EVIDENCE FOR, AND PROPERTIES OF, THE NEW CHARGED HEAVY LEPTON* †

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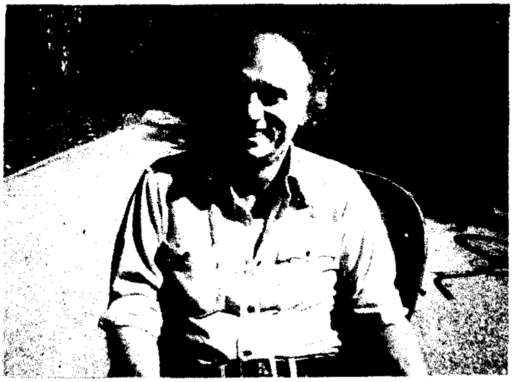

ABSTRACT

This paper summarizes the evidence for, and the properties of, the mass 1.9 ± .1 GeV/c^2 charged heavy lepton recently found in e^+e^- annihilation.

Cet article est un résumé concernant les évidences en faveur et les propertiétés du lepton lourd chargé de masse 1.9 ± .1 GeV/c^2 découvert récemment dans l'annihilation e^+e^-.

CONTENTS

1. INTRODUCTION

It is very likely that a mass 1.90 ± .10 GeV/c^2 charged heavy lepton has been found in e^+e^- annihilation. This paper summarizes the evidence for the new lepton and then presents what we know so far about its properties. The summary of the evidence is very brief; the original papers must be consulted for details on the event selection criteria, on the elimination of conventional explanations, and for the background calculations.

When we first found evidence for this new particle -- the eμ events in the data of the SLAC-LBL Magnetic Detector Collaboration[1] -- we called the particle U as a temporary name because its nature was unknown. Since there is now substantial evidence that it is a lepton, we wish to designate it by a lower case Greek letter. We use $\tau^{\pm}$ because it appears to be the third charged lepton to be found and τριτον means third in Greek. We feel the old use of τ to designate the three pion decay mode of the K is now obsolete.

2. THEORY

Since the τ lepton is experimentally found to decay only thru the weak interactions we consider those theories in which there are no electromagnetic decays or in which the electromagnetic decays are very strongly suppressed.

A. Sequential Heavy Lepton: A sequential heavy lepton[2] has its own unique lepton number giving a sequence:

$$\begin{array}{ll} e^{\pm} & \nu_e, \bar{\nu}_e \\ \mu^{\pm} & \nu_\mu, \bar{\nu}_\mu \\ \tau^{\pm} & \nu_\tau, \bar{\nu}_\tau \\ \cdot & \cdot \\ \cdot & \cdot \\ \cdot & \cdot \end{array} \qquad (1)$$

and all lepton numbers are separately conserved. Hence

$$\tau^- \not\to e^- + \gamma, \quad \tau^- \not\to \mu^- + \gamma \qquad (2)$$

cannot occur. The decay occurs only thru the weak interactions, the purely leptonic modes being

$$\tau^- \rightarrow \nu_\tau + e^- + \bar{\nu}_e$$
$$\tau^- \rightarrow \nu_\tau + \mu^- + \bar{\nu}_\mu \qquad (3)$$

For a sufficiently large τ mass there are also hadronic decays

$$\tau^- \rightarrow \nu_\tau + \text{hadrons} \qquad (4)$$

Table I gives the expected branching ratios for a mass 1.9 GeV/c^2 sequential heavy lepton using conventional weak interaction theory as worked out by Thacker and Sakurai[3] and by Tsai.[4] For future use we note that most of the decay modes contain only one charged particle, indeed 85% of the decays give one charged particle.

B. Paraleptons: Llewellyn Smith[6] defines paraleptons as charged heavy leptons with the same lepton number as the oppositely charged e or μ; hence such leptons cannot decay electromagnetically. Thus Bjorken and Llewellyn Smith[7] define the E^- and M^- to have the lepton numbers of the e^+ and μ^+ respectively. The lower bounds on the $M^\pm$ mass set by Barish et al.[8] means that the M cannot be produced by currently operating e^+e^- colliding beams machines. The $E^\pm$ with decay modes

$$E^- \rightarrow \bar{\nu}_e + e^- + \bar{\nu}_e \qquad (5a)$$

$$E^- \rightarrow \bar{\nu}_e + \mu^- + \bar{\nu}_\mu \qquad (5b)$$

$$E^- \rightarrow \bar{\nu}_e + \text{hadrons} \qquad (5c)$$

is not excluded by existing neutrino production data.

C. Ortholeptons: Ortholeptons[6] are charged heavy leptons with the same lepton number as the same charge e or μ. Ordinarily the e^* with the same lepton number as the e^- would decay electromagnetically

$$e^{*-} \rightarrow e^- + \gamma \qquad (6)$$

However, the coupling constant at the $e^*e\gamma$ vertex is arbitrary as pointed out by

TABLE I

Predicted branching ratios for a τ^- sequential charged heavy lepton with a mass 1.9 GeV/c^2, an associated neutrino mass of 0.0, and V-A coupling. The predictions are based on Refs. 3 and 4 as discussed in Ref. 5. The hadron continuum branching ratio assumes a threshold at 1.2 GeV for production of $\bar{u}d$ quark pairs whose final state interaction leads to the hadron continuum

decay mode	branching ratio	number of charged particles in final state
$\nu_\tau e^- \bar{\nu}_e$	.20	1
$\nu_\tau \mu^- \bar{\nu}_\mu$	.20	1
$\nu_\tau \pi^-$	.11	1
$\nu_\tau K^-$	.01	1
$\nu_\tau \rho^-$	.22	1
$\nu_\tau K^{*-}$	.01	1
$\nu_\tau A_1^-$	.07	1, 3
ν_τ(hadron continuum)$^-$	.18	1, 3, 5

Low[9]; and we may make it so small that the weak decays

$$e^{*-} \to \nu_e e^- \bar{\nu}_e,\ \nu_e \mu^- \bar{\nu}_\mu,\ \nu_e \text{hadrons} \qquad (7)$$

are stronger than the decay in Eq. 6. A similar remark holds for the μ^{*-} with the lepton number of the μ^-. We also call such leptons excited electrons or excited muons.

