AN EXPERIMENTAL UPPER LIMIT FOR THE τ LIFETIME

PLUTO Collaboration

G. ALEXANDER[1], L. CRIEGEE, H.C. DEHNE, K. DERIKUM, R. DEVENISH, G. FLÜGGE, G. FRANKE, Ch. GERKE, P. HARMS, G. HORLITZ, Th. KAHL[2], G. KNIES, E. LEHMANN, R. SCHMITZ, R.L. THOMPSON[3], U. TIMM, P. WALOSCHEK, G.G. WINTER, S. WOLFF and W. ZIMMERMANN

Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

W. WAGNER

I. Physikalisches Institut der RWTH Aachen, Germany

V. BLOBEL, L. BOESTEN, A.F. GARFINKEL[4], B. KOPPITZ, E. LOHRMANN[5], W. LÜHRSEN and H. SPITZER

II. Institut für Experimentalphysik der Universität Hamburg, Germany

A. BÄCKER, J. BÜRGER, C. GRUPEN and G. ZECH

Gesamthochschule Siegen, Germany

and

H. MEYER, M. RÖSSLER and K. WACKER

Gesamthochschule Wuppertal, Germany

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Two methods for setting an upper limit on the τ lifetime using events assigned to $\tau^+\tau^-$ production in e^+e^- annihilation in the centre of mass energy range 3.9 to 5 GeV are discussed. The combined result is a 95% CL upper limit for the τ lifetime of 9.0×10^{-12} s.

Investigations of anomalous lepton production (e, μ) in e^+e^- annihilations have led to the discovery of a new heavy lepton [1], the τ, the mass of which has recently been measured accurately to be 1.782 GeV/c^2 [2]. The τ has been observed to decay to pure leptonic states $e\nu\nu$ and $\mu\nu\nu$ as well as to semihadronic channels [3,4]. Several schemes have been proposed for the classification of the τ in relation to the "old" lighter leptons (e, ν_e and μ, ν_μ) [5]. The simplest scheme (which is also consistent with all experimental results) is one in which the τ is a left-handed lepton accompanied by its own light neutrino ν_τ and its interactions conserve a new τ lepton number. Assuming the conventional weak V − A interactions, the τ lifetime $t_0(\tau)$ is related to the μ lifetime $t(\mu)$ by [6]

$$t_0(\tau) = \mathrm{BR}(\tau^- \to e^- \overline{\nu}_e \nu_\tau) \times (m_\mu/m_\tau)^5 \times t(\mu), \qquad (1)$$

where m_τ and m_μ are, respectively, the masses of the

[1] On leave from Tel-Aviv University, Tel-Aviv, Israel.
[2] Now at Max-Planck-Institut für Physik und Astrophysik, München.
[3] Now at Humboldt University, Arcata, CA, USA.
[4] Now at Purdue University, Lafayette, IN 47907, USA.
[5] Now at CERN, Geneva, Switzerland.

τ and μ leptons, and $\mathrm{BR}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)$ is the decay branching ratio of $\tau^- \to e^- \bar{\nu}_e \nu_\tau$. Using the values $m_\tau = 1.782\ \mathrm{GeV}/c^2$ and $\mathrm{BR}(\tau^- \to e^- \bar{\nu}_e \nu_\tau) = 18.3\%$ [‡1], $t_0(\tau)$ can be calculated to be $t_0(\tau) = 0.295 \times 10^{-12}$ s.

Many alternative schemes have been proposed, for example that the τ has "old" lepton number, or that the τ occurs as a singlet, or that the τ is accompanied by a heavier neutral partner. In these cases the lifetime is either longer than $t_0(\tau)$ or is a free parameter determining the coupling strength to the old leptons [7].

For τ's with an energy of 2.25 GeV – the mean energy in this experiment – the lifetime calculated above is equivalent to a mean decay length of 0.07 mm, which cannot be measured directly in the PLUTO detector. However, it is still of interest to set an upper limit on the lifetime which could restrict the possible classification schemes for the τ. Two methods have been used. In the first method $\tau^+\tau^-$ events where a lepton is identified from one τ decay and three charged hadrons are measured to come from the other decay are used to measure directly the flight distance between the primary vertex and the decay vertex, taken to be the vertex formed by the three hadrons (see fig. 1a). For the second a parameter r_{min} is defined, where

‡1 Experimental values for m_τ and $B(\tau \to e\nu\nu)$ are taken from ref. [4].

