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τ STUDIES FROM DELCO[1]*

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ABSTRACT

Data obtained at SPEAR in the DELCO experiment show conclusively that the τ is a spin 1/2 lepton. The electron momentum spectrum (characterized by a Michel parameter, ρ=0.66±0.13) observed in the decay $\tau^- \to \nu_\tau e^- \bar{\nu}_e$ shows excellent agreement with a V-A current. The τ mass is found to be 1782^{+2}_{-7} MeV/c^2 and the mass of the ν_τ is less than 250 MeV/c^2 (95% CL). We measure the branching ratio for $\tau^- \to \nu_\tau e^- \bar{\nu}_e$ is (0.160±0.013) and for $\tau^- \to \nu_\tau + \geq$ (3 charged particles)$^-$ is (0.32±0.05). We have observed a clear signal of the decay $\tau^- \to \pi^- \nu_\tau$ and find the branching ratio to be (0.083±0.03).

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I. INTRODUCTION

It is now three years since Perl et al.[2] made the original observation of anomalous $e\mu$ events in e^+e^- annihilation and suggested they were the decay products of a new heavy lepton. Subsequent data taken at both SPEAR and DORIS as reviewed by Perl[3] last Fall were not capable of elimination of the possibility of an obscure charm phenomenon generating these events.

Accordingly the first of the three fundamental τ questions we address in this talk is to demonstrate conclusively that the τ is indeed a spin 1/2 lepton (and especially is not associated with charm). The other two questions, to which we will provide partial answers, are: what is the 'ν_τ' produced in the τ^- decay and does the τ decay via the old weak current or a new one?

II. APPARATUS

DELCO is well suited to studies of the τ since it possesses a large solid angle Cerenkov counter which can identify electrons with excellent discrimination against hadrons. The apparatus, which is shown in Figs. 1a) and 1b), consists of a set of cylindrical multiwire proportional chambers (MWPC) followed by a one-atmosphere ethane

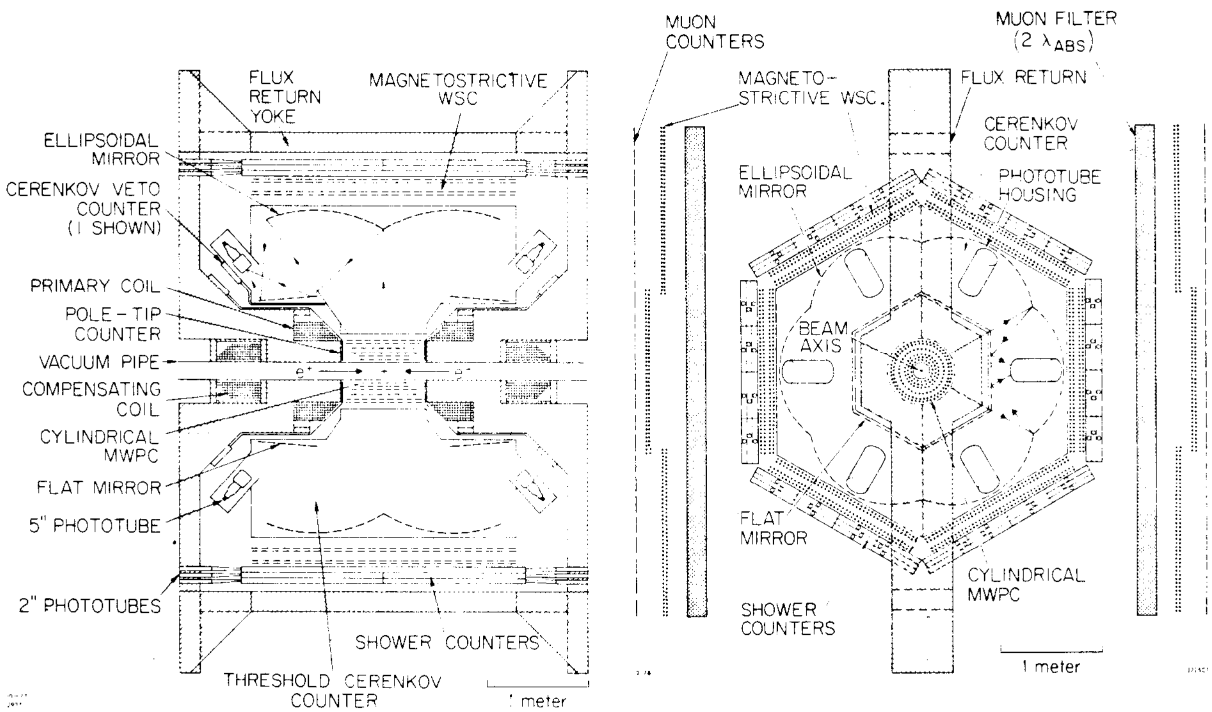

Fig. 1a)   Fig. 1b)