3. EVIDENCE FOR EXISTENCE OF THE τ: $e\mu$ EVENTS

The reaction

$$e^+ + e^- \to e^\pm + \mu^\mp + \text{no other particles detected} \qquad (8)$$

produced thru

$$\begin{array}{lll} e^+ + e^- \to & \tau^+ & + \tau^- \\ & \downarrow & \quad \downarrow \\ & \bar{\nu}_\tau e^+ \nu_e & \quad \nu_\tau \mu^- \bar{\nu}_\mu \end{array}$$

is a very distinctive signature for τ pair production.

A. SLAC-LBL Magnetic Detector Collaboration Data: Such $e\mu$ events were first found in 1975 by this collaboration and analyses of these events have been published.[10,11] It was very important to show that these events did not come from

$$e^+ + e^- \to e^\pm + \mu^\mp + \text{hadrons} \qquad (10)$$

in which the hadrons escaped detection. This is because an alternative source of $e^\pm \mu^\mp$ pairs is the joint semi-leptonic decay of a pair of charmed hadrons (h_c) thru reaction sequences like

$$\begin{array}{llll} e^+ + e^- \to & h_c^+ & + \ h_c^- & + \text{perhaps hadrons} \\ & \downarrow & \quad \downarrow & \\ & e^+ \nu_e \text{ hadrons} & \quad \mu^- \bar{\nu}_\mu \text{ hadrons} & \end{array} \qquad (11)$$

This has been eliminated[11] as a major source of the $e\mu$ events in Eq. 8 because there are simply far too few events of the form

$$e^+ + e^- \to e^\pm + \mu^\mp + \text{detected hadrons} \qquad (12)$$

to explain the number of events of the form of Eq. 8. Charged hadrons, π^o's and K_S^o's are directly eliminated. The possibility of the undetected hadrons being K_L^o's is eliminated by the natural assumption that K_S^o's and K_L^o's would occur at equal rates in the reaction in Eq. 10. The elimination of the possibility of undetected neutrons is discussed later.

In the paper the analysis of the SLAC-LBL Magnetic Detector Group's eμ data is based upon a total of 190 events including a background contamination of 46 events yielding 144 net eμ events. These events are produced in the E_{cm} range of 3.8 to 7.8 GeV.

B. PLUTO Group Data: The PLUTO Group[12,13] has recently described 12 eμ events with a background of < 1.5 events produced in the E_{cm} range 4.0 to 4.8 GeV. The importance of these events is that they have much less background contamination than the SLAC-LBL events, they agree with the SLAC-LBL events in their momentum and angle distributions, and they agree with the SLAC-LBL events in their production cross section. It is also very important that they can show directly[12,13] that their events do not come from the reaction in Eq. 10.

4. CONSISTENCY OF THE eμ EVENT DISTRIBUTIONS WITH THE LEPTON HYPOTHESIS

It is necessary to show that the momentum and angular distributions of the eμ events are consistent with the theory of the purely leptonic, 3-body, decay modes of Eq. 3. In comparing the SLAC-LBL data with theory we must take account[10,11] of the geometric acceptance of the apparatus; and of the eμ event selection criteria on the e and μ momentum

$$p_e > 0.65 \text{ GeV/c}, \quad p_\mu > 0.65 \text{ GeV/c}, \tag{13a}$$

and of the cut on the acoplanarity angle

$$\theta_{copl} > 20^o \tag{13b}$$

To combine the momentum spectra at different E_{cm} we define a scaled momentum parameter r (called ρ in previous papers)

$$r = (p - 0.65)/(p_{max} - 0.65) \tag{14}$$

where p is p_e or p_μ in GeV/c and p_{max} is its maximum value. The range of r is $0 \lesssim r \lesssim 1$.

