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LIFETIME MEASUREMENTS AND TAU PHYSICS AT PEP*

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ABSTRACT

Recent updates on the measurements of the τ and D^0 lifetimes by the Mark II Collaboration and on measurements of the τ and B – hadron lifetimes by the MAC Collaboration are presented. A new determination of an upper limit for the tau neutrino mass by the Mark II Collaboration and a recent measurement of Cabibbo-suppressed tau decay branching ratios from the DELCO Collaboration are also presented.

INTRODUCTION

Studies of the semi-leptonic branching ratios and the lifetimes of weakly decaying particles provide unique tests of the standard theory of weak interactions. Past measurements of these quantities for the heavy lepton, τ, and for charm and bottom hadrons indicate that our understanding of weak interactions is nearly complete. However, new measurements of high accuracy are necessary to test the correctness of alternative theoretical models[1] and to provide experimental values for fundamental weak-interaction parameters which are not well-known and cannot be predicted from the standard theory.

Electron-positron storage rings such as PEP provide suitable, and in cases such as a probe of the ν_τ mass, unique laboratories for producing such measurements. Charm and bottom hadrons and heavy leptons are copiously produced and easily distinguished from the backgrounds due to light quarks and processes other than one-photon annihilation. This paper will first focus on new measurements of the τ, D^0 , and B hadron lifetimes from the PEP experiments. A new upper bound on the ν_τ mass and a high-accuracy measurement of branching ratios for Cabibbo-suppressed τ decays will follow. Since no discussion of the PEP detectors will be given here, the reader is referred to Ref. 2 for details on the hardware for each experiment.

THE MARK II MEASUREMENT OF THE τ LIFETIME

The Mark II Collaboration has made a precise measurement of the τ lepton lifetime by using a high-precision drift chamber, called the vertex detector, which is situated inside the main Mark II drift chamber. A brief description of the vertex detector and its performance is given in Ref. 3.

A clean sample of τ events was made by selecting events which had either a 1+3 or 3+3 topology (i.e. have 1 or 3 tracks recoiling against 3 tracks pointing

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into the opposite hemisphere) and energy and momentum properties characteristic of τ decays. Specifically, events were chosen if they had 4 or 6 charged tracks with 0 net charge and total energy between 5 and 26 GeV. The lower limit on the total energy rejected τ pairs produced from 2-photon collisions while the upper limit rejected radiative Bhabha and muon pairs which had converted photons. Each event was divided into two jets by a plane perpendicular to the thrust axis. Events were rejected unless one of the jets contained exactly three prongs which had an invariant mass between 0.7 and 1.5 GeV/c^2 and energy between 3 and 15 GeV. Furthermore, all tracks in one jet were required to be more than 120° from all tracks in the opposite jet. All tracks were required to be well-measured in both the vertex detector and main drift chamber. Monte Carlo calculations were used to estimate backgrounds in the final sample of 4% from low-multiplicity hadronic events and 3% from two-photon produced τ pairs.

The decay length for taus decaying into 3 prongs was determined by estimating the most probable distance, in the plane perpendicular to the beams, between the beam position and the 3-prong vertex given the τ flight direction, and the vertex and beam positions with their errors[4]. The τ flight direction was approximated as being equal to the direction of the 3-prong momentum vector. The sine of the angle between the beam line and this momentum vector was then used to determine the 3-dimensional decay length.

Figure 1 shows the distribution of calculated decay length errors for the τ sample. It should be noted that the average error of $\sim$ 1 mm is roughly equal to the expected average decay length of 700 μ for taus at PEP energies. Figure 2(a) shows the distribution of measured decay lengths for those events from the τ sample which have a decay length error less that 1.4 mm. The distribution obviously has a positive mean as well as a tail of positive lengths. The mean decay length of this distribution was found by a maximum likelihood fit of the data to an exponential decay distribution convoluted with a Gaussian resolution function whose width is equal to the error calculated event-by-event. The mean decay length found by this technique is 621± 52μ .

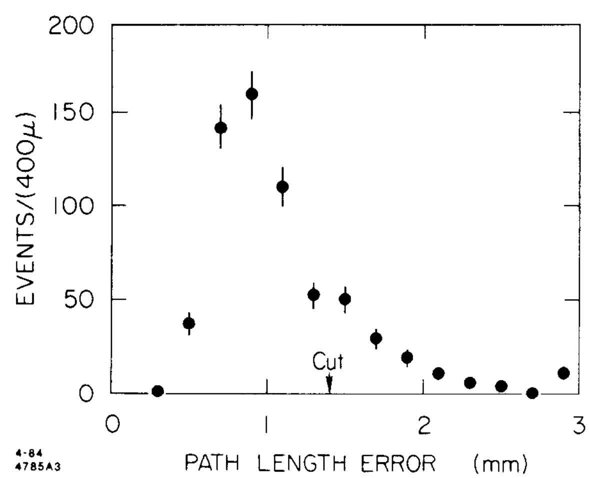

Fig. 1. Calculated decay length error for Mark II τ sample.