Fig. 1 a) Polar and b) Azimuthal projections of the apparatus.

threshold Cerenkov counter, magnetostrictive wire spark chambers (WSC) and a segmented Pb/scintillator shower counter (6 rl. total). These components subtend 60% of the full solid angle. Charged particles are tagged over 95% of 4π steradians by the MWPC and annular scintillation counters (P counters) which detect particles at angles between 15° and 35° to the beam axis. Two Pb walls, followed by WSC and scintillation counters, provide muon identification over 20% of 4π steradians. A particle must traverse typically 2 absorption lengths of material to be tagged as a muon. This represents the best compromise between hadron discrimination and muon range at these low energies. A magnet provides an analyzing field integral of 1.7 kG-m which results in a momentum accuracy of $\sigma_p/P=8P$ (GeV)% due to measurement errors and 5.2% due to multiple coulomb scattering.

III. THE τ IS A SPIN 1/2 LEPTON

A. Event Selection

Since the τ is expected to have an appreciable electronic branching ratio ($\sim$0.2) and, for a mass $\sim$2 GeV/c^2 decay predominantly into only 1 charged particle, the primary evidence for its existence has been provided by the 'anomalous' two prong lepton events ($e\mu$, $e(\mu)X$, $X\neq e(\mu)$).

Our analysis is based on a sample of eX events selected by the following cuts:

i) Two tracks of opposite charge are required, each possessing an in-time shower counter pulse exceeding 0.3 minimum ionizing particles (mips).

ii) The tracks are acoplanar by at least 20° in order to attenuate the background from Bhabha (e^+e^-) events accompanied by particle misidentification. (The acoplanarity angle is defined as the angle between the two planes containing a track and the beam axis).

iii) One track is identified as an electron by an in-time Cerenkov pulse in the appropriate cell and the other as not an electron by the absence of such a pulse. At low momenta the curvature of the tracks results in a poor Cerenkov detection efficiency as illustrated in Fig. 2. On this basis we allow a minimum momentum of 0.2 GeV/c for the electron and 0.3 GeV/c for the X particle.

iv) Events with an in-time P counter tag are rejected in order to ensure the maximum rejection against events containing four or more charged particles.

v) Events consistent with the process $e^+e^-\to e^+e^-\gamma$ (remaining in the sample due to a missed Cerenkov tag) are removed. A photon is defined by an in-time shower counter pulse unassociated with either charged track.

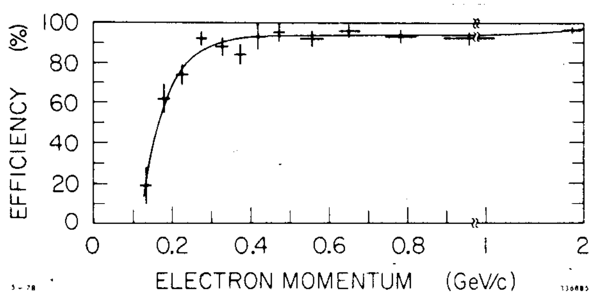

Fig. 2 - Cerenkov counter detection efficiency vs. momentum. The data points are derived from the final states e^+e^-, $e^+e^-\gamma$ and $e^+e^-e^+e^-$ and are confirmed by Monte Carlo simulations. The asymptotic efficiency includes geometrical losses due to mirror edges.

The number of events satisfying these requirements is 840 of which 535 have no detected photons.

B. Backgrounds

We will now consider the residual backgrounds. This discussion is important because the data statistically allow fairly precise measurements to be made.

The first background we will consider involves particle misidentification. It is expected to involve only misidentified electrons since the Cerenkov counter provides a strong π rejection ($P_{\pi\to e} \sim 3.10^{-4}$). This is confirmed by the observed shower counter pulse heights shown in Figs 3a) and b). The electron pulse height distribution shows no evidence of any non-showering particles but the enhanced tail on the X distribution indicates a 10% contribution from misidentified electrons. We reduce this background to 4% at a loss of 12% of real events by placing a requirement of less than 3.3 mips on the X particle. The final data sample is 692 events of which 459 have no photons.

A further background may result from incomplete detection of the two-photon interaction $e^+e^- \to e^+e^-\mu^+\mu^-$. This has been measured as <2±0.5% of the signal by counting events with same-sign tracks and is in agreement with an independent calculation[4]. A measurement of both this background and that due to particle misidentification has been obtained from data at E_{CM}=3.10(ψ), 3.50 and 3.52 GeV. The ψ measurement is insensitive to the two-photon background in contrast with the 3.50 and 3.52 data and we thereby find this process to be small in comparison with particle misidentification.