Figure 1 and 2 show that the r distributions are well fit by a lepton with

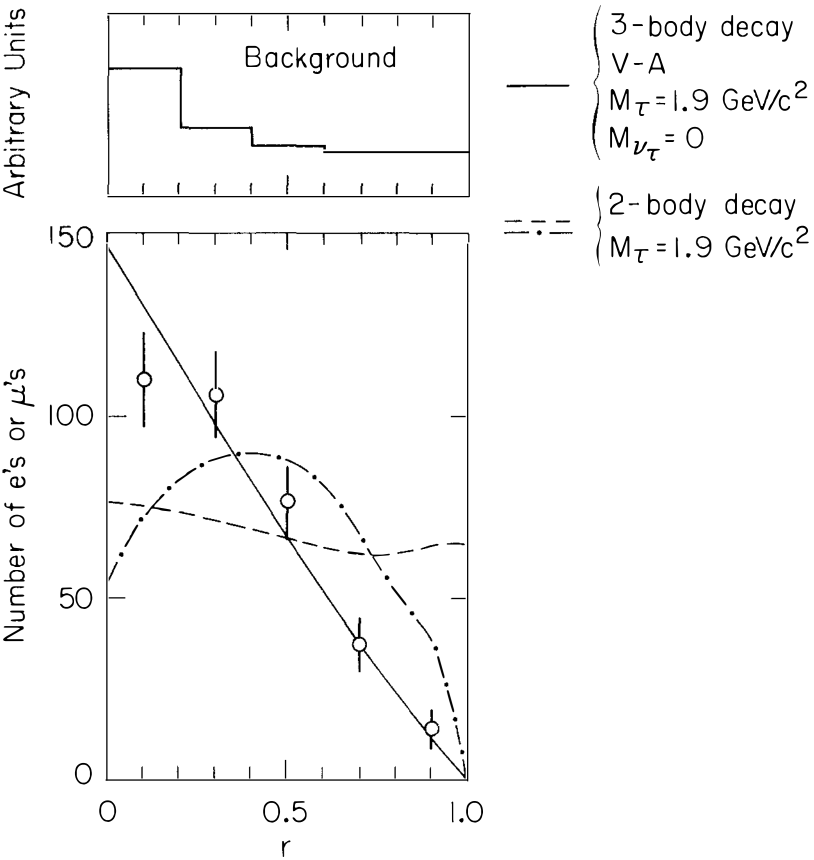

FIG. 1 -- The lower figure shows the r distribution (Eq. 14) for $3.8 \lesssim E_{cm} \lesssim 7.8$ GeV with background subtracted. The solid curve is for the 3-body, leptonic decay of the τ (Eq. 3) with the indicated parameters. The dash and dash-dot curves are for 2-body leptonic decay modes of a boson; the former is for nc spin alignment of the boson, and the latter is for a spin 1 boson produced only in the helicity = 0 state.

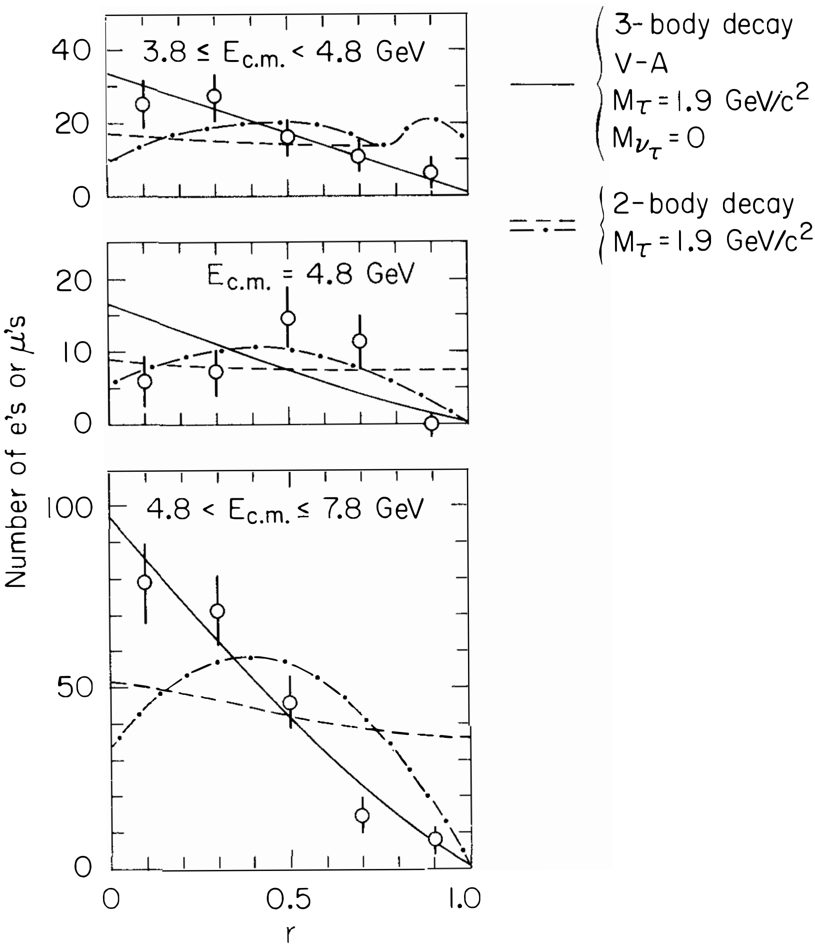

FIG. 2 -- The r distributions for three E_{cm} ranges with background subtracted. See the caption to Fig. 1.