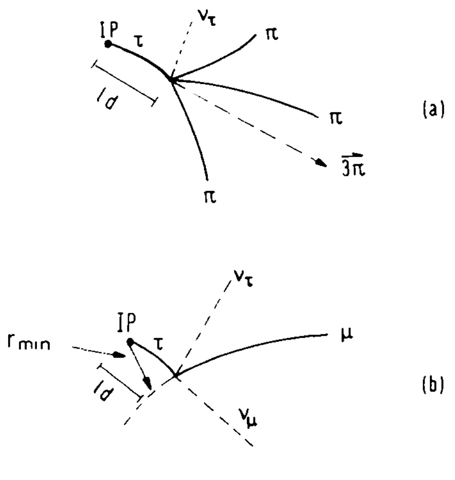

Fig. 1. (a) Illustration of the direct method for measuring the τ decay length (l_d) from $\tau \to \nu 3\pi$ decays. IP stands for interaction point. (b) Illustration of the transverse projected distance of closest approach (r_{min}) to the interaction point.

r_{min} is the distance of closest approach of a track to the interaction point, projected onto a plane perpendicular to the beam line (see fig. 1b). The r_{min} distribution of the tracks from τ events with one identified μ and one other charged particle is measured. The lifetime is then deduced by comparing the width of the measured r_{min} distribution with Monte Carlo simulations in which the τ has a finite lifetime [‡2].

The experiment was carried out with the PLUTO magnetic detector at the DORIS e^+e^- storage rings at DESY. In the PLUTO detector muons are identified within $0.43 \times 4\pi$ sterad by their range, requiring a penetration of 68 cm of iron, corresponding to a muon momentum of at least 1 GeV/c [9]. Within $0.5 \times 4\pi$ sterad electrons and photons are identified by the showers produced behind two concentric lead cylinders placed in the detector at radii of 38 and 59 cm and having 0.44 and 1.7 radiation lengths, respectively [10]. Electron candidate tracks are further required to satisfy $p_e \geqslant 400\ \mathrm{MeV}/c$ and $|\cos\theta| < 0.55$, where θ is the production angle of the track. Charged tracks are measured with 14 cylindrical proportional chambers and the track fitting procedure takes into account multiple scattering and energy loss by ionisation in the detector material.

We consider first the analysis where we attempt to determine directly the decay length. We have selected events assigned to the reaction

$$e^+e^- \to \tau^\mp\tau^\pm, \quad \tau \to \ell^\pm\nu\nu \quad (\ell = e \text{ or } \mu), \quad \tau \to \nu\pi^+\pi^-\pi^\mp \qquad (2)$$

by applying the following cuts to our 4-prong charged balanced event sample collected at centre of mass energies between 3.9 and 5 GeV [10].

(1) One and only one lepton candidate (e or μ).

(2) The kinematics of the events must be compatible with the reaction (2).

(3) The missing mass must be at least 0.9 GeV/c^2.

We find 38 events of this type. The method is sketched in fig. 1a, the decay point of the τ can be determined from the intersection of the 3 non-leptonic tracks. If $m_{\nu_\tau} = 0$ then the cosine $\cos\delta(\vec{\tau}\cdot\vec{3\pi})$ can be calculated for each event and the distribution is strongly peaked

‡2 Preliminary results from this method have been reported previously, see ref. [8].

near $\cos\delta = 1$, indicating that to a good approximation the flight direction of the τ is that of the 3π system. Using the 32 events with $\delta < 45°$ we constrain the decay point to lie on the flight line of the 3π system, starting from the known interaction point. We determine the true e^+e^- interaction vertex using well defined collinear tracks from the QED reactions $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to e^+e^-$ extrapolated back to the vertex position. The true vertex distribution is found to be of a gaussian form with $\sigma_x = 0.3$ mm and $\sigma_y = 0.2$ mm compatible with the DORIS beam dimensions ($\sigma_x = 0.4$ mm in the beam plane and $\sigma_y = 0.2$ mm transverse to the beam plane) [11]. The vertex distribution along the beam direction is much wider and has the value of $\sigma_z = 6$ mm. The decay length (l_d) can now be measured and since the energy of the τ is known in the laboratory system from the production process each decay length can be converted into a decay time t. The resolution in t is related to the measured resolution in l_d by the factor m_τ/cp_τ, from which it can be seen that for events with energies near to threshold there is a considerable loss in resolution. We find the best result within our limited statistics and energy range by demanding that E_{cm} be greater than 4.8 GeV. The mean decay time of the 12 remaining events is measured to be

$$t(\tau) = (6 \pm 12) \times 10^{-12}\,\mathrm{s}. \qquad (3)$$

We have checked that there is no systematic shift from zero by measuring the mean "decay time" from a sample of 300 hadronic 4-prong events *without* leptons (but satisfying the remaining kinematic cuts described above). Although the direct method is attractive in that it does not rely on a Monte Carlo simulation it is limited by the small number of events suitable for the analysis.