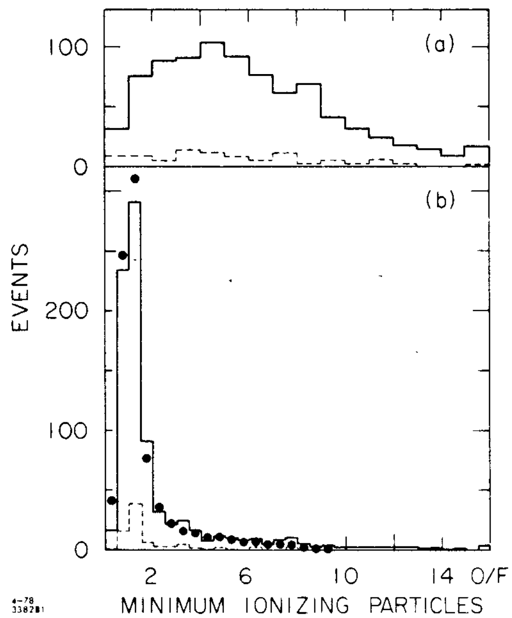

Fig. 3a) Shower counter pulse height distribution for electrons in the eX events.

Fig. 3b) Pulse height distribution for the X particle. The dots indicate the pulse heights expected from a sample of 33% μ's and 66% π's (which is compatible with the observed ratios). The dashed histograms were obtained at centre of mass energies below charm threshold.

The third and most crucial background, due to charmed particles, will be discussed in the next section.

C. τ Cross Section and Charm Background

The production cross section ratios, $R^{2P}_{eX}(\sigma(e^+e^-\to eX)/\sigma(e^+e^-\to\mu^+\mu^-))$ for eX events with no detected photons are shown in Fig. 4a) and for all eX events in Fig. 4b). The normalization is made to wide angle Bhabha pairs appropriately corrected at the ψ and ψ' to account for the vacuum polarization enhancement of the single photon propogator. The data were corrected for the detection efficiency which varies by less than 2% up to E_{CM}=4.5 GeV and decreases by 10% (for eX (all) events) at the highest energy.

The data exhibit a distinct threshold which occurs below charm threshold (3726±1.8 MeV, i.e. $2M_{D^0}$). A comparison of the 70 events observed in the range $3.57 \leq E_{CM} \leq 3.72$ GeV[5] with those at higher energies in terms of rate, angular and momentum distributions and associated photons shows both sets of data to be consistent with the hypothesis of a common origin. For example, the electron momentum distribution (Fig. 5) shows good agreement with the spectrum expected from τ decays (in addition to a contribution from particle misidentification and a measurement error tail). From the shower counter pulse height information (indicated by dashed lines

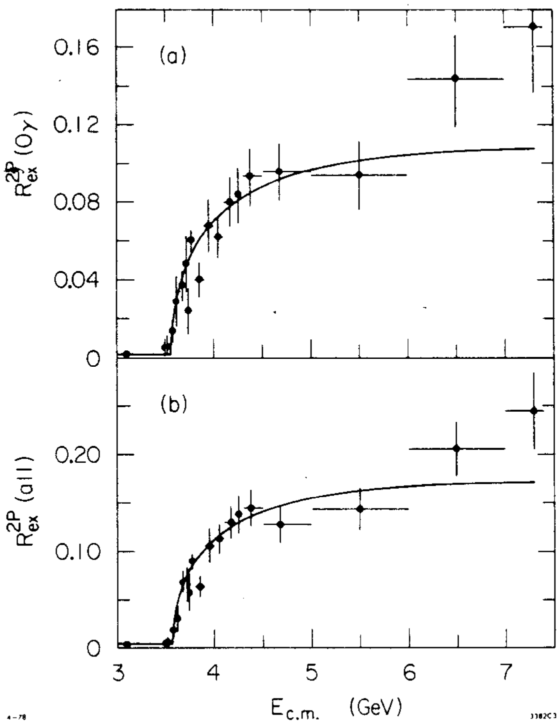

Fig. 4a)

The production cross section ratio, R_{ex}^{2P}, for eX events with no detected photons. The fitted curve (χ^2/dof= 17.3/15) indicates the cross section expected from a spin 1/2 τ lepton.

Fig. 4b)

R_{ex}^{2P} for all eX events (χ^2/dof=17.1/15). Both fits have excluded the ψ'' point ($3.75 \leq E_{CM} \leq 3.80$ GeV) because of possible charm contamination.