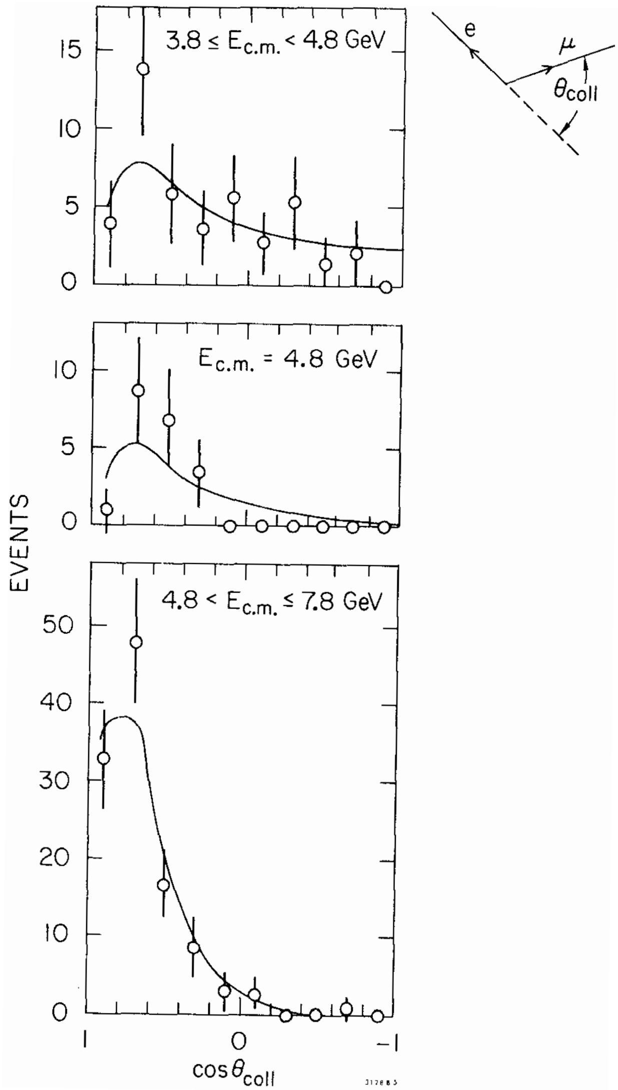

FIG. 3 -- The cos θ_{coll} distribution for three E_{cm} energy ranges. The solid line is for m_τ = 1.9 GeV/c^2, m_{ν_τ} = 0.0 and V-A coupling.

$m_\tau = 1.9$ GeV/c^2, $m_{\nu_\tau} = 0.0$ and V-A coupling. Only our old $E_{cm} = 4.8$ GeV data is a poor fit as we have noted previously.[10,11] Incidentally the hypothesis that the τ is a boson, with the purely leptonic 2-body decays $\tau^- \to e^- \bar{\nu}_e$, $\mu^- \bar{\nu}_\mu$, is eliminated by this data.

Figure 3 shows that the collinearity angle distributions,

$$\cos \theta_{coll} = -(\underset{\sim}{p}_e \cdot \underset{\sim}{p}_\mu)/(|\underset{\sim}{p}_e||\underset{\sim}{p}_\mu|) \tag{15}$$

are also fit by the $m_\tau = 1.9$, $m_{\nu_\tau} = 0.0$, V-A model.

5. EVIDENCE FOR EXISTENCE OF THE τ: $e^\pm \chi^\mp, \mu^\pm \chi^\mp$ EVENTS

Another strong signature for the τ is the sequence of reactions

$$\begin{array}{ccccc} e^+ + e^- \to & \tau^+ & + & \tau^- & ; \\ & \downarrow & & \downarrow & \\ & \bar{\nu}_\tau \mu^+ \nu_\mu & & \nu_\tau \chi^- + \text{neutral particles} & \end{array} \tag{16}$$

because as pointed out in Sec. 2A, 85% of the decay modes of a 1.9 GeV/c^2 τ contain only 1 charged particle. Explicitly the signature is a 2-charged prong lepton inclusive event of the form

$$\begin{array}{l} e^+ + e^- \to e^\pm + \chi^\mp + \geq 0 \text{ photons} \\ e^+ + e^- \to \mu^\pm + \chi^\mp + \geq 0 \text{ photons} \end{array} \tag{17}$$

Here χ is a charged lepton or hadron. Such events, called $e^\pm \chi^\mp$ or $\mu^\pm \chi^\mp$, are unlikely to come from charmed hadrons, because as indicated by Eq. 11, relatively high multiplicities occur when charmed hadrons are produced and decay.

<u>A. Maryland-Princeton-Pavia $\mu^\pm \chi^\mp$ Data:</u> Such events were first found by M. Cavalli-Sforza et al.[14] As analyzed by Snow[15] these events are consistent with the existence of the τ.

<u>B. SLAC-LBL Magnetic Detector Collaboration $\mu^\pm \chi^\mp$ Data:</u> Feldman et al.,[16] have published $\mu^\pm \chi^\mp$ data which requires the existence of the τ and will be used later in this paper. This data gives a very significant signal in the E_{cm} range of 5.8 to 7.8 GeV.

<u>C. PLUTO Group $\mu^\pm \chi^\mp$ Data:</u> The PLUTO group has reported[12,13] a significant $\mu^\pm \chi^\mp$ signal in the E_{cm} range of 4.0 to 4.8 GeV. They have attributed these

events to a charged lepton with a mass of roughly 1.95 GeV/c^2.

D. DASP Group $e^{\pm}\chi^{\mp}$ Data: Very recently the DASP Group reported[17,18] $e^{\pm}\chi^{\mp}$ events in the E_{cm} range of 4.0 to 5.0. The observed production cross section[17,18] and the e momentum distribution[17] are those expected from the τ.

To summarize, all e^+e^- annihilation experiments which should see the $e^{\pm}\chi^{\mp}$ or $\mu^{\pm}\chi^{\mp}$ signature of the τ have seen such events.

6. LEPTONIC NATURE OF THE τ

There are two kinds of data which argue for the leptonic nature of the τ. First, the existence of $e^{\pm}\mu^{\mp}$ and $\mu^{\pm}\chi^{\mp}$ events at large E_{cm} means that the pure pair production reaction $e^+e^- \rightarrow \tau^+\tau^-$ is occuring at large E_{cm}. It is very unlikely that 1.9 GeV/c^2 mass hadrons can be produced in a pure pair production reaction at large E_{cm}.

