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PROPERTIES OF THE τ LEPTON*

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ABSTRACT

We review the measured properties of the τ lepton and its neutrino. A constrained fit to the world data gives a τ branching fraction to an electron plus neutrinos (B_e) of (17.4 ± 2.1)% and B_μ/B_e = 1.07 ± 0.17. New data on the $\tau \to \pi\nu$ mode are in agreement with the expected branching fraction. There is evidence for the $\tau \to A_1\nu$ mode, but the A_1 resonance cannot be conclusively established from the current data. The DELCO experiment establishes the τ mass to be 1782^{+2}_{-7} MeV/c^2 and the ν_τ mass to be less than 250 MeV/c^2. It also excludes V+A as a τ-ν_τ coupling and strongly favors V-A.

I. INTRODUCTION

The timing of this series of conferences has been in good coincidence with the turning points in the history of the τ lepton. I should like to briefly review this history by quoting from the proceedings of past neutrino conferences. At Neutrino-75 at Balaton I reported[1]

> "The primary evidence is 24 events...which appear to contain an electron and a muon, but no other visible charged or neutral particles.... Various internal checks make it very unlikely that these events come from known processes. Possible processes which could give events of this type are heavy lepton production or production of a new heavy spin one boson which decays weakly...We have not yet been able to determine which process is occurring"

(Invited talk presented at the International Conference on Neutrino Physics—Neutrinos '78, Lafayette, Ind., 28 April–2 May 1978.)

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During the following year we collected additional data and studied the momentum spectrum of the leptons and the presence or absence of other particles in these events. We concluded that the lepton momentum spectrum was characteristic of a three-body decay and that, by elimination, the missing particles had to be neutrinos. Thus at Neutrino-76 in Aachen, Martin Perl was able to report:[2]

> "We conclude that of the hypotheses considered in this paper, the only one compatible with all our data is that the U particle is a heavy lepton."

The problem at this point was that all of the evidence came from a single experiment, the SLAC-LBL Magnetic Detector at SPEAR, and one that admittedly had poor lepton identification. Independent confirmation was badly needed. It came during the following year from DORIS, and at Neutrino-77 at Elbrus, in his summary talk Bjorken stated:[3]

> "Given the confirmatory evidence provided by the PLUTO and DASP measurements, the real existence of anomalous eμ, eh, and μh events seems to be quite firm. No hypothesis accounts so well for the observations as that of a sequential heavy lepton τ, with its own neutrino ν_τ."

We are now at Neutrino-78 and you have just heard the beautiful new results from the DELCO experiment.[4] It is clear that at this conference we are entering a new stage in the history of the τ. Its existence and general identification are accepted and we are beginning the detailed measurements of its properties.

It is in this spirit that I have prepared this review. In the next section we shall review the measurements of τ branching fractions, first the general modes, then a more detailed look at the semihadronic modes, and finally, a review of upper limits for rare modes. In Sections III through VII we shall briefly review measurements of the τ mass, the ν_τ mass, the τ spin, the τ lifetime, and the τ-ν_τ coupling. We shall conclude in Section VIII with a discussion of the type of lepton the τ could be.

II. BRANCHING FRACTIONS

Figure 1 illustrates the three possible τ decay modes in the standard model. In each case the τ decays to its own neutrino, ν_τ, and the charged weak current, which can materialize as an $e\bar{\nu}_e$, a $\mu\bar{\nu}_\mu$, or a $d\bar{u}$ pair. The $d\bar{u}$ quark pair (or more precisely the $d'\bar{u}$ pair, where $d' \equiv d\cos^2\theta_C + s\sin^2\theta_C$) forms a hadronic system such as a charged π, ρ, or A_1. There are three general observations that we can make from Figure 1:

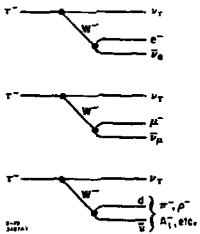

Fig. 1 τ decay modes

(1) Each of the diagrams has equal weight since all of the couplings to the weak current are equal, with the proviso that the last diagram stands for three diagrams corresponding to the three colors of quarks. Thus, there are five equivalent diagrams and so the electronic branching fraction should be 20%. QCD corrections give an enhancement to the semi-hadronic final states and reduce the prediction for the electronic branching fraction to 18%.[5]

(2) Many of the branching fractions for the semi-hadronic modes are precisely predicted. For example, the coupling of both the μ and the π to the weak current is known from the measurements of their lifetimes. Thus, the ratio of branching fractions for $\tau \to \pi\nu$ to that for $\tau \to \mu\bar{\nu}\nu$ is precisely predicted. We shall return to a discussion of the predictions for the semi-hadronic modes in Section II.B.