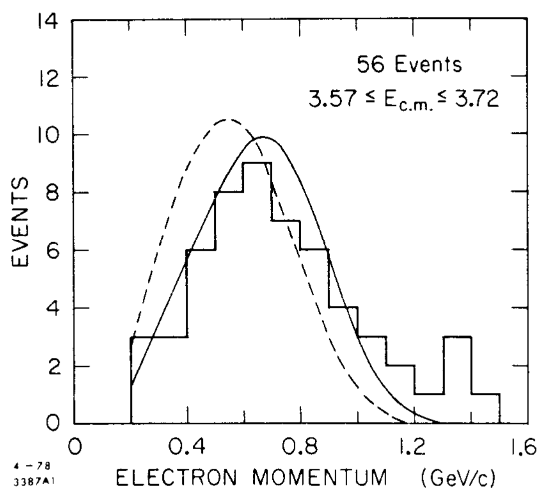

Fig. 5

The electron momentum distribution for the eX events below charm threshold. Only electrons which are subtended and detected by the outer WSC have been included. The curves show the expected distributions from a τ with V-A (solid line) and V+A (dashed line) couplings.

in Fig. 3), we determine that the 70 events contain less than 5 misidentified events. We conclude that the anomalous two-prong electron events occur below charm threshold.

Above threshold we may estimate the charm background in these data by a comparison with the multiprong electron events ($e^{\pm} + \geq 2$ charged particles, denoted MP_e). The latter have a large contribution from the semi-leptonic decays of charmed particles and their cross section[6] displays substantial structure at centre of mass energies near 4 GeV. For example, at E_{CM}=4.25 GeV, the MP_e cross section falls to (50±10)% of the value in the region between 4.0 and 4.2 GeV. (If we subtract the independently measured τ contribution to the MP_e events this relative decrease (25±15)% is even more pronounced.) The data of Fig.4 do not display a similar structure.

A priori we expect the largest charm contribution at the ψ'' (3770) where pure $D\bar{D}$ final states are produced. A crude early estimate[6] predicted that (30±15)% of the eX events at the ψ'' may result from charm. An upper limit of 20% (95% CL) can now be measured directly from the data by observing the deviation between the ψ'' data point and the fit. We expect charm contamination to be negligible at higher energies when inelastic charm production dominates.

The data of Fig. 4 have been fitted by the theoretical cross section for pair production of a spin 1/2 lepton superposed on a constant background term. The latter predicts a background of (5±3)% due to particle misidentification in agreement with the independent shower pulse height study. Both sets of data are well fitted by the hypothesis of a spin 1/2 τ and give a value for the τ mass of (1782^{+2}_{-7}) MeV/c^2.

D. Branching Ratio Measurements

The fit in Fig. 4a) yields $2b_e\, b_{x,0\gamma} = 0.105 \pm 0.007$, where b_e is the branching ratio for $\tau^- \rightarrow \nu_\tau\, e^- \bar{\nu}_e$ and $b_{x,0\gamma}$ is the branching ratio for $\tau^- \rightarrow \nu_\tau$ + 1 charged particle ($\neq$e) + no detected photons. The fitted value for $2\, b_e\, b_{x,0\gamma}$ varies by less than the quoted error if data above E_{CM}=6 GeV is excluded. Theoretically, the value of $b_{x,0\gamma}$ is expected to be dominated by three decay modes ($\mu^- \bar{\nu}_\mu\, \nu_\tau$, $\pi^- \nu_\tau$ and $\pi^- \pi^0\, \nu_\tau$) and have the approximate value $(0.98+0.59+0.36\times 1.09)\, b_e = 2.0\, b_e$[7]. The factor 0.36 indicates the probability that both photons in the π^0 decay escape detection. A detailed determination of the ratio $b_{x,0\gamma}/b_e$, based on the relative τ decay rates of Ref. 7, combined with the data of Fig. 4a) yields $b_e = 0.160 \pm 0.013$. The error, which is largely systematic, is rather small since this determination of the cross section is proportional to b_e^2 .

The fit in Fig. 2b) determines $2b_e\ (1-\ b_e-\ b_{mp})=0.168\pm0.008$, where b_{mp} is the branching ratio for $\tau^- \to \nu_\tau + \geq$ (3 charged particles)$^-$. Applying our measurement of b_e gives $b_{mp}=0.32\pm0.05$. We have made an independent measurement of b_{mp} by plotting the ratio of the observed MP_e events to the observed eX events above a minimum electron momentum (Fig. 6). This ratio falls as the cutoff momentum is raised, reflecting the relatively soft electron spectrum resulting from charm decays. Above $\sim$1.1 GeV momentum the ratio has the constant value of 1.8 ± 0.3 and indicates a common source for the electrons in both the MP_e and eX events. The value of b_{mp} is then given by $(b_{mp}\cdot\varepsilon_{mp})/(b_x\cdot\varepsilon_x) = 1.8\pm0.3$, where $\varepsilon_{mp,x}$ are the appropriate detection efficiencies and $b_x=1-b_e\ -b_{mp}$. The final result is $b_{mp}=0.32\pm0.05$, in agreement with the previous determination.