A control sample of simulated τ decays was formed from hadronic events with seven of more charged tracks in order to check for biases in the vertex reconstruction program and fitting procedure. Since the decay length error depends, in part, on the opening angles and momenta of the 3-prongs in τ decays, sets of 3-prongs from hadronic events were required to have opening angles and kinematics similar to those of τ decay products before being included in the control sample. The control sample tracks were then run through the same track quality cuts and vertexing procedure as the τ sample tracks. Figure 2(b) shows the distribution of decay lengths for control sample tracks. In contrast to Fig. 2(a), we see that the distribution is symmetric and has a relatively small mean of $79 \pm 23\mu$. Studies of a control sample derived from Monte Carlo produced events indicate that the positive offset is due to the relatively long lifetimes of charm and bottom hadrons which have slipped into the sample. Thus, it is believed that the large positive offset of Fig. 2(a) is due largely to a finite τ lifetime.

Monte Carlo studies estimate that the measured mean of $621 \pm 52\mu$ must be increased by $31 \pm 22\mu$ to properly account for the $\sim 7\%$ background contamination of the τ sample by low-multiplicity hadrons and 2-photon produced τ pairs. The error on this correction is purely due to the statistical error coming from the Monte Carlo calculation. This gives a preliminary value for the mean τ decay length of $652 \pm 55\mu$ (statistical error only).

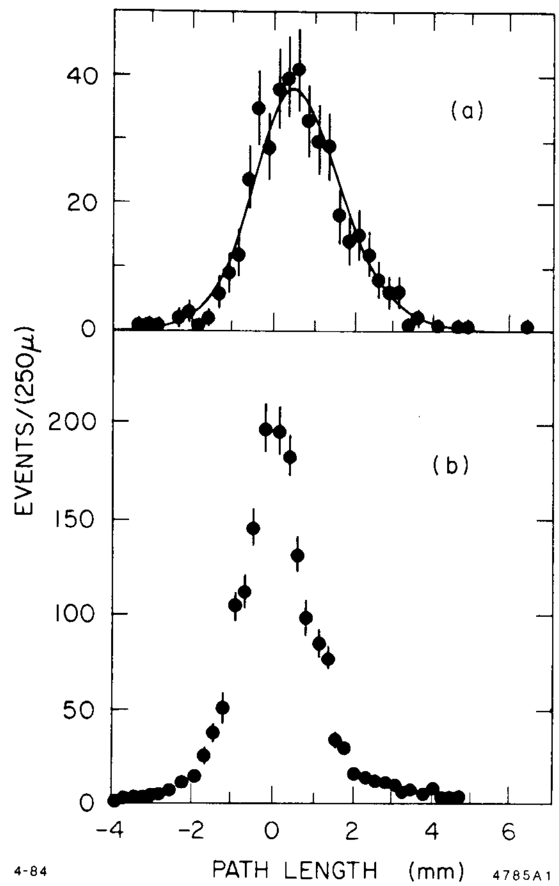

Fig. 2. Measured decay lengths for (a) τ sample; (b) hadron control sample. The solid curve in the top figure is the result of the best fit to the data as described in the text.

Several sources of systematic error have been evaluated. For example, the agreement between the means of the real and Monte Carlo control samples indicate that any offset in the measured mean decay length due to multiple scattering or mismeasurement of the angles of tracks in the 3-prong vertex must be less than 30μ. Shifts in the beam position affect the mean by $\pm 15\mu$. Reasonable variations in the track quality cuts or the 1.4 mm cut on decay length error produce changes of $\pm 20\mu$ and $\pm 25\mu$, respectively. The bias arising from the approximation that the τ flight direction is equal to the 3-prong momentum vector direction is about $\pm 2\mu$. The background correction error is, of course, $\pm 22\mu$. An error of $\pm 15\mu$ was added in to cover any unknown biases. These values were added in quadrature to obtain a systematic error of $\pm$ 67 μ . Therefore, the Mark II Collaboration reports a preliminary value of $652 \pm 55 \pm 67\mu$ for the mean τ decay length. A Monte-Carlo study of the mean τ energy which includes radiative corrections gives $\langle E_\tau \rangle = 13.88$ GeV. This was used to derive a lifetime value of

$$\tau_\tau = (2.80 \pm 0.24 \pm 0.30) \times 10^{-13} s.$$

A comparison of this measurement with values reported by other experiments is presented in Fig. 3.