For the second method we use the two-prong τ data collected at centre of mass energies between 3.9 and 5 GeV [9]. Events with at least one identified muon with $p_\mu > 1$ GeV/c and one and only one other track were selected. Further cuts were then applied to reduce the background from cosmic rays and QED reactions.

(1) Events with photons and electron candidates are removed by demanding at most 3 hit wires not associated with tracks.

(2) The unidentified track should have a momentum of at least 400 MeV/c.

(3) The acoplanarity angle between the tracks ($\Delta\phi$) should lie in the interval $15° < |\Delta\phi| < 165°$.

(4) Both tracks should have at least 10 coordinates, this implies a production angle of $|\cos\theta| < 0.64$, and ensures that the method is insensitive to the poorly determined σ_z of the interaction point.

(5) The missing mass squared should be at least $0.43 \times E_b^2$, where E_b is the beam energy (in GeV).

In this way we have 65 events assigned to the reactions,

$$\begin{aligned} e^+e^- \to\ & \tau^\pm \to \mu^\pm\nu\nu \quad (\mu^\pm \text{ identified}) \\ & + \tau^\mp \to \mu^\mp\nu\nu \quad (\text{unidentified charged particle}) \\ & \qquad\quad \pi^\mp\nu\,, \end{aligned} \qquad (4)$$

with a small contamination from

$$\begin{aligned} \tau \to\ & \rho^\mp\nu \\ & \to \pi^0\pi^\mp \quad \pi^0 \text{ not seen.} \end{aligned}$$

The method adopted to set an upper limit on the τ lifetime is based on the fact that a non-zero τ decay length will broaden the r_{min} distribution of tracks from the τ decays (see fig. 1b). The 130 tracks from the 65 events assigned to reaction (5) above have the r_{min} distribution shown in fig. 2. It has a gaussian form with $\sigma(r_{min})$ of 2.9 ± 0.17 mm.

For comparison we have studied two control samples of promptly produced tracks, the first consisting of hadrons and the second of muons. The first sample

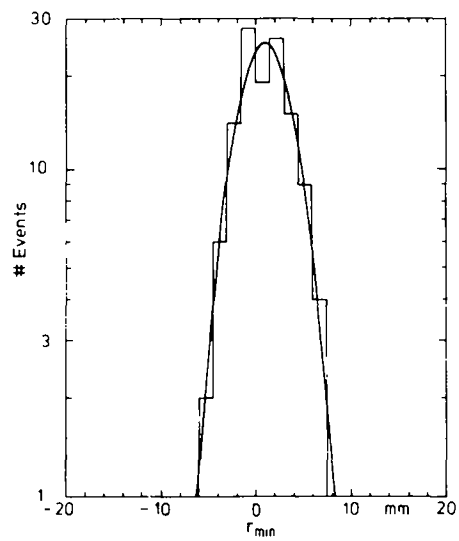

Fig. 2. The r_{min} distribution for the two-prong τ data sample.

was obtained from hadron events at the J/ψ resonance and in the range 3.6 to 5 GeV centre of mass energy. The tracks were selected with identical criteria as applied to the unidentified track of the τ sample. The r_{min} distribution obtained at the different energies are found to be gaussian with a $\sigma(r_{min})$ averaged over all energies of 3.77 ± 0.06 mm. The second control sample of events with promptly produced muons comes from the reaction

$$e^+e^- \to \psi(3.7) \to J/\psi\, \pi\pi \\ \qquad\qquad \to \mu^+\mu^- , \tag{5}$$

and from radiative muon pair production

$$e^+e^- \to \mu^+\mu^-\gamma . \tag{6}$$

Events from reaction (5) are identified by demanding one muon with $p > 1$ GeV/c and at least 3 prongs. Events from reaction (6) were selected by one identified muon and requiring an opening angle of less than 165° and a missing mass squared of less than $0.43 \times E_b^2$. The $\sigma(r_{min})$ values for reactions (5) and (6) average to give 2.52 ± 0.13 mm, which is significantly smaller than that obtained from the hadron samples. This observation is readily understood in terms of the nuclear scattering contribution which is absent in the muon samples. It is also important to note that the $\sigma(r_{min})$ value obtained for the τ data lies between the values from the hadron and muon samples. This is to be expected as long as the τ decay length (l_d) is small compared to $\sigma(r_{min})$ since the unidentified tracks in the τ sample consist of a mixture of π's and μ's. More exactly for the processes in the τ sample we find that μ and π tracks are in the proportions 3.3/1 using the known branching ratios [3]. In addition for the ρ channel we have used the fact that in the PLUTO detector there is a 20% chance to miss the photons from π^0 decays [9]. From this mixture of tracks and the measured σ for hadrons and muons we would expect σ = 2.86 mm. This value will be used to normalise the Monte Carlo calculation to be described below.

