

PROPERTIES OF THE PROPOSED τ CHARGED LEPTON[★]

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The anomalous $e\mu$ and 2-prong μx events produced in e^+e^- annihilation are used to determine the properties of the proposed τ charged lepton. We find the τ mass is $1.90 \pm 0.10 \text{ GeV}/c^2$; the mass of the associated neutrino, ν_τ , is less than $0.6 \text{ GeV}/c^2$ with 95% confidence; $V - A$ coupling is favored over $V + A$ coupling for the $\tau - \nu_\tau$ current; and the leptonic branching ratios are $0.186 \pm 0.010 \pm 0.028$ from the $e\mu$ events and $0.175 \pm 0.027 \pm 0.030$ from the μx events where the first error is statistical and the second is systematic.

There is now substantial evidence [1–8] that anomalous $e^\pm\mu^\mp$, 2-prong $\mu^\pm x^\mp$, and 2-prong $e^\pm x^\mp$ events (where the x is not a μ or e respectively) are produced in e^+e^- annihilation. All of this evidence is consistent with the hypothesis that these events are the decay products from the production of a pair of new charged leptons: $e^+e^- \rightarrow \tau^+\tau^-$. This paper uses the $\mu^\pm x^\mp$ events [4] and a newly enlarged sample of $e^\pm\mu^\mp$ events (all obtained in the SLAC-LBL magnetic detector at SPEAR) to determine various properties of the τ , including: the τ mass, the τ -neutrino coupling, the leptonic branching ratios, and the τ production cross section. In deriving these properties we use the model^{†1} in which the τ is a sequential charged lepton [1, 9, 10] with a unique and separately conserved lepton number, and hence with a unique associated neutrino ν_τ .

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^{†1} Alternative models in which the τ is a weakly decaying hadron or carries the lepton number of the muon are not consistent with the published evidence as discussed in ref. [1]. Ref. [9] shows that the τ is not an electron-related paralepton. If the τ is an electron-related ortholepton with electromagnetic decay modes strongly suppressed relative to weak decay modes the conclusions of this paper are unchanged.

Mass of the τ . To determine the mass of the τ (m_τ) we use 144 $e\mu$ events (after the subtraction of background events using the methods of ref. [2]) of the form

$$e^+ + e^- \rightarrow e^\pm + \mu^\mp + \text{no other detected particles.} \quad (1)$$

In the sequential lepton model these events are explained by the reaction sequence: $e^+ + e^- \rightarrow \tau^+ + \tau^-$, $\tau^+ \rightarrow \bar{\nu}_\tau + e^+ + \nu_e$, $\tau^- \rightarrow \nu_\tau + \mu^- + \bar{\nu}_\mu$. We have three methods for measuring m_τ . In the first method we define a pseudotransverse momentum, p_T , by finding an axis in the $e\mu$ plane (fig. 1) such that the perpendicular components of the e and μ with respect to that axis are equal and a minimum. Explicitly,

$$p_T = |\mathbf{p}_e \times \mathbf{p}_\mu| / |\mathbf{p}_e - \mathbf{p}_\mu|,$$

where \mathbf{p}_e and \mathbf{p}_μ are the momenta of the e and μ respectively. We then compare the average value of p_T in our data with a theoretical prediction made with a Monte Carlo method which takes into account the acceptance of the detector and our cuts on the $e\mu$ events:

$$p_e > 0.65 \text{ GeV}/c, \quad p_\mu > 0.65 \text{ GeV}/c, \quad \theta_{\text{copl}} > 20^\circ, \quad (2)$$

where θ_{copl} is the acoplanarity angle between the plane containing the e and the incident e^+ beam and the plane containing the μ and the incident e^+ beam. The p_T distribution for $E_{\text{cm}} > 4.8 \text{ GeV}$, fig. 1a, yields $\langle p_T \rangle = 0.481 \pm 0.016 \text{ GeV}/c$ after correction for contamination from background events. Comparing this result with the theoretical dependence of $\langle p_T \rangle$ on m_τ ,