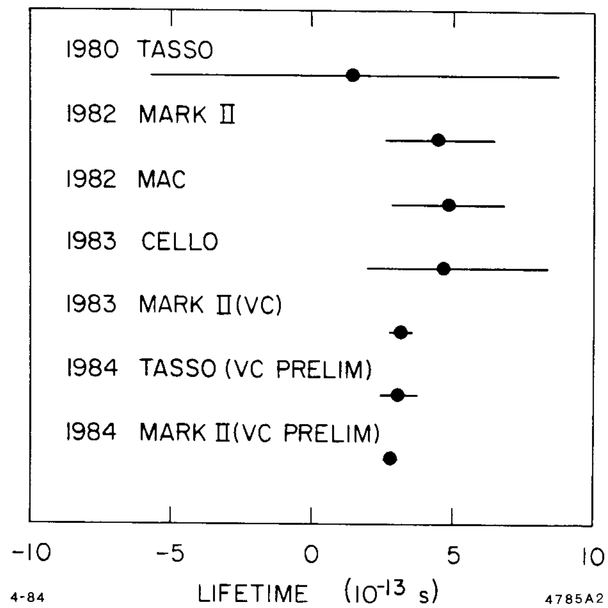

Fig. 3. Measurements of the τ lifetime from Ref. 5.

From the standard theory, we expect that

$$\tau_\tau = \tau_\mu \left(\frac{m_\mu}{m_\tau} \right)^5 Br(\tau \to e\nu_e \, \bar{\nu}_\tau)$$

if we assume that the τ coupling to the charged weak current has the universal Fermi strength and a V-A form and that the ν_τ is massless. Assuming for the moment that $m_{\nu_\tau} = 0$, then the ratio of weak coupling strengths for taus and muons is

$$\frac{g_\tau}{g_\mu} = 1.00 \pm 0.053 \pm 0.054$$

Assuming that e - μ - τ universality holds perfectly, then the present measurement places constraints on the mass of the ν_τ [6]. Figure 4 shows the prediction for τ_τ as a function of ν_τ mass along with the 95% CL limit stemming from the Mark II measurement. Here the 1σ error was made by adding the statistical and systematic errors in quadrature. The limit of 250 MeV/c^2 on the mass of the ν_τ from studies of the decay spectra for $\tau \rightarrow e\nu_\tau \bar{\nu}_e$ and $\tau \rightarrow \pi\nu_\tau$ by the DELCO[7] and Mark II [8] collaborations is also shown.

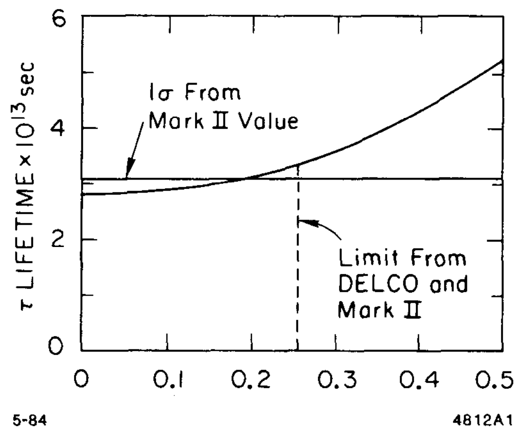

Fig. 4. τ lifetime as a function of ν_τ mass.

THE MARK II MEASUREMENT OF THE D^0 LIFETIME

The Mark II collaboration has also measured the lifetime of D^0 mesons using techniques very similar to those used in the τ lifetime measurement. In this case, a clean sample of D^0 mesons was identified by observing the reaction

$$e^+e^- \rightarrow D^{*+} + X$$
$$\quad\quad \hookrightarrow D^0\pi^+$$
$$\quad\quad\quad\quad \hookrightarrow K^-\pi^+$$

(Reference to a particle state will always imply the sum of that state and its charge conjugate state.) Previous studies[9] have shown that this reaction can be isolated with little background for high values of z, where z is the energy of the D^{*+} divided by the beam energy. Once these events have been identified, then the most probable decay length for each D^0 is calculated from the vertex position of the K and π tracks from the D^0 , the beam position, and the errors in these quantities just as for tau events. The decay lengths were then converted into proper decay times using the measured D^0 momenta.