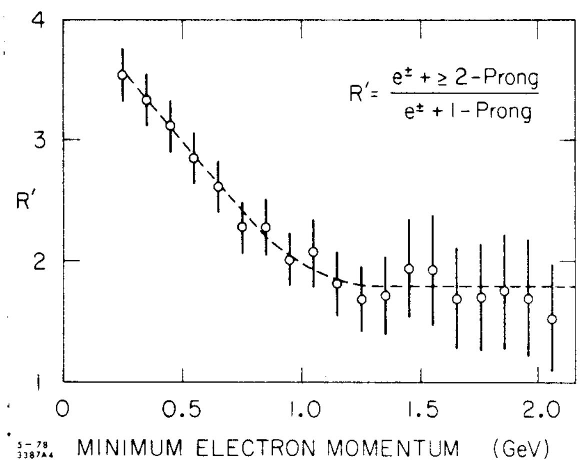

Fig. 6

The ratio of observed multi-prong electron events to the observed two prong electron events at electron momenta above the value indicated on the horizontal axis. The dashed curve is hand-drawn.

The values for b_e and b_{mp} are in agreement with earlier measurements,[3] and with theoretical expectations for a sequential lepton at this mass. The measurement of b_e is however in disagreement with a para-electron assignment for the τ which would lead to a value almost twice as large. In the framework of the τ decaying via a conventional weak interaction the values of b_e and b_{mp} essentially measure the strength of axial vector decays involving odd numbers ($\geq$ 3) of pions. The contribution to b_{mp} from the vector hadronic current has been calculated[7] from measurements of $e^+e^-\to$n-even pions at $\sqrt{s} < m_\tau$. After subracting this contribution there remains a residue of $(1.3\pm0.4)\ b_e$ (i.e. a branching ratio 0.21 ± 0.06) due to axial decays into $\geq$ 3 charged particles.

E. <u>Why do These Data Imply the τ is a Spin 1/2 Lepton?</u>

First it is clear that the eX events are unrelated both to old physics (since a distinct threshold exists far above the old physics region) and to charm.

Can the eX events be hadronic in origin? If they resulted from the decay of a baryon pair there must always be two baryons in the final state. This contradicts the mass limit placed on the neutral in $e\nu_e$ + neutral as discussed below. If the eX events were produced by a meson and its anti-particle then the threshold behaviour should show a p^3 behaviour, characteristic of p-wave production, in order to conserve parity. The abrupt rise in cross section above threshold (Fig. 7) rules out p-wave production. Two different bosons of opposite parity could be produced in a relative s-state but only one would decay weakly and the events would always be accompanied by photons. This is in contradiction with observation.

The smooth cross sectional behaviour and constant high energy value betokens a leptonic origin for these events. Half integer spin assignments other than J=1/2 result in divergent high energy behaviour[8] which disagree strongly with these data.

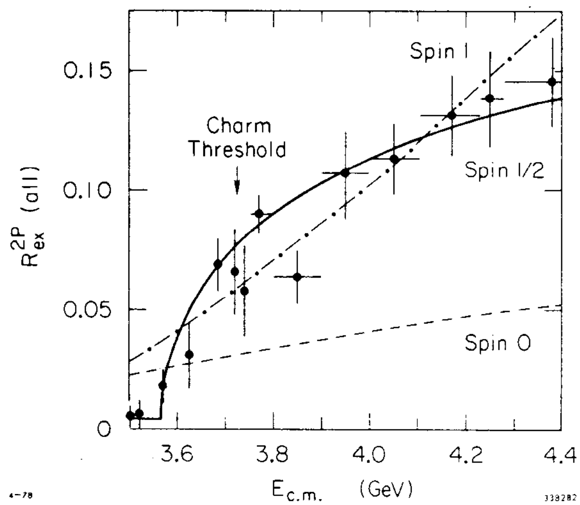

Fig. 7

R^{2P}_{ex} for all eX events with $3.50 \le E_{CM} \le 4.40$. The fitted curves indicate the threshold behaviour for a pair of particles with spin 0 (dashed), 1/2 (solid) and 1 (dot-dashed).