Second, as shown in Fig. 4, the observed eμ production cross sections, $\sigma_{e\mu}$, fits the point particle production cross sections for a heavy lepton. Here (with $s = E_{cm}^2$)

$$\sigma_{e\mu}(s) = 2A_{e\mu}(s)B_eB_\mu\sigma_{\tau\tau}(s) \qquad (18a)$$

where

$$\sigma_{\tau\tau}(s) = \frac{2\pi\alpha^2\beta(3-\beta^2)}{3s} \qquad (18b)$$

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 βc is the velocity of the τ, and $A_{e\mu}(s)$ is a calculated acceptance. The solid curves in Fig. 4 are for m_τ = 1.8 or 2.0 and the product B_eB_μ is adjusted to give a best fit. If we multiply the right side of Eq. 18a by a form factor squared F_τ^2, where F_τ = constant/s, we get a very poor fit -- the dashed curve in Fig. 4, Hence while we cannot rule out a weak form factor effect, $\sigma_{e\mu}$ is certainly consistent with the τ being a point particle, as a lepton is expected to be.

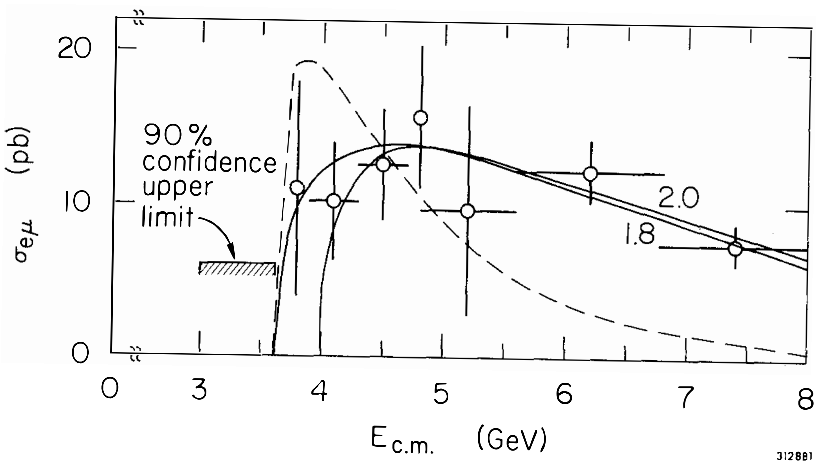

FIG. 4 -- The observed eμ production cross section, $\sigma_{e\mu}$. The vertical lines are statistical errors, the horizonal lines show the E_{cm} range covered by each point. No events before background subtraction were found in the E_{cm} range of 3.0 to 3.6 GeV. We show the 90% confidence upper limit on $\sigma_{e\mu}$ if 2.3 events had been found. The curves are explained in the text.

7. ANOMALOUS e^+e^- AND $\mu^+\mu^-$ PAIRS AND ELIMINATION OF THE ELECTRON RELATED PARALEPTON HYPOTHESIS

If the τ is a lepton with conventional weak interactions we must see non-coplanar, anomalous e^+e^- and $\mu^+\mu^-$ pairs as well as $e^{\pm}\mu^{\mp}$ pairs. For example $\mu^+\mu^-$ pairs come from

$$e^+ + e^- \rightarrow \begin{array}{c}\tau^+ \\ \downarrow \\ \bar{\nu}_\tau \mu^+ \nu_\mu\end{array} + \begin{array}{c}\tau^- \\ \downarrow \\ \nu_\tau \mu^- \bar{\nu}_\mu\end{array} \tag{19a}$$

giving

$$e^+ + e^- \rightarrow \mu^+ + \mu^- + \text{no other detected particles} \tag{19b}$$

Unfortunately the reaction in Eq. 19 has large backgrounds from quantum electrodynamic processes such as $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ and $e^+e^- \rightarrow \gamma\gamma\mu^+\mu^-$ in which the e^+e^- or $\gamma\gamma$ are not detected. After subtracting these backgrounds, the SLAC-LBL Magnetic Detector Collaboration data gives[19] for the ratios of the observed cross sections :

$$\text{For } 4.8 < E_{cm} \lesssim 6.8 \qquad \frac{\sigma_{ee}}{\sigma_{e\mu}} = .54 \pm .3, \quad \frac{\sigma_{\mu\mu}}{\sigma_{e\mu}} = .50 \pm .2$$

$$\text{For } 6.8 < E_{cm} \lesssim 7.8 \qquad \frac{\sigma_{ee}}{\sigma_{e\mu}} = .59 \pm .3, \quad \frac{\sigma_{\mu\mu}}{\sigma_{e\mu}} = .47 \pm .2 \tag{20}$$

These results are preliminary, in particular σ_{ee} may be systematically 20 or 30% too high. The cuts in Eq. 13 were used, as well as requiring

$$(\text{missing mass})^2 > 2.0(\text{GeV}/c^2)^2 \tag{21}$$

Equations 21 eliminates background from ee $\rightarrow$ eeγ and ee $\rightarrow$ $\mu\mu\gamma$.

For sequential heavy leptons or for ortholeptons $B_e = B_\mu$. Hence we expect

$$\frac{\sigma_{ee}}{\sigma_{e\mu}} = \frac{\sigma_{\mu\mu}}{\sigma_{e\mu}} = 0.5 \tag{22}$$

in agreement with the data in Eq. 20. However in a paralepton theory the decay mode $\tau^+ \rightarrow e^+\nu_e\nu_e$ has two identical neutrinos in the final state which interfere constructively.[7,20] This leads to $B_e = 2B_\mu$ and we expect[21]

$$\frac{\sigma_{ee}}{\sigma_{e\mu}} = 1.0 \ , \ \frac{\sigma_{\mu\mu}}{\sigma_{e\mu}} = 0.25 \qquad (23)$$

This contradicts the data in Eq. 20 and eliminates the possibility that the τ is an electron related paralepton. As we pointed out in Sec. 2B the muon related paralepton possibility was already ruled out.