(3) Most τ decays will contain only one charged particle. Clearly the decays to e's, μ's, π's, and ρ's contain only one charged particle, and it will turn out that about half of the semi-hadronic modes contain one charged particle. Thus $\tau^+\tau^-$ production will be most prominent in events with only two charged particles.

A. General Modes

From the preceding discussion it is clear that $\tau^+\tau^-$ production can be most easily measured by studying e^+e^- annihilation events with two charged particles in which at least one is a lepton. There are five possibilities: eμ, ee, μμ, ex, and μx, where x stands for any charged particle. Seven experiments have measured one or more of these modes.[6-14] Table I gives a list of these experiments and the modes which each measured.

From these measurements we want to derive the branching fractions for τ decay into $e\nu\bar{\nu}$ (B_e), $\mu\nu\bar{\nu}$ (B_μ), one charged hadron plus neutrals (B_{1h}), and three or more charged hadrons plus neutrals (B_{3h}), subject to the constraint that the sum of these four modes is unity. Table II gives the results of the 14 measurements listed in Table I. An attempt has been made here to determine precisely the quantity that each experiment measured. In general, experiments measure

Table I. Experiments which have measured $\tau^+\tau^-$ production, the method of electron identification (if relevant), and the modes measured.

Experiment	Institutions	Laboratory	e^- ident.	Modes				
				$e\mu$	ee	$\mu\mu$	ex	μx
SLAC-LBL	LBL SLAC	SPEAR (West pit)	Lead-scintillation counters	X	X	X		X
PLUTO	DESY Hamburg Siegen Wuppertal	DORIS	Lead-proportional chambers	X				X
DASP	Aachen DESY Hamburg Munchen Tokyo	DORIS	Cerenkov counters (ex) or lead proportional chambers ($e\mu$)	X			X	X
LGW	Hawaii LBL Northwestern SLAC	SPEAR (West pit)	Lead-glass counters	X			X	
MPP	Maryland Pavia Princeton	SPEAR (East pit)	-					X
Iron Ball	Colorado Pennsylvania Wisconsin	SPEAR (East pit)	-			X		
DELCO	Irvine Los Angeles Stanford Stony Brook	SPEAR (East pit)	Cerenkov counters				X	

products or combinations of products of these four basic branching fractions, and then use either theoretical assumptions or other experimental measurements to derive the branching fractions quoted in their papers. Thus the values quoted in Table II are derived from the results given in the referenced papers, but in some cases may not be explicitly found there. Table II also includes two

Table II. Measurements of B_e, B_μ, B_{1h}, and B_{3h}

Mode	Measurement	Experiment	Result	Reference
eμ	$\sqrt{B_e B_\mu}$	SLAC-LBL	.186 ± .030	6
eμ	$\sqrt{B_e B_\mu}$	PLUTO	.145 ± .040	7
eμ	$\sqrt{B_e B_\mu}$	DASP	.182 ± .031	8
eμ	$\sqrt{B_e B_\mu}$	LGW	.224 ± .055	9
ee	B_e/B_μ	SLAC-LBL	1.12 ± 0.48	10
μμ	B_μ/B_e	SLAC-LBL	1.40 ± 0.48	10
μμ	B_μ	Iron Ball	.22 ± .08	11
ex	$B_e(B_\mu+B_{1h})$	DASP	.086 ± .012	8
ex	$B_e(B_\mu+B_{1h})$	LGW	.151 ± .064	9
ex	$B_e(B_\mu+B_{1h})$	DELCO	.084 ± .013	12
μx	$B_\mu(1-B_{3h})$	SLAC-LBL	.149 ± .034	6
μx	$B_\mu(1-B_{3h})$	PLUTO	.109 ± .025	13
μx	$B_\mu(1-B_{3h})$	MPP	.170 ± .085	14
μx	B_μ/B_e	DASP	.92 ± .32	8
e-any	B_{3h}	DELCO	.32 ± .05	12
μ-any	B_{3h}	PLUTO	.30 ± .12	13

measurements of B_{3h} which were determined by studying the multiplicity accompanying a single lepton in regions in which charmed particle production is unimportant.

The results of constrained fits to the 16 measurements in Table II are given in Table III. One fit has been done leaving B_e and B_μ free and the other has constrained $B_\mu = 0.973\ B_e$, its theoretical value. Both fits are extremely good and, in fact, all 16 measurements agree with the fit results within one standard deviation of the experimental errors. Although no single experiment has done a particularly sensitive job of testing e-μ universality in τ decays, the result of all measurements taken together provides a reasonably stringent limit on its violation. Also, it is impressive that there is essentially perfect agreement between the theoretical prediction for the electronic mode, 18%, and the results of the fits.