IV. WHAT IS 'ν_τ' PRODUCED IN τ^- DECAY?

Before introducing a new neutrino it is important to investigate whether the 'ν_τ' is actually one of the old neutrinos. The experimental status of such assignments is summarized in Table I under the general assumption of full strength weak couplings. The conclusions of Table I may prove to be incorrect in the presence of lepton mixing or new S, P, T couplings.[9]

None of these experiments excludes the possibility that the 'ν_τ' is actually an old neutrino but with the 'wrong' handedness and produced only in τ decay. For example the 'ν_τ' may be a right-handed neutrino with the same lepton number as ν_μ or ν_e (or a left-handed antineutrino with the lepton number of $\bar{\nu}_\mu$ or $\bar{\nu}_e$).

We can investigate these assignments by measuring the electron momentum spectrum produced in the decay $\tau^- \to \nu_\tau e^- \bar{\nu}_e$. As can be seen

Table I: Experimental Status of τ Neutrino Assignments

Neutrino Coupling to τ^-	Left or Right Handed?	τ Type	Excluded?	Experiment
ν_μ	LH	Ortho muon (Excited muon)	Yes	1) Normal $\nu_\mu \to \mu^-$ cross section at high energies 2) $\nu_\mu \not\to e^-$
$\bar{\nu}_\mu$	RH	Para muon	Yes	1) $\nu_\mu \not\to \mu^+$ 2) $\mu\mu/e\mu$ rate $\neq 1$
ν_e	LH	Ortho Electron (Excited electron)	No	(Poor ν_e beams)
$\bar{\nu}_e$	RH	Para electron	Yes	1) $ee/e\mu$ rate $\neq 1$

from Figs. 8a) and b) a left-handed 'ν_τ' should result in a harder electron momentum spectrum than that of a right-handed 'ν_τ'. The first case corresponds to a V-A coupling which is characterised by the Michel parameter[10], $\rho = 0.75$ (as observed in μ^- decay) and the latter case corresponds to a V+A coupling characterised by $\rho=0$.

Unfortunately we do not have the luxury of a sample of stationary τ's so the observed electron spectrum (Fig. 9) is not as dramatic as the sketches in Fig. 8. The conclusion we draw from the fits to this spectrum (Table II) is that there is excellent agreement with a V-A coupling whereas a V+A coupling has a very low probability (<< 1%). The data also disfavour (at the 2σ level) an intermediate coupling such as pure V or pure A (which are characterised by a ρ parameter of 0.38). The effect of radiative corrections to the electron spectrum[11] leads to an appreciable softening and can be reasonably approximated by a modification of the 'bare' Michel parameter. The ρ value becomes 0.64 for a V-A coupling and -0.17 for a V+A coupling. Finally we note that any charm contamination in these data would cause a bias away from the V-A result towards a softer spectrum.

The effect of a non-zero ν_τ mass will also result in a softer electron spectrum. Since the V+A hypothesis is ruled out for any value of m_{ν_τ} we fixed the ρ parameter at 0.64 in this study. From the measured χ^2 variation with non-zero ν_τ masses[12] we determine $m_{\nu_\tau} < 0.25$ GeV/c^2 (95% CL).

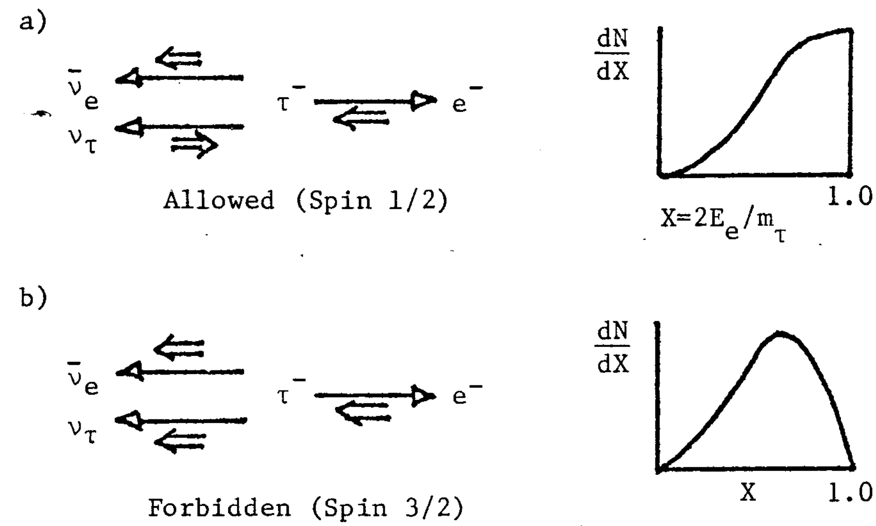

Fig. 8a) and 8b)

a) The configuration corresponding to maximum electron energy and a left-handed ν_τ followed by the resulting electron energy spectrum in the τ rest frame.

b) A similar treatment for the case of a right-handed ν_τ.