8. PROPERTIES OF THE τ

Using the data of the SLAC-LBL Magnetic Detector Collaboration we find the τ to have the following properties

A. τ Mass: Using the eμ events we can find the τ mass, m_τ, in three ways. First as shown in Fig. 5, we define a pseudo-transverse momentum, $p_\perp$, by finding an axis AA' such that the perpendicular momentum components of the e and μ are equal and minimum. We then compare the average value of $p_\perp$ in the data with a theoretical prediction made with a Monte Carlo method. Our second way is to use the average value of cos θ_{coll}, Eq. 15, and again compare data with theory. A third way[22] uses the r distribution comparing the number of events with $.6 \lesssim r \lesssim 1.0$ to the nummber with $.2 \lesssim r < .6$. Table II gives the results. For what we shall call our standard model, $m_{\nu_\tau} = 0.0$ and V-A coupling, we combine the $p_\perp$ and cos θ_{coll} methods to obtain

$$m_\tau = 1.90 \pm .10 \qquad (24)$$

where the error includes systematic uncertainties.

Some other observations on Table II are:

a. The high and low E_{cm} ranges give the same values within errors of m_τ, a nice demonstraction that we are dealing with the same particle over the entire E_{cm} range.

b. The $p_\perp$ value for E_{cm} = 4.8 GeV is high, we have noted before[11] that this set of data looks different in the r distribution, but the difference is not statistically significant.

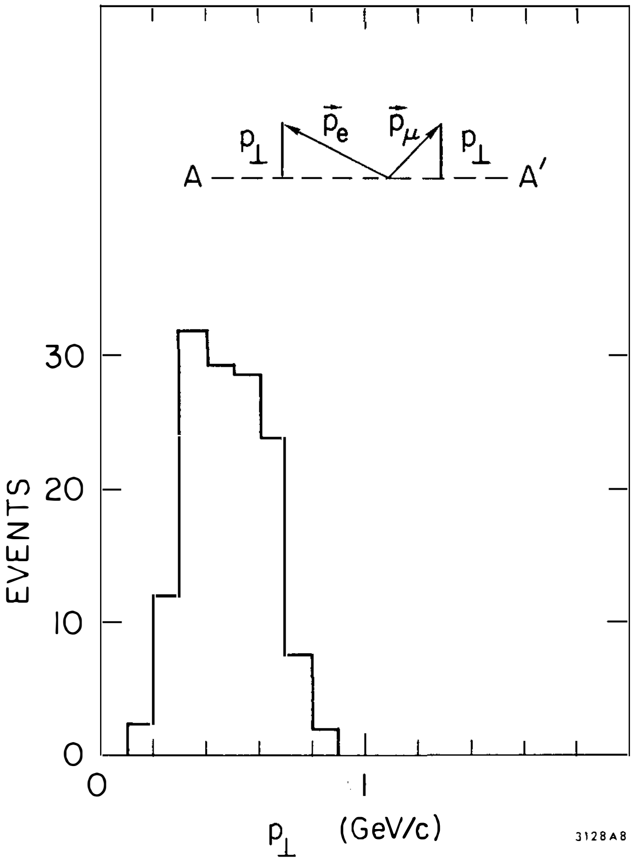

FIG. 5 -- The $p_\perp$ distribution for all eμ events not corrected for background.

TABLE IIA

Mass measurments of the τ in GeV/c^2, assuming V-A coupling for the $\tau-\nu_\tau$, and m_{ν_τ} = 0.0. The three methods are based on: $p_\perp$, the pseudo-transverse momentum; cos θ_{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		
	$p_\perp$	cos θ_{coll}	r
$3.8 \leq E_{cm} < 4.8$	1.88 ± .08	1.91 ± .25	1.83 ± .06
$E_{cm} = 4.8$	2.11 ± .13	1.82 ± .22	1.83 ± .08
$4.8 < E_{cm} \leq 7.8$	1.86 ± .08	1.85 ± .12	2.27 ± .31
$3.8 \leq E_{cm} \leq 7.8$	1.91 ± .05	1.85 ± .10	1.88 ± .06

TABLE IIB

Mass measurements of the τ in GeV/c^2 for two models: V-A coupling for the $\tau-\nu_\tau$ and m_{ν_τ} = 0.5 GeV/c^2; and V+A coupling for the $\tau-\nu_\tau$ and m_{ν_τ} = 0.0. The three methods: $p_\perp$, cos θ_{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		
	$p_\perp$	cos θ_{coll}	r
V-A m_{ν_τ} = 0.5 GeV/c^2	2.01 ± .05	1.90 ± .09	1.70 ± .12
V+A m_{ν_τ} = 0.0	2.12 ± .05	1.95 ± .10	upper limit is 1.76 with 95% confidence.

c. If m_{ν_τ} is 0.5 GeV/c^2, m_τ increases a little.

d. A model with V+A coupling and m_{ν_τ} = 0.0 gives inconsistent values of m_τ.

As a check of these m_τ determinations, we show in Table III $P_T(m_\tau)$, the probability that all eμ events produced at $E_{cm} \lesssim 2m_\tau$ come from background. Since we have no eμ events at E_{cm} < 3.8 GeV, $P_T(m_\tau < 1.9)$ = 100%. Thus $P_T(m_\tau)$ is a threshold probability. Table III also gives a χ^2 goodness of fit probability, $P_F(m_\tau)$, which uses Eq. 18 and ignores all data with $E_{cm} \lesssim 2m_\tau$. Table III agrees with Eq. 24. The P_T values in Table III show that we should not take m_τ > 2.05 GeV/c^2 unless forced to do so by other measurements.