The effect of a non-zero τ decay length on the r_{min} distribution has been studied with the help of a Monte Carlo program generating $\tau^+\tau^-$ events according to reactions (4). In the program the experimental conditions and the subsequent event analysis have been simulated in all their details. The measurement errors were adjusted in the program to agree with results from hadron tracks. With this program we generated r_{min} distributions corresponding to l_d = 0, 1, 2, and 3 mm imposing the same cuts as used for the τ data. If we apply the selection criteria applied to the hadronic control sample then we find a $\sigma(r_{min})$ for $l_d = 0$ compatible with that measured for hadronic events. This should be so but we expect that the *relative* variation of $\sigma(r_{min})$ with l_d will be the same for a mixed muon–hadron track sample. To enable an upper limit to be calculated we normalise the Monte Carlo $\sigma(r_{min})$ for $l_d = 0$ to the value of 2.86 mm found from hadronic and muon control samples as described above. With this normalisation the Monte Carlo results for $\sigma(r_{min})$ are shown in fig. 3 as a function of l_d (solid line), together with the data point from the τ events. Using this figure we can convert the measured $\sigma(r_{min})$ into a measured mean decay length l_d. Knowing the average τ momentum to be 1.374 GeV/c for our data sample we can convert l_d into a measured mean lifetime of

$$t(\tau) = (2.4 \pm 4.2) \times 10^{-12}\,\mathrm{s}. \tag{7}$$

(The error includes the statistical uncertainty of the Monte Carlo calculation.)

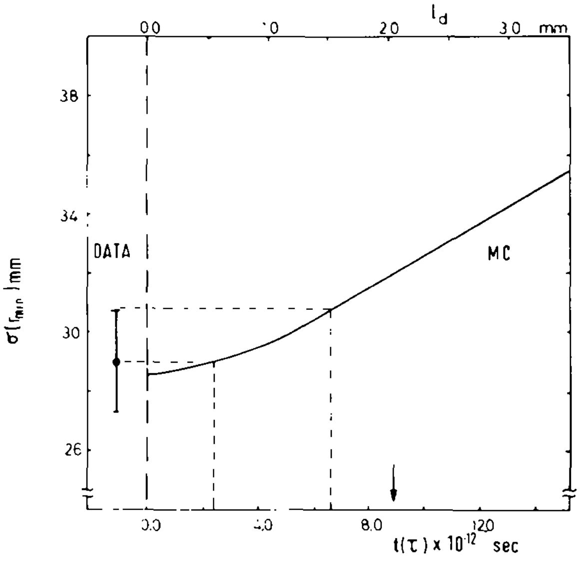

Fig. 3. The variation of $\sigma(r_{min})$ with decay length l_d from the Monte Carlo study together with the data point from the τ events. The upper scale shows l_d in mm, the lower scale the corresponding $t(\tau)$ for our average τ momentum of 1.374 GeV/c. The arrow indicates the final result for the 95% CL upper limit for $t(\tau)$ (eq. (8) of the text).

Combining the results of both methods we obtain an upper limit at the 95% CL of

$$t(\tau) < 9.0 \times 10^{-12}\,\mathrm{s}, \tag{8}$$

or

$$t(\tau)/t_0 < 31.$$

This result is compatible with the "standard model" of a sequential heavy lepton with its own neutrino and lepton number though we are still an order of magnitude away from a critical test. It is also consistent with the preliminary upper limit (95% CL) of 3.0×10^{-12} s reported by the DELCO group [12]. If we consider instead a typical model in which the τ is accompanied by a heavier neutral partner N then the τ can only decay if N mixes with μ and e neutrinos. From the experimental limits on the violations of μ–e universality limits can be set on the magnitude of the mixing parameters which in turn imply a value for t/t_0 of greater than 50 [7]. While we cannot exclude such a model it is clear that our result makes such a possibility rather unlikely.

It is also of interest to compare our result with that of a recent neutrino scattering experiment [13] setting an upper limit on direct electron production from μ neutrino scattering on neon. The result at 90% CL is

$$(\nu_\mu + \mathrm{N_e} \to \underset{\hookrightarrow e^-}{\mathrm{L}^-} + x)/(\nu_\mu + \mathrm{N_e} \to \mu^- + x) \leqslant 3 \times 10^{-3}.$$

If we assume that the τ has μ lepton number then this result can be converted into a lower limit on the τ lifetime of $t/t_0 > 40$ to be compared with our upper limit of 31.

To conclude we have measured an upper limit for the τ lifetime of 9×10^{-12} s (95% CL). This result makes it unlikely that the τ has μ lepton number or that the τ neutrino is heavier than the τ itself.

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