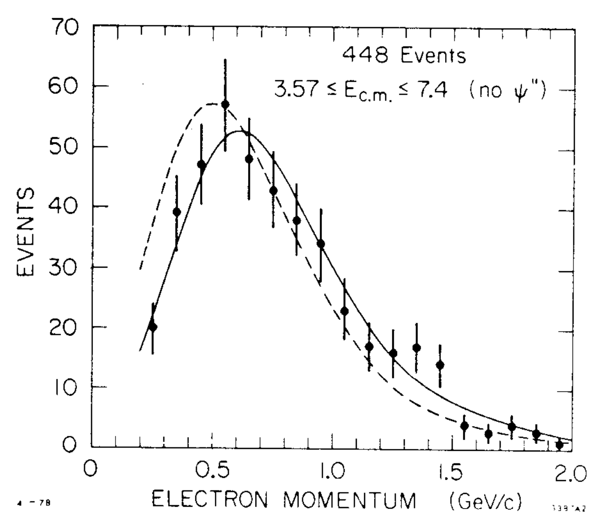

Fig. 9

The electron momentum spectrum for eX events after excluding data taken at the ψ''. The solid (dashed) line is a V-A(V+A) fit with zero ν_τ mass.

Table II: Summary of the Fits to the Data of Fig. 9

Coupling	Value of Michel Parameter, ρ	χ^2/dof
V+A	0	36.0/17
V-A	0.75	12.3/17
ρ - free parameter	0.66±0.13	11.8/16

In summary we have found the ν_τ to be left-handed and therefore confirmed the validity of the exclusion of the τ by ν_μ experiments as an ortho muon. This conclusion and the experimental limit on m_{ν_τ} are valid under the assumption of the absence of Cabibbo-like mixing of the leptonic doublets. It is not yet fully experimentally excluded that $m_{\nu_\tau} > m_\tau$ and the τ decays at a reduced rate (constrained by the e-μ and β-μ universality limits) to old neutrinos.

V. DOES THE τ DECAY VIA THE OLD WEAK CURRENT?

We have already provided some information towards this question by observing that the decay proceeds via a left handed current in agreement with that observed in all other charged current weak interactions.

The calculations of τ branching ratios, based on the known weak current, allow another test of this hypothesis. With one exception, all the decay modes which have been experimentally accessible have agreed with the theoretical calculations (albeit in some cases with rather large errors of approximately a factor of 2).

The exception, reported[13] by DASP at the Hamburg conference last year, was a measurement of the decay $\tau^- \to \pi^- \nu_\tau$ substantially below the theoretical expection. The calculation is on very solid ground as can be seen from the diagrams of Fig. 10. If the same W is responsible for the four decays indicated then $b_\pi/b_e = 0.59$ (b_π=0.094 for b_e=0.16) where b_π is the branching ratio for $\tau^- \to \pi^- \nu_\tau$. The experimental measurement was reported in two forms: firstly $b_e\, b_\pi = 0.004\pm0.005$ ($b_\pi = 0.025\pm0.031$ for $b_e = 0.16$) or, alternatively, an observation of 2 eπ events when 7.3 were expected based on the detection of 12 eμ events. (The latter form is insensitive to an error in b_e).

Accordingly we have made a measurement of b_π in these data. Two prong eX events were selected according to the criteria discussed previously but with the additional requirement that the X particle travels towards the muon filter and has sufficient momentum to penetrate (typically 0.8 GeV/c after including momentum measurement errors).

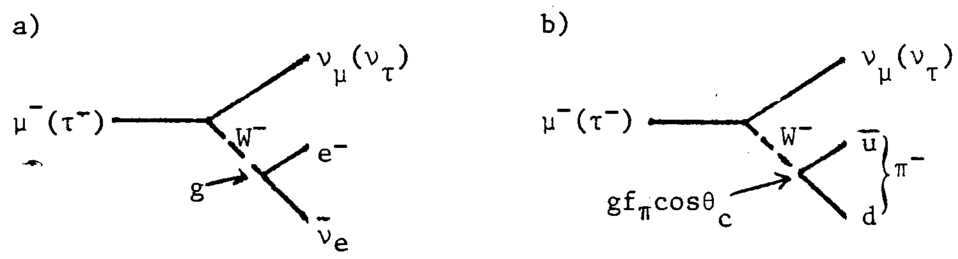

Fig. 10 Diagrams used to calculate the decay rates of:

a) $\mu^- \to \nu_\mu\ e^-\ \bar{\nu}_e$ and $\tau^- \to \nu_\tau\ e^-\ \bar{\nu}_e$

b) $\pi^- \to \mu^-\ \nu_\mu$ and $\tau^- \to \pi^-\ \nu_\tau$

Twenty-five events survive these requirements from the data collected after installation of the muon filter. After subtraction of an estimated single background event the remaining events were distributed according to Table III: 10 $e\mu$, 10.7 $e\pi$ and 3.3 $e\pi + \geq 1\gamma$. The observed distribution is in good agreement with the absolute