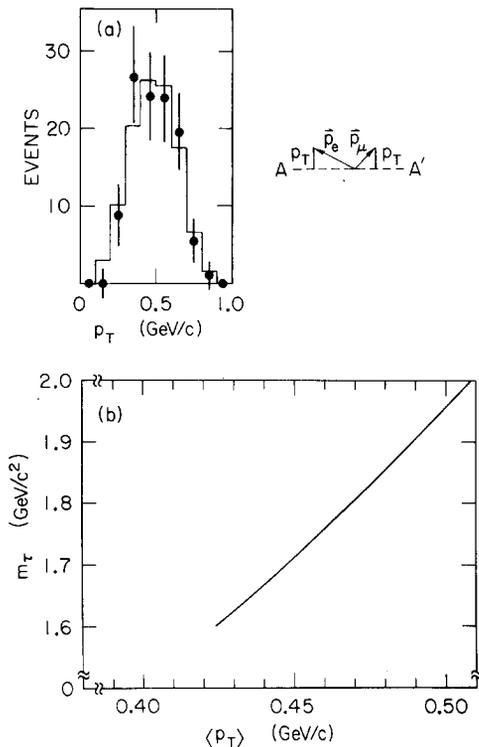


Fig. 1(a) The distribution in p_T for $e\mu$ events with $E_{cm} > 4.8$ GeV, corrected for contamination by background events. The solid line is a theoretical calculation of this distribution for a lepton with $m_\tau = 1.9$ GeV/c², $m_{\nu_\tau} = 0.0$, and V - A coupling. (b) The theoretical relation between m_τ and $\langle p_T \rangle$ for a lepton with $m_{\nu_\tau} = 0.0$ and V - A coupling, for the range of E_{cm} values of the events in (a)

Table 1A

Mass measurements of the τ in GeV/c², assuming V - A coupling for the $\tau - \nu_\tau$, and $m_{\nu_\tau} = 0.0$. The three methods are based on: p_T , the pseudo-transverse momentum; $\cos \theta_{coll}$, the cosine of the collinearity angle; and r , the scaled momentum distribution. They are explained in the text. The errors are statistical.

E_{cm} range (GeV)	Method		
	p_T	$\cos \theta_{coll}$	r
$3.8 \leq E_{cm} < 4.8$	1.88 ± 0.08	1.91 ± 0.25	1.83 ± 0.06
$E_{cm} = 4.8$	2.11 ± 0.13	1.82 ± 0.22	1.83 ± 0.08
$4.8 < E_{cm} \leq 7.8$	1.86 ± 0.08	1.85 ± 0.12	2.27 ± 0.31
$3.8 \leq E_{cm} \leq 7.8$	1.91 ± 0.05	1.85 ± 0.10	1.88 ± 0.06

fig. 1b, we obtain $m_\tau = 1.86 \pm 0.08$ GeV/c² for V - A coupling and assuming the mass of the ν_τ (m_{ν_τ}) is 0. Values of m_τ for other E_{cm} ranges are given in table 1.

The second method for determining m_τ compares the measured average value of $\cos \theta_{coll}$ with theory using a procedure analogous to the p_T method. Here

$$\cos \theta_{coll} = -(\mathbf{p}_e \cdot \mathbf{p}_\mu) / |\mathbf{p}_e| |\mathbf{p}_\mu|.$$

The third method uses the r distribution, fig. 2, where

$$r = (p - 0.65) / (p_{max} - 0.65), \quad 0 \leq r \leq 1.$$

Here p is the momentum of the e or μ in GeV/c; and p_{max} , the maximum value of p , depends on m_τ . To determine m_τ we use the ratio of the number of events with $r \geq 0.6$ to the number with $0.2 \leq r \leq 0.6$ ^{#2}.

Table 1 summarizes the results of these mass determinations. For what we call our standard model, V - A coupling and $m_{\nu_\tau} = 0.0$, we combine these results to obtain

$$m_\tau = 1.90 \pm 0.10 \text{ GeV}/c^2,$$

where we have given more weight to the p_T method, and the error includes systematic errors. These systematic errors are primarily due to the effect of the cuts, eq. (2), on the comparison of measured values with theory. Although this mass is surprisingly close to the masses of the singly charmed D^0 and D^\pm mesons; there

^{#2} The region $r < 0.2$ is not used because later in this paper we want to use this mass determination to examine the nature of the $\tau - \nu_\tau$ coupling by a method which is independent of small r values.

Table 1B

Mass measurements of the τ in GeV/c² for two models: V - A coupling for the $\tau - \nu_\tau$ and $m_{\nu_\tau} = 0.5$ GeV/c²; and V + A coupling for the $\tau - \nu_\tau$ and $m_{\nu_\tau} = 0.0$. The three methods: p_T , $\cos \theta_{coll}$, and r ; are explained in the text. The entire $3.8 \leq E_{cm} \leq 7.8$ range is used and the errors are statistical.