B. Semi-hadronic Modes

Many details of the semi-hadronic decays are predicted in the standard model.[15,16] As we mentioned previously, the ratio between

Table III. Results of constrained fits to the measurements listed in Table II.

	B_e and B_μ free	$B_\mu = 0.973\ B_e$
B_e(%)	17.4 ± 2.1	18.6 ± 1.5
B_μ(%)	18.7 ± 2.0	17.9 ± 1.5
B_{1h}(%)	31.6 ± 5.7	30.9 ± 5.5
B_{3h}(%)	32.3 ± 3.7	32.8 ± 3.5
B_μ/B_e	1.07 ± 0.17	

the leptonic decays and the $\pi\nu$ mode is precisely predicted from the pion lifetime. The vector decays, which are decays to even numbers of pions plus a neutrino, are precisely predicted from measurements of e^+e^- annihilation via the conserved vector current hypothesis.[17] The decay to $\rho\nu$ is the largest component of this class. For the axial-vector decays, the A_1 plays the same role as the ρ does for vector decays. For this reason, it is hoped that τ decays will provide a convenient way to study the A_1, which has proved so difficult to isolate in hadronic interactions.[18] The $A_1\nu$ branching fraction can be calculated from the $\rho\nu$ branching fraction with the aid of Weinberg's sum rules.[19] τ decays involving kaons will be suppressed by $\tan^2\theta_C$ in the standard model. A summary of these predictions is given in Table IV under the assumption that B_e=B_μ=18%.

Table IV. Predictions for τ branching fractions under the assumption that B_e=B_μ=.18.

Mode	Branching fraction(%)	Input
$e\bar{\nu}\nu$	18	measurement
$\mu\bar{\nu}\nu$	18	measurement
$\pi^-\nu$	10	π decay
$\rho^-\nu$	20	CVC + e^+e^- annihilation
$(4\pi)^-\nu$	10	CVC + e^+e^- annihilation
$A_1\nu$	9	Weinberg sum rules
$(K + n\pi)^-\nu$	4	$\tan^2\theta_C$
$(3 \text{ or } 5\pi)^-\nu$	11	remainder

We shall now briefly review the measurements on three classes of semi-hadronic decay modes: $\rho\nu$, $(3\pi)\nu$ and $(4\pi)\nu$, and $\pi\nu$.

1. The $\rho\nu$ Mode

The DASP group has studied the $\rho\nu$ decay mode by searching for events with two charged particles plus two photons which are consistent with being the decay products of a π^0.[20] Figure 2a shows the invariant mass of one of the charged particles and the π^0. There is a peak at the ρ mass. The shaded events are those in which the remaining charged particle is identified as an electron. There is sizable fraction of such events, as would be expected for τ decays. Figure 2b shows the momentum spectrum of the ρ. Aside from some background at low momentum, it agrees well with the hypothesis of τ pair production. From these data the DASP group derives a branching fraction for the $\rho\nu$ mode of (24 ± 9)% in good agreement with the theoretical expectation of 20% from Table IV.

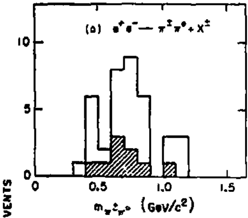

Fig. 2(a). Invariant mass distribution of $\pi^\pm\pi^0$ mass in events with two charged particles and a π^0 detected.

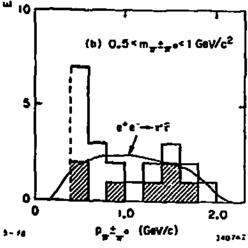

Fig. 2(b). The momentum distribution of $\rho^\pm$. The shaded events have the remaining charged particle identified as an electron. The data are from the DASP experiment.[20]

2. $(3\pi)\nu$ and $(4\pi)\nu$ Modes

The PLUTO[21] and SLAC-LBL[22] groups have studied τ decays to three charged pions plus a neutrino. These decays are of particular interest since the long-sought A_1 meson is expected to be prominent in the three pion mass spectrum.

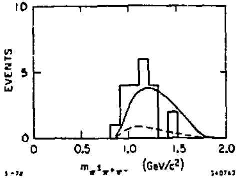

Fig. 3. Invariant mass distribution of $\rho^0\pi^\pm$ combinations in events with an e and three charged pions detected which are compatible with $\tau^+\tau^-$ decays. The solid curve represents a non-resonant $\rho^0\pi^\pm$ spectrum from τ decay. The dashed line represents an estimate of the background. The data are from the PLUTO experiment.[21]

The PLUTO group studied events with an electron, three charged pions, and no photons. A study of dipion masses showed that the entire signal was consistent with two of the pions forming a ρ^0. The $\rho^0\pi$ mass spectrum is shown in Fig. 3. There is a peak at 1.1 GeV/c^2 with a full width of 250 MeV/c^2 and this peak is fit well by a resonance shape. However the peak has a 5% confidence level for a fit to non-resonant τ decay into $\rho\pi\nu$.