Table III: Comparison of the Predicted and Observed Particle Composition of the eX Events

Event Type	Predicted Rate				Observed Rate	
	$\tau\bar{\tau}\to$				After Background Subtraction	Background Removed
	$e\mu$	$e\pi$	$e\rho$ etc.	Total		
$e\mu$	8.9	0.9	0.2	10.0	10	0
$e\mu + \geq 1\gamma$	0	0	0.3	0.3	0	0
$e\pi$	0.5	9.0	2.3	11.8	10.7	0.3
$e\pi + \geq 1\gamma$	0	0	2.7	2.7	3.3	0.7

predicted rates based on the known luminosity and theoretical branching ratios with b_e set to 0.16. Note that we do not distinguish between a π and a K but assume Cabibbo suppression is valid in τ decays.[13] We have also included the measured particle misidentification probabilities, $P_{\mu\to\pi} = 0.05$ and $P_{\pi\to\mu} = 0.10\pm0.04$. The good agreement between observed and predicted events of the type $e\pi + \geq 1\gamma$ and $e\mu$ completely eliminates the possibility that the observed $e\pi$ events result from a fluctuation in the ρ contribution or in the muon misidentification probability.

We conclude that we have observed the decay mode $\tau^- \to \pi^-\ \nu_\tau$ and measure its branching ratio to be (.083$\pm$.03) assuming our earlier measurement of b_e. The observed momenta (Figs. 11a) and 11b)) are consistent with those expected from τ decays and in particular we note that the pions do not cluster at the low momentum cut which would suggest ρ or μ contamination.

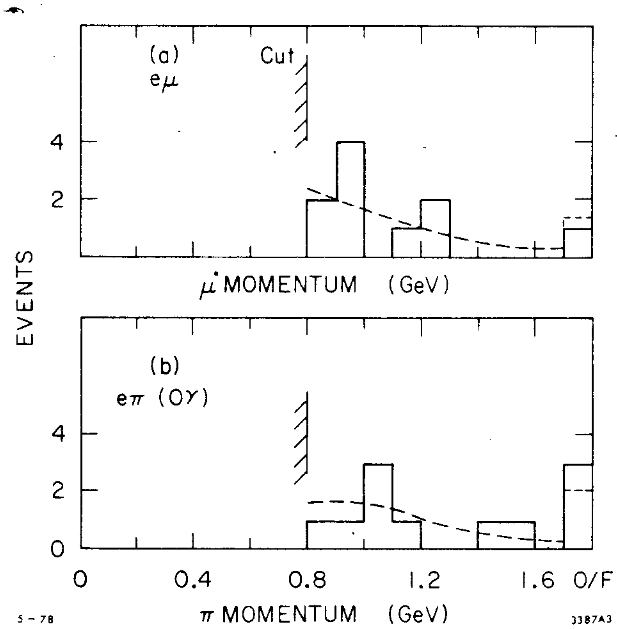

Fig. 11a)

Momentum spectrum of the μ in the $e\mu$ events.

Fig. 11b)

Momentum spectrum of the π in the $e\pi$ (0γ) events.

The dashed lines indicate the predicted shapes expected from τ decays.

VI. CONCLUSIONS

We have determined from the cross sectional behaviour of the eX events that the τ is a spin 1/2 lepton with mass 1782^{+2}_{-7} MeV. The electron momentum spectrum is in good agreement with a left-handed V-A coupling characterised by a Michel parameter, $\rho = 0.66 \pm 0.13$. This measurement rules out a right-handed V+A coupling and disagrees with an intermediate coupling such as pure V or A at the 2σ level. The electron spectra place an upper limit on the τ neutrino mass of 0.25 GeV/c^2 (95% CL). We have measured the branching ratio $\tau^- \to \nu_\tau\, e^-\, \bar{\nu}_e$ to be (0.160 ± 0.013) and $\tau^- \to \nu_\tau + (\geq 3$ charged particles$)$ to be (0.32 ± 0.05). In addition we have observed a clear signal of the decay $\tau^- \to \nu_\tau\, \pi^-$ and measure the branching ratio to be (0.083 ± 0.03). All measurements are consistent with the hypothesis of τ decays involving the same charged current found in all other weak decays.

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