Model	Method		
	p_T	$\cos \theta_{coll}$	r
V - A $m_{\nu_\tau} = 0.5 \text{ GeV}/c^2$	2.01 ± 0.05	1.90 ± 0.09	1.70 ± 0.12
V + A $m_{\nu_\tau} = 0.0$	2.12 ± 0.05	1.95 ± 0.10	Upper limit is 1.76 with 95% confidence

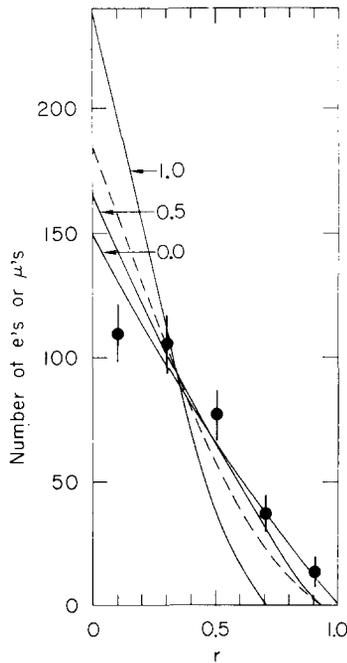


Fig. 2. The r distribution for all events corrected for background. The solid curves are for $m_\tau = 1.9 \text{ GeV}/c^2$ and V - A coupling with m_ν in GeV/c^2 as indicated. The dashed curve is for V + A coupling with $m_\tau = 1.90 \text{ GeV}/c^2$ and $m_{\nu\tau} = 0.0$.

is substantial evidence [1] that the anomalous $e\mu$ events do not come from the decay of the D mesons.

A direct comparison of this m_τ determination with the observed $e\mu$ production cross section, $\sigma_{e\mu}$, is presented in fig. 3. The curves are given by the equations

$$\sigma_{e\mu}(s) = 2A_{e\mu}(s) B_e B_\mu \sigma_{\tau\tau}(s), \quad (3a)$$

$$\sigma_{\tau\tau}(s) = 2\pi\alpha^2\beta(3 - \beta^2)/3s. \quad (3b)$$

B_e and B_μ are the branching ratios for τ^- goes to $\nu_\tau e^- \bar{\nu}_e$ and $\nu_\tau \mu^- \bar{\nu}_\mu$ respectively and $s = E_{cm}^2$. $A_{e\mu}(s)$, a calculated acceptance which includes the detector efficiencies, is roughly independent of E_{cm} and is about 6%. The curves are for $m_\tau = 1.8$ or $2.0 \text{ GeV}/c^2$ and the product $B_e B_\mu$ is adjusted for each mass choice to give the best fit. The χ^2 probability of these fits is 90%. As m_τ is increased above $1.9 \text{ GeV}/c^2$, an increasing number of $e\mu$ events must be attributed to background. This leads to a probability of less than 0.8% that $m_\tau \geq 2.10 \text{ GeV}/c^2$.

τ neutrino mass. To set a limit on m_ν we use the r distribution on fig. 2. The solid curves are for m_τ