In searching for the above-mentioned decay sequence, no attempt at particle identification was made. Instead, all tracks in hadronic events were tried as both kaons and pions. All oppositely charged Kπ pairs with invariant mass between 1.72 and 2.00 GeV/c^2 were considered D^0 candidates. Their momenta were then constrained using the D^0 mass. Each candidate pair was combined with additional pions of appropriate charge in the events, and those combinations with a small mass difference and z greater than 0.6 were considered D^{*+} candidates. Track quality and vertex quality cuts were then applied to ensure that the decay tracks had not scattered or suffered tracking confusion due to the dense environment in hadronic events. Complete details of these cuts can be found in Ref. 10.

Figure 5 shows the mass difference of events which survived all cuts. The 27 events in the peak centered at 145 MeV/c^2 were used in the lifetime measurement. The combinatorial hadronic background under the peak is estimated to be 2 events. Monte Carlo calculations were used to estimate that 3% of the D^{*+} events in the peak come from B meson decays.

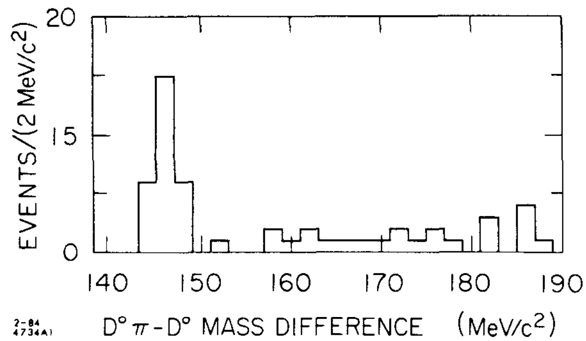

Fig. 5. Mass difference of D^{*+} candidates.

A histogram of the proper decay times for the 27 D^{*+} candidates is presented in Fig. 6(a) along with a curve showing the expected shape of the distribution. A maximum likelihood fit of the data to an exponential decay distribution convoluted with a Gaussian resolution function yields a mean decay time of $(4.2^{+1.3}_{-1.0}) \times 10^{-13}$ s. (statistical errors only). The fit allowed for the presence of combinatorial background (which is shown below to have a small mean lifetime) and B decays in the lifetime sample.

To aid in the evaluation of the systematic error on the measurement, a control sample was formed by making fake D^{*+} decays out of hadronic tracks with approximately the same kinematics as true D^{*+} decays. The lifetimes from this sample are shown in fig. 6(b). Note that the distribution is quite symmetric and has a small mean of $(0.4 \pm 0.2) \times 10^{-13}$ s. A similar study of a control sample made from Monte Carlo produced events was found to have a mean of $(0.5 \pm 0.2) \times 10^{-13}$ s when bottom and charm hadron lifetimes were set to their currently measured values[11]. The agreement between the measurements made on real and Monte Carlo data lead to the conclusion that any systematic mismeasurement of the mean lifetime must be small. Taking into account the effect of reasonable variations in the beam positions, the calculated errors, and the background estimates, the Mark II group assigns a systematic error of 1.0×10^{-13} s, to the measurement, thereby leading to a lifetime value of $\tau_{D^0} = (4.2^{+1.3}_{-1.0} \pm 1.0) \times 10^{-13}$ s.

Figure 7 compares this result to recently published values of τ_{D^0} from other experiments. As can be seen from the plot, the D^0 lifetime measurements are now quite consistent, statistically. The world average for τ_{D^0} is $(4.0^{+0.5}_{-0.4}) \times 10^{-13}$ s, if the current Mark II value is included in the determination.

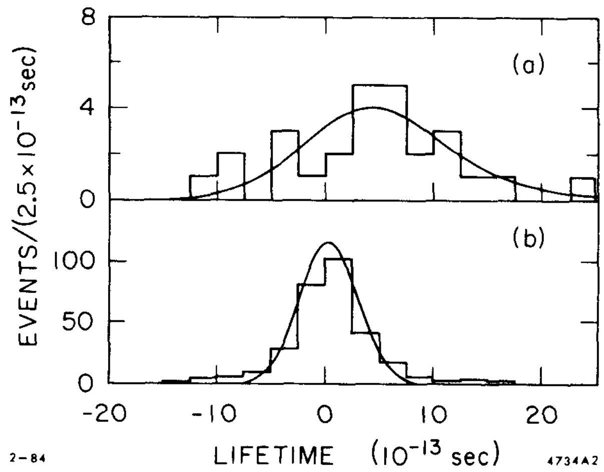

Fig. 6. Distribution of measured decay times for (a) D^{*+} candidates; (b) hadronic control sample. The solid curves are the best fits to the data.