B. τ Neutrino Mass: To set a limit on m_{ν_τ} we use the r distribution in Fig. 6. The solid curves are for m_τ = 1.90 GeV/c^2, V-A coupling, and m_{ν_τ} = 0.0, 0.5 and 1.0 GeV/c^2 respectively. As m_{ν_τ} increases the quality of fit decreases. The 95% confidence upper limit on m_{ν_τ} is

$$m_{\nu_\tau} < 0.6 \text{ GeV}/c^2 \; ; \text{ for } m_\tau = 1.90 \text{ GeV}/c^2, \text{ V-A} \qquad (25)$$

We note; this limit on m_{ν_τ} eliminates the possibility that ν_τ is actually a neutron, in the decay

$$\tau^- \to e^- + \bar{\nu}_e + n \quad ; \qquad (26)$$

τ being then a heavy proton -- an old conjecture of M. Goldhaber.[24] As indicated indirectly by Table II, if we increase m_τ we can increase the limit on m_{ν_τ}. We have not yet determined how much we can increase the limit on m_{ν_τ} in this way because the three methods of determining m_τ (using $p_\perp$, using cos θ_{coll}, and using r) are affected differently.

C. τ-ν_τ Coupling: As shown in Fig. 6 with m_τ = 1.9 GeV/c^2 and m_{ν_τ} = 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. However most of the poor fit comes from the r = .1 point and we should be a little suspicious of this point since it is closest to the p = 0.65 GeV/c cut. If we use only the four higher r points, the χ^2 probability for V+A coupling is 5%. Also from Table II we note that V+A coupling gives inconsistent m_τ fits. Therefore in our present

TABLE III

Probabilities that the mass m_ν can yield the observed $\sigma_{e\mu}$ cross section in Fig. 4. $P_T(m_\nu)$ is the probability that all $e\mu$ events produced at $E_{cm} \lesssim 2\ m_\tau$ come from background. $P_F(m_\tau)$ is the χ^2 goodness of fit probability for the data in Fig. 4.

m_τ (GeV/c^2)	$P_T(m_\tau)$	$P_F(m_\tau)$
1.7	} no $e\mu$ events	.9
1.8	with E_{cm} < 3.8 GeV	.9
1.9	0.10	.9
1.95	0.06	.9
2.00	0.06	.9
2.05	0.06	.9
2.10	0.008	.8
2.15	0.002	.7

TABLE IV

Values of the leptonic branching ratios B_e and B_μ, and $R_\tau = \sigma_{\tau\tau}$(measured)/$\sigma_{\tau\tau}$(Eq. 18b) from $e\mu$ and $\mu^\pm\chi^\mp$ events in Refs. 11 and 16. We assume V-A coupling, m_τ = 1.9 GeV/c^2, m_{ν_τ} = 0.0.

Parameter	Value	Statistical Error	Systematic Error	Data Used	Assumptions
$B_e = B_\mu$	0.186	$\pm$.010	$\pm$.028	$e\mu$	$B_e = B_\mu$, $R_\tau = 1$
B_μ	0.175	$\pm$.027	$\pm$.030	$\mu^\pm\chi^\mp$	$B^*_\chi = .85$, $R_\tau = 1$
R_τ	0.89	$\pm$.29	$\pm$.27	$e\mu$, $\mu^\pm\chi^\mp$	$B_e = B_\mu$, $B^*_\chi = .85$

*see Eq. 27b

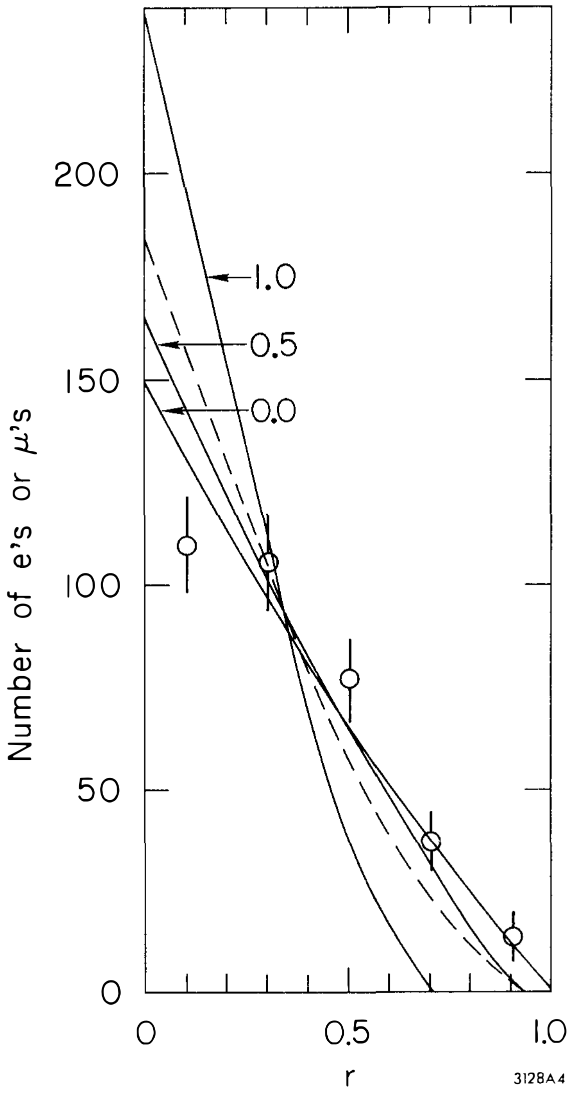

FIG. 6 -- The r distribution for all events corrected for background. The solid curves are for m_τ = 1.9 GeV/c^2 and V-A coupling with m_{ν_τ} in GeV/c^2 as indicated. The dashed curve is for V+A coupling with m_τ = 1.90 GeV/c^2 and m_{ν_τ} = 0.0.

data V-A coupling gives a better fit than V+A coupling for $m_\tau = 1.9$ and $m_{\nu_\tau} = 0.0$. Increasing m_{ν_τ} makes the V+A fit worse. However we have to study our systematic errors before we can make a definitive statement as to how poor is the fit to our data for V+A coupling.