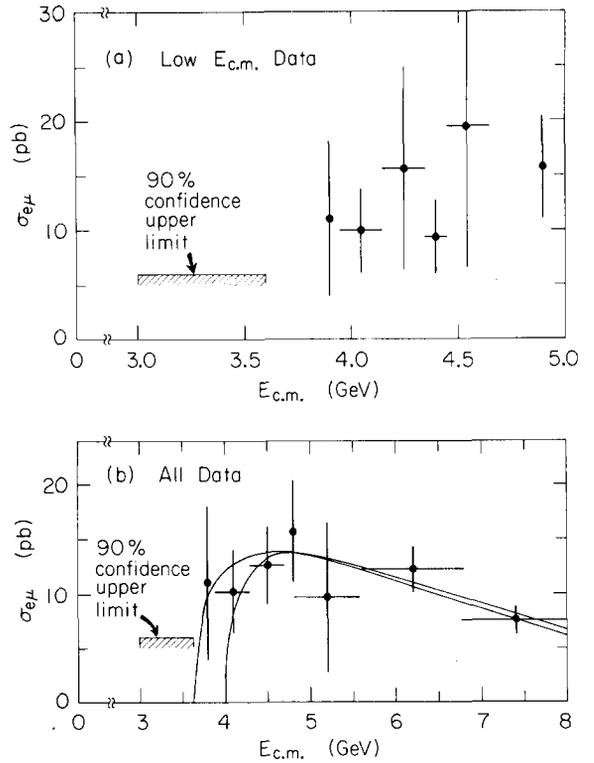


Fig. 3. The observed $e\mu$ production cross section, $\sigma_{e\mu}$. The vertical lines are statistical errors, the horizontal lines show the E_{cm} range covered by each point. No events before background subtraction were found in the E_{cm} range of 3.0 to 3.6 GeV. We show the 90% confidence upper limit on $\sigma_{e\mu}$ if 2.3 events had been found. (a) the low E_{cm} region. We note that there is no enhancement in $\sigma_{e\mu}$ at $E_{cm} = 4.05$ or 4.4 GeV where there is enhanced charmed particle production [11]. (b) The entire E_{cm} region. The data in the lower E_{cm} region has been combined into fewer points. The curves are explained in the text.

$= 1.90 \text{ GeV}/c^2$, V - A coupling, and $m_{\nu\tau} = 0.0, 0.5$ and $1.0 \text{ GeV}/c^2$ respectively. As $m_{\nu\tau}$ increases the quality of fit decreases. The 95% confidence upper limit on $m_{\nu\tau}$ is

$$m_{\nu\tau} < 0.6 \text{ GeV}/c^2; \text{ for } m_\tau = 1.90 \text{ GeV}/c^2, \text{ V - A.}$$

This upper limit decreases by about $0.1 \text{ GeV}/c^2$ for a $0.1 \text{ GeV}/c^2$ increase in m_τ .

$\tau - \nu_\tau$ coupling. As shown in fig. 2 with $m_\tau = 1.9 \text{ GeV}/c^2$ and $m_{\nu\tau} = 0.0$ a V + A coupling of the τ to the ν_τ is a poor fit. The χ^2 probability is about 0.1% compared to a χ^2 probability of 50% for V - A. Most of the poor fit to V + A comes from the $r < 0.2$ point which is closest to the $p = 0.65 \text{ GeV}/c$ cutoff. Al-

though we have no evidence for any systematic effect of the cutoff on the r distribution, we have also tested the V + A fit for the $r \geq 0.2$ data. We then find a χ^2 probability for V + A coupling of 5%, which is not a compelling argument against V + A coupling. However, an additional argument against V + A coupling appears in the bottom line of table 1B. We are not able to get a consistent determination of m_τ for V + A coupling. Therefore in our present data, V - A coupling gives a better fit than V + A coupling for $m_\tau = 1.9 \text{ GeV}/c^2$ and $m_\nu = 0.0$. Increasing $m_{\nu\tau}$ makes the V + A fit worse.

Leptonic branching ratios. We obtain the leptonic branching ratios from the $e\mu$ events by fitting eqs. (3) to the data in fig. 3 assuming $B_e = B_\mu$. We find for our standard model:

$$B_e \equiv B_\mu = 0.186 \pm 0.010 \pm 0.028, \quad (4a)$$

where the first error is statistical and the second is systematic. Independently we can obtain B_μ from the μx events by assuming that their source is the reaction sequence $e^+ + e^- \rightarrow \tau^+ + \tau^-$, $\tau^+ \rightarrow \bar{\nu}_\tau + \mu^+ + \nu_\mu$, $\tau^- \rightarrow \nu_\tau + 1$ charged particle + ≥ 0 photons; by using the equation

$$\sigma_{\mu x}(s) = 2A_{\mu x}(s)B'_\mu B_x \sigma_{\tau\tau}(s);$$

and by assuming the theoretical [10, 1] value $B_x = 0.85$ for the probability that the τ decays to a single charged particle. We find for our standard model

$$B'_\mu = 0.175 \pm 0.027 \pm 0.030, \quad (4b)$$

where the first error is statistical and the second is systematic. We note that the results in eqs. (4a) and (4b) agree with each other and with theory [1]. If there are contributions to our $e\mu$ or μx events from anomalous sources other than τ production, these branching ratios will decrease.

Contribution of $\tau^+\tau^-$ production to R . We measure the contribution of $\tau^+\tau^-$ production to the total cross

section by rewriting eq. (3b) in the form

$$\sigma_{\tau\tau}(s) = 2\pi\alpha^2\beta(3 - \beta^2)R_\tau/3s,$$

where R_τ is 1 for a point particle. Then eqs. (4a) and (4b) take the form $B_\mu \sqrt{R_\tau} = 0.186$, $B'_\mu R_\tau = 0.175$. Equating B_μ with B'_μ we obtain

$$R_\tau = 0.89 \pm 0.29 \pm 0.27,$$

where the first error is statistical and the second is systematic.

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