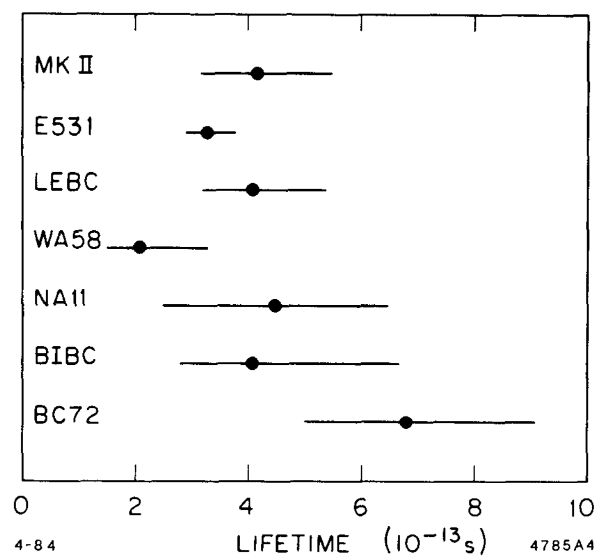

Fig. 7. Measured values of the D^0 lifetime as of the fall of 1983 from Ref. 11. The current Mark II value is at the top.

THE B-LIFETIME MEASUREMENT FROM MAC

Last summer, two PEP experiments, Mark II and MAC, reported measurements of the lifetime of B hadrons[12,13] which were surprisingly long. Both experiments made their measurements by studying the impact parameter distribution of leptons coming primarily from the semi-leptonic decay of B hadrons. The MAC Collaboration reports here an updated value[14] for their measurement using the same method as last year on a data sample with enhanced statistics.

Several experiments have isolated hadronic events containing primary bottom quarks by identifying leptons from semi-leptonic B decay. Since the mass of the b quark is considerably higher than that of the u,d,s, or charm quarks, the decay of a B hadron can impart correspondingly greater momentum and transverse momentum, p_T (measured with respect to the thrust axis of the event), to the lepton. Thus, B events can be "tagged" by searching for high p,p_T leptons in hadronic events. Once such a lepton is found, then, as will be shown below, a measurement of its impact parameter (i.e. its distance of closest approach) to the primary vertex of the event gives a measurement of the lifetime of the B hadron that produced it.

The MAC Collaboration selected hadronic events containing electrons or muons with $p > 2$ GeV/c and $p_T > 1.5$ GeV/c. They have estimated the fractions of bottom, charm, and light-quark background in their B-enriched samples to be approximately 50% , 20% , and 30% , respectively. The charm fraction includes leptons from the decay sequence b→ c→ electron or muon.

Figure 8 shows a schematic view of a B hadron decay projected onto the plane perpendicular to the beam axis. ℓ is the B flight distance, Ψ is the angle between the lepton and the B hadron trajectory, and δ is the impact parameter of the lepton relative to the primary vertex. The B flight direction was approximated to be along the thrust axis and the primary vertex was assumed to be the beam position. δ is signed in the following way: define a vector which points from the primary vertex to the intersection of the lepton and B trajectories. If this vector points into the same hemisphere as the lepton trajectory, then δ is positive. If the lepton trajectory were mismeasured so that the intersection was to the left of the origin or if the B decayed into a backward-going lepton, then δ is negative.

The average impact parameter for the event sample is given by

$$< \delta > = < \beta\gamma sin\Psi sin\theta > c\tau = \alpha c\tau$$

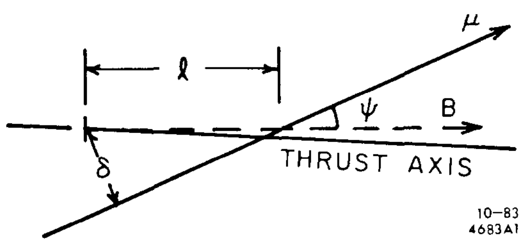

Fig. 8. Decay of a B hadron produced in an e^+e^- collision. Variables are explained in the text.