D. <u>Leptonic Branching Ratios and the Contribution of $\tau^+\tau^-$ Pair Production To R</u>: From Eq. 18a we have:

$$\sigma_{e\mu}(s) = 2A_{e\mu}(s)B_e B_\mu \sigma_{\tau\tau}(s) \qquad (27a)$$

For the observed $\mu^\pm \chi^\mp$ cross sections we have

$$\sigma_{\mu\chi}(s) = 2A_{\mu\chi}(s)B_\mu B_\chi \sigma_{\tau\tau}(s) \qquad (27b)$$

where B_χ is the branching ratio of the τ to all one charged particle decay modes (Table I). Using the SLAC-LBL Magnetic Detector Collaboration eμ and $\mu^\pm \chi^\mp$ data we obtain the results in Table IV. The leptonic branching ratios obtained in different ways are consistent with each other and with the theoretical expectation, Table I. And the contribution to R of $\tau^+\tau^-$ pair production is consistent with 1 as expected for a spin ½ point particle.

E. <u>Hadronic Branching Ratios</u>: At present we only know from the measured purely leptonic branching ratios that $1 - .37 \pm .06 = .63 \pm .06$ of the decay modes are not pure leptonic and that some hadrons have been detected in the τ decay.[5,16] But we do not know if this .63 fraction consists of the other decay modes listed in Table I, or if the various modes are in the expected proportions.

F. <u>Other Decay Modes</u>: G. Feldman[25] using SLAC-LBL Magnetic Detector Collaboration data has set the following 90% confidence upper limits on decay modes.

$$\frac{\Gamma(\tau^- \to e^- + \gamma) + (\tau^- \to \mu^- + \gamma)}{\Gamma(\tau^- \to \text{all})} \lesssim 6.0\%$$

$$\frac{\Gamma(\tau^- \to \ell^-\ell^+\ell^-)}{\Gamma(\tau^- \to \text{all})} \lesssim 0.6\%$$

Here ℓ means e or μ and $\ell^-\ell^+\ell^-$ means the sum over <u>all</u> combinations of e's and μ's.

9. Acknowledgement

The SLAC-LBL Magnetic Detector Collaboration data presented here, perhaps more than any other data of the collaboration, represents the combined efforts of the collaboration because to acquire this data every part of the detector had to work well.

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REFERENCES

1. M.L. Perl in Proceedings of the Summer Institute on Particle Physics, (SLAC, Stanford, Calif., 1975); also issued as SLAC-PUB-1664.
2. M.L. Perl and P. Rapidis, SLAC-PUB-1496 (1974) (unpublished), contains early references.
3. H.B. Thacker and J.J. Sakurai, Phys. Lett. 36B, 103(1971).
4. Y.S. Tsai, Phys. Rev. D4, 2821(1971).
5. G.J. Feldman in Proceedings of the 1976 Summer Institute on Particle Physics, (SLAC, Stanford, Calif., 1976); also issued as SLAC-PUB-1852 (1976).
6. C.H. Llewellyn Smith, Oxford University Preprint 33/76 (1976), submitted to Proc. Royal Soc.
7. J.D. Bjorken and C.H. Llewellyn Smith, Phys. Rev. D7, 88(1973).
8. B.C. Barish et al., quoted by D.C. Cundy in Proceedings of the XVII International Conference on High Energy Physics (London, 1974), p IV-147.
9. F.E. Low, Phys. Rev. Lett. 14, 238(1965).
10. M.L. Perl et al., Phys. Rev. Lett. 35, 1489(1975).
11. M.L. Perl et al., Phys. Lett. 63B, 117(1976).
12. H. Meyer in Proceedings of the Orbis Scientiae - 1977 (Coral Gables, 1977) to be published.
13. V. Blobel in Proceedings of the XII Recontre de Moriond (Flaine, 1977), edited by Tran Thanh Van, R.M.I.E.M. Orsay, to be published.
14. M. Cavalli-Sforza et al., Phys. Rev. Lett. 36, 588(1976).

15. G. Snow, Phys. Rev. Lett. 36, 766(1976).

16. G.J. Feldman *et al.*, Phys. Rev. Lett. 38, 177(1976).

17. R. Felst, paper presented at the Chicago Meeting of the American Physical Society (February 1977).

18. W. Wallraff in *Proceedings of the XII Recontre de Moriond* (Flaine, 1977), edited by Tran Thanh Van, R.M.I.E.M. Orsay, to be published.

19. F.B. Heile, Bull. Am. Phys. Soc. 21, 568(1976), and to be published.

20. A. Ali and T.C. Yang, Phys. Rev. D14, 3052(1976).

21. As pointed out by Y.S. Tsai, due to our kinematic cuts the predicted ratio are $\sigma_{ee}/\sigma_{e\mu} = 0.86$, $\sigma_{\mu\mu}/\sigma_{e\mu} = 0.29$.

22. This method avoids the $0 \lesssim r < .2$ region where the r distribution may be affected by the $p \gtrsim 0.65$ GeV/c cut, and emphasizes the $0.6 \lesssim r \lesssim 1.0$ region which is sensitive to the maximum observed p's.

23. M. Goldhaber, Phys. Rev. Lett. 1, 12(1958).

24. G.J. Feldman, private communication.