$

where $\vec{p}_{3\pi}$ is the total momentum of the three pion system.

Figure 2 shows the calculated error in the decay length, which depends on the opening angles and orientation of the decay. In contrast to previous experiments, the average uncertainty in the decay length is comparable to, not five to ten times greater than, the expected decay length. Consequently, the statistical power of the experiment is improved by roughly this same factor, and the measurement bias is significantly reduced.

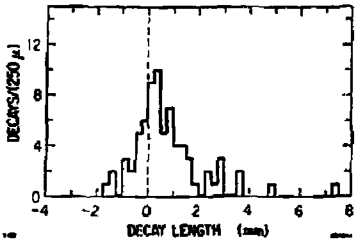

Fig. 3 : Measured decay lengths.

The measured decay lengths are shown in Figure 3, where we have included only those events with decay length errors less than 1.5 mm. The mean of the distribution is obviously positive and its shape is asymmetric. We fit the distribution with a maximum likelihood technique which takes the decay length error into account event-by-event. The fitting function is the convolution of the gaussian decay length error and an exponential decay distribution. We find that the average decay length is 710 ± 120 μ.

6. Checks and Corrections. We have checked our tracking, vertexing, and fitting programs with simulated data generated by Monte Carlo techniques. Roughly 1000 decays were generated for each of three lifetimes, $\tau_\tau = 0$, $\tau_\tau = 2.8 \times 10^{-13}$ s, and $\tau_\tau = 5.6 \times 10^{-13}$ s; they were then analyzed with the same programs used for actual data analysis. Table I summarizes the average decay lengths generated for each of the three lifetimes, and the decay length determined by fitting the "measured" decay length distribution. This demonstrates that our analysis technique is accurate.

Table I
Monte Carlo Simulation

Lifetime (10^{-13} s)	Average Decay Length Generated (μ)	Average Decay Length Fit (μ)
0	0	45 ± 25
2.8	644	605 ± 35
5.6	1338	1240 ± 50

We performed an additional check by analyzing pseudo-tau decays in hadronic events. Three particle combinations were chosen in hadronic events to mimic the properties of the three pion tau decays as accurately as possible. The average "decay length" for these combinations was 250 ± 40 μ; our hadron Monte Carlo events gave a decay length of 275 ± 50 μ. The presence of charm decays explains the finite decay length, and the Monte Carlo correctly simulates the data.

We studied systematic effects by re-analyzing the data with different assumptions about the beam position, beam width, resolution, and fitting function. The observed variations lead us to assign a systematic error of ± 150 μ to the decay length.

Using a Monte Carlo calculation, we estimate that 10% of our tau candidates are hadrons. This leads to a + 50 μ correction in the average decay length. Initial state radiation lowers the average tau energy from its nominal 14.5 GeV to 13.8 GeV.

Incorporating both these corrections, we find $\tau_\tau = 3.31 \pm .57 \pm .60 \times 10^{-13}$ s, where the first error is the statistical error, and the second is the systematic. This value is consistent with theoretical expectation. Our measurement is compared to the other measurements which have appeared in the literature or were presented to this conference in Table II. The number of decays studied and the average decay length error are also shown for comparison. All the experiments are consistent with the expected lifetime. The present experiment confirms that the tau couples to the charged weak current with universal strength within the 10% statistical and systematic errors.

Table II

Experiment	Number of Decays	Average Decay Length Error (mm)	τ_τ (10^{-13} s)
TASSO[2]	599	10	0.8 ± 2.2
MARK II[3]	126	4	4.6 ± 1.9
MAC[4]	280	4	$4.1 \pm 1.2 \pm 1.1$
CELLO[5]	78	6	$4.7 \pm^{3.9}_{2.9}$
MARK II Vertex Detector	71	0.9	$3.31 \pm .57 \pm .60$

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