where θ is the polar angle between the lepton and the beam axis ($\sin\theta$ is included since only the projected impact parameter is measured). The constant α was determined from Monte Carlo studies which took into account the measured branching fractions for bottom and charm, the measured fragmentation function parameters, and the population-weighted charm lifetime value of 5.5×10^{-13} s. The values found for α were 0.45 for bottom, 0.15 for charm, and approximately 0 for K and π decays and γ conversions. As stated before, a large value of α is expected for B decays due to the large b-quark mass which allows large p_T and therefore large values for the angle Ψ in Fig. 8 . The impact parameters of leptons from K or π decays or γ conversions tend to be symmetric about 0, thus leading to a small mean value for δ . Thus, on the basis of Monte Carlo study, it is expected that $<\delta>$ will be 129 ± 5 μ for leptons from B's, 25 ± 10 μ for charm-produced leptons, and 22 ± 6 μ for non-leptonic background tracks (since some high p, p_T hadrons do come from B decays). These values were calculated assuming a B lifetime of 10^{-12} s and a charm lifetime of 5.5×10^{-13} s.

The distribution of impact parameters weighted by their reciprocal squared errors is shown in Figs. 9(a) and (b) for the electron and muon samples. The medians were found to be $83 \pm 42\mu$ and $159 \pm 39\mu$, respectively. These graphs were found to be quite different from the distribution of weighted impact parameters of hadronic tracks which passed the same p, p_T cuts as the lepton sample tracks. The control sample has a median of $23 \pm 7\mu$, which compares well with the value expected from the Monte Carlo study. It was concluded from this that the large positive medians seen in the lepton samples is due largely to a long B lifetime. The exact value of τ_B comes from the solution of the equation

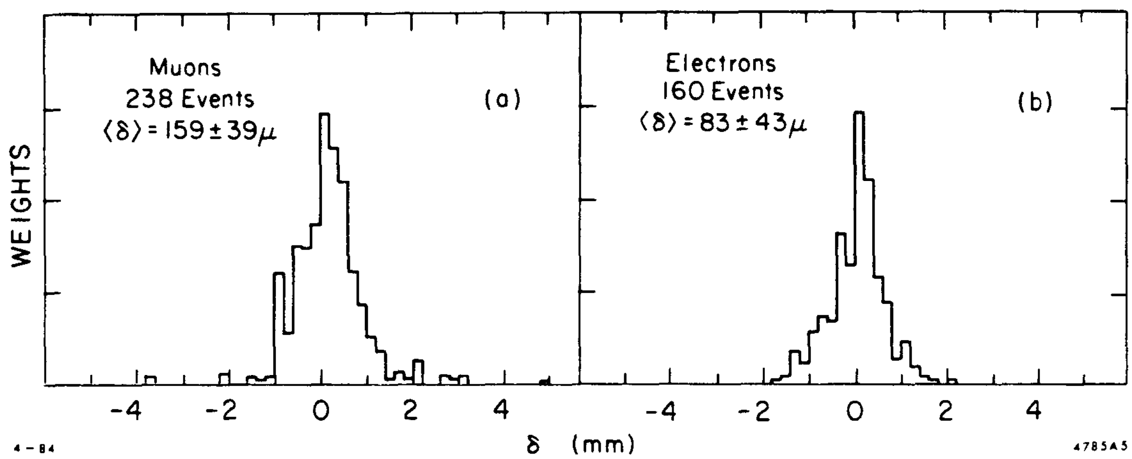

Fig. 9. Weighted impact parameters for (a) electrons; (b) muons. Preliminary data from MAC.

$$< \delta > = f_B \alpha c \tau_B + f_c \delta_c + f_{bg} \delta_{bg}$$

where f_B , f_c , and f_{bg} are the fractions of bottom, charm and background events in the lepton sample, and δ_c , δ_{bg} are the mean impact parameters for charm and background events as determined from the Monte Carlo and the control sample. The MAC Collaboration reports as a preliminary answer

$$\tau_B = (1.6 \pm 0.4 \pm 0.3) \times 10^{-12} s.$$

This answer compares favorably with the values of $(1.20^{+.45}_{-.36} \pm 0.3) \times 10^{-12}$ s and $(1.8 \pm 0.6 \pm 0.4) \times 10^{-12}$ s published by Mark II and MAC last summer.

Of course, all of the data used in last year's measurement was included in the present update, however, several improvements in the analysis have been made. First, new data was used to increase the number of events in the lepton sample by a factor of 1.5. Second, the track resolution of MAC was improved by $\sim$ 20% by using information from the calorimeters to get a better estimate of the track momentum. This provided a better determination of the track curvature, and, therefore, increased resolution on the extrapolation of the track back to the vicinity of the beam spot. Thirdly, better determinations of the b,c semi-leptonic branching ratios have helped reduce the systematic error.

The MAC group has also measured the τ lifetime using this technique. Figure 10 shows the weighted impact parameter distribution for all tracks in 1+1 and 1+3 type τ events. The median value is $54 \pm 7\mu$. Comparison of this value with that of a Monte Carlo τ sample made with the canonical lifetime yielded a preliminary value of $(3.2 \pm 0.6 \pm 0.6) \times 10^{-13}$ s for the τ lifetime.

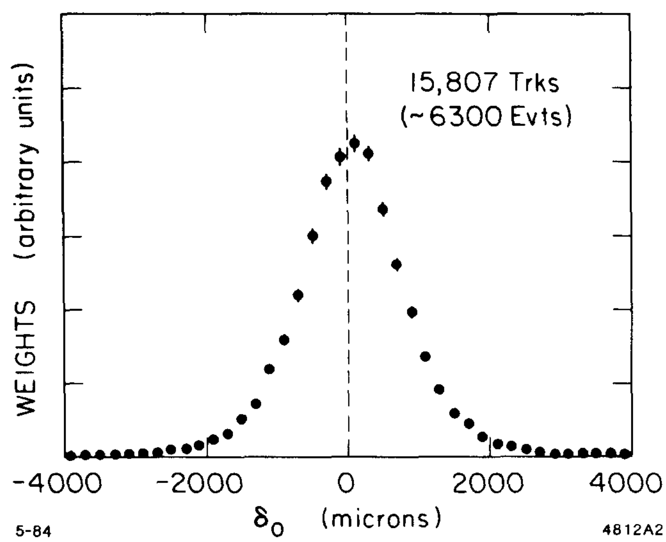

Fig. 10. Weighted impact parameters of tracks from τ events. Preliminary data from MAC.

MARK II UPPER LIMIT ON THE ν_τ MASS

The Mark II Collaboration has determined a new upper bound[15] on the ν_τ mass by studying the invariant mass spectrum of the 4π state in the decay $\tau \rightarrow 3\pi^{\pm}\pi^{0}\nu_\tau$. Previous measurements placed a bound of 250 MeV/c^2 on the mass of ν_τ by studying the electron spectrum[7] of $\tau \rightarrow e\bar{\nu}_e\, \nu_\tau$ and the pion spectrum of $\tau \rightarrow \pi\nu_\tau$ [8]. At PEP energies, it is expected that the 4π channel will be a more sensitive probe of the ν_τ mass since the invariant mass of the 4π state approaches the τ mass, thereby leaving less available phase space for a massive ν_τ .

Tau events were selected by looking for events with four charged prongs which had zero net charge and a 1+3 topology. The events were also required to have at least two photons detected in the liquid argon calorimeter. Events were rejected unless one and only one π^0 could be reconstructed from all combinations of the detected photons. The momenta of these photons were then constrained using the π^0 mass. Low-multiplicity hadrons were rejected by demanding that the two τ decays were collinear to within 50° and by demanding that the energy of the 4π state be greater than 8 GeV for 4π invariant masses less than 1.5 GeV/c^2 and greater than 10 GeV for 4π invariant masses greater than 1.5 GeV/c^2 .

A plot of 4π invariant masses is shown in Fig. 11 along with curves showing the expected shape of the data for ν_τ masses of 0 and 200 MeV/c^2. Since an upper limit on the mass of the ν_τ was desired, the curves were generated assuming that the $\tau \rightarrow 3\pi^{\pm}\pi^{0}\nu_\tau$ channel is dominated by a ρ' resonance with the unfavorable parameters of mass 1.65 GeV/c^2 and width of 400 MeV/c^2. Only the 14 events with invariant mass greater than 1.5 GeV/c^2 were used. A maximum likelihood technique applied to these 14 events determined that the mass of the ν_τ must be less than 164 MeV/c^2 at the 95% CL.

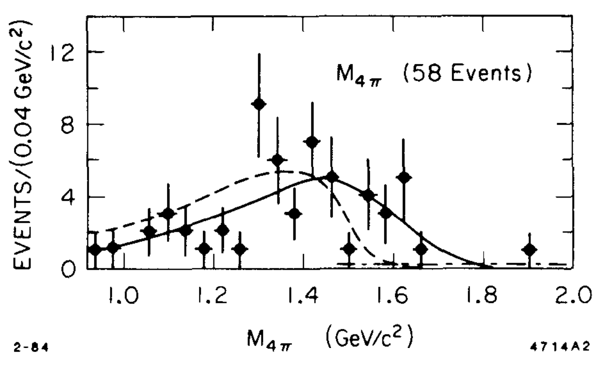

Fig. 11. $3\pi^{\pm}\pi^{0}$ invariant masses. The solid and dashed curves are the expected shape of the data for a ν_τ mass of 0 and 200 MeV/c^2, respectively.

The branching fractions for the Cabibbo-allowed reactions such as $\tau \to \pi\nu_\tau$ and $\tau \to \rho\nu_\tau$ are well-measured and in good agreement with standard theoretical estimates. Since Cabibbo-suppression of weak decays involving strange particles is an important part of the standard weak interaction theory, it is also necessary to test the theoretical estimates of Cabibbo-suppressed decays such as $\tau \to K\nu_\tau$ to ensure that the τ is in fact a sequential lepton with non-anomalous couplings to the weak charged current. The DELCO collaboration has done just such a test[16] by making a precise measurement of the branching ratios for $\tau \to K\nu_\tau$ and $\tau \to K\nu_\tau + n\pi^0$.

They found events containing the above-mentioned decays by identifying isolated kaons in 1+1, 1+2, and 1+3 event topologies (where it is assumed that detector acceptance and tracking inefficiencies produced 1+2 events from 1+3 decay modes). The cuts were as follows: events with 2 to 4 charged prongs were divided into two jets along their thrust axes. Those events which had one or both jets containing a single prong within the Cerenkov detector acceptance were considered as possible candidates. Events in which the isolated prong had no Cerenkov signal and a momentum greater than 3.5 Gev/c were considered $\tau \to K$ candidates. The momentum cut of 3.5 GeV/c is 3 standard deviations (in terms of the DELCO momentum resolution) above the 2.6 GeV/c Cerenkov threshold for pions. Background from low multiplicity hadrons was reduced by demanding that the thrust of the jet opposite the isolated kaon be greater than 0.95 and by demanding that the invariant mass of the tracks in that jet be less than 2.1 GeV/c^2 . There were 56 such events identified in 106 pb^{-1} of data. Events from the reaction $\tau \to K\nu_\tau$ were separated from those of the $\tau \to K\nu_\tau + n\pi^0$ reaction by demanding that the pulse height within $\pm 45°$ of the kaon track be consistent with that expected from a single minimum ionizing particle.

The amount of low multiplicity hadronic background in the data sample was found by relaxing the cut on N_{opp} , the number of prongs opposite the isolated kaon. Two events were found with N_{opp} greater than 3. Using this number and the shape of the N_{opp} distribution derived from a Lund Monte Carlo calculation, the experimenters estimated that 3.7 ± 2.3 of their 56 event sample is due to hadronic contamination. Monte Carlo estimates of the background in the $\tau \to K\nu_\tau$ sample from the mode $\tau \to K\nu_\tau + n\pi^0$ where the photons from the π^0 fall outside the shower counter acceptance yielded a value of 12%. Table I summarizes the breakdown of the number of signal events and the background estimates. A Monte Carlo calculation of the acceptance for the two Cabibbo-suppressed reactions lead to the reported branching fraction values shown in Table II. It should be noted that the ratio of branching fraction to error for the DELCO measurement is comparable to that measured for Cabibbo-allowed τ decay modes. The Mark II results[17,18] and the theoretical estimates are also presented for comparison with the DELCO values. All the results are in reasonable agreement leading once again to the conclusion that the τ is a sequential lepton with the same weak interactions as the electron and muon.

Table I
Summary of Cabibbo-Suppressed τ Decay Measurement

Topology	1 - 1 prong	1 - 3 prong	Total for $K\nu_\tau$	Total for $K\nu_\tau + n\pi^0$
Number of events	38	16	21	56
Background due to				
Cerenkov inefficiency	0.3± 0.3	0.1± 0.1	0	0.5±0.5
Hadrons	0.3± 0.3	1.9± 1.6	1.0± 0.9	2.7±2.1
Other tau decays			4.1± 1.1	
Total background	0.6± 0.4	2.0± 1.6	5.1± 1.4	3.2±2.2

Table II
Branching ratios for K and K* decay modes of the τ

Decay Modes	measured DELCO	measured Mark II	expected
$\tau \to K\nu_\tau + n\pi^0$	1.71 ± 0.29%		1.31 ± 0.13%
$\tau \to K^*\nu_\tau$		1.7± 0.7%	1.04 ± 0.15%
$\tau \to K\nu_\tau$	0.59± 0.18%	1.3± 0.5%	0.71 ± 0.10%

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