The SLAC-LBL group studied events with a muon, three charged pions, and any number of photons. The three pion mass spectrum after background subtractions is shown in Fig. 4 for cases in which no photons, one or two photons, and more than two photons are observed. In the first two cases there is a significant signal in the vicinity of 1.1 GeV/c^2. The momentum spectra of the muon and the three charged pions in this mass region agree with hypothesis of pair production, as seen in Fig. 5. Figure 6 shows fits to the three pion mass spectrum with no detected photons under three hypotheses: (a) that all the events are due to $\tau \to \pi^\pm\pi^+\pi^-\nu^0$, where the π^0 is not detected, (b) that all the events are due to $\tau \to \rho^0\pi\nu$, where the $\rho^0\pi$ is non-resonant, and (c) that all the events are due to $\tau \to A_1\ \nu \to \pi^\pm\pi^+\pi^-\nu$. Fits to the first two hypotheses have only a few percent confidence level but cannot be excluded. The resonant hypothesis is a good fit with A_1 mass of 1.1 GeV/c^2 and full width of 200 MeV/c^2.

Thus, both experiments have strong evidence for an A_1 meson with mass of 1100 MeV/c^2 and width of .00 to 250 MeV/c , but neither experiment can conclusively establish it.

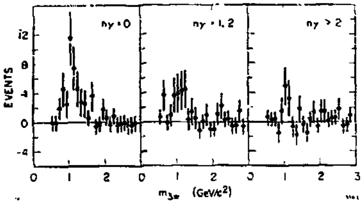

Fig. 4. Invariant mass distributions of three pions in events in which they are detected along with a muon and zero, one or two, or more than two photons. The distributions have been corrected for hadron misidentification as a muon. The data are from the SLAC-LBL and LGW experiments.[22]

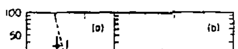

Fig. 5(a) Momentum distribution of muons in events in the .95 < $m_{3\pi}$ < 1.25 GeV/c^2 region of Fig. 4(a) and (b). The solid and dashed curves are the expected spectra from τ decays and charmed particle decays.

(b) Momentum distribution of the three pion system in these events. The solid and dashed curves are the spectra expected for $\tau \to 3\pi\nu$ and $\tau \to 4\pi\nu$ decays.

The PLUTO group measures the $\tau \to \rho^0\pi\nu$ branching fraction to be (5 ± 1.5)%. The SLAC-LBL group obtains an (18 ± 6.5)% branching fraction for $\tau \to \pi^\pm\pi^+\pi^- + n\pi^0\nu$. By using the number of observed photons, in principle it is possible to unfold this branching fraction for the number of π^0's produced. In practice the statistical accuracy is rather poor. The results are (7 ± 5)% for $\tau \to \pi^\pm\pi^+\pi^-\nu$ and (11 ± 7)% for $\tau \to \pi^\pm\pi^+\pi^-\pi^0\nu$. All of these results are consistent with the theoretical predictions given in Table IV.

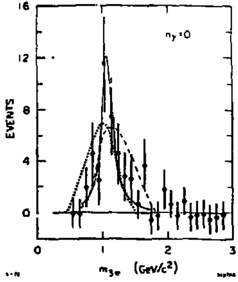

Fig. 6. Data from Fig. 4(a) with fits to different hypotheses. The dotted line represents $\tau \to \pi^\pm\pi^+\pi^-\pi^0\nu$ decays, the dashed line represents non-resonant $\tau \to \pi^\pm\pi^+\pi^-\nu$ decays, and the solid line represents $\tau \to A_1\nu$ decays where the A_1 has a mass of 1.1 GeV/c² and width of 200 MeV/c².

3. The $\pi\nu$ Mode

Last summer at the Hamburg Photon-Lepton Symposium, the DASP group reported that the $\tau \to \pi\nu$ branching fraction was substantially smaller than expected.[20] This was rather surprising since, as we have already discussed, the $\pi\nu$ mode is completely predicted and a failure of this prediction would imply, at the least, that different weak currents were important in τ and π decays. The DASP group searched for a high momentum pion ($\gtrsim$1 GeV/c) with an electron or any charged particle and no detected photons. Twelve $e\pi$ events were expected but only four were seen. When any charged particle plus a pion was required only 17 events were found and 44 were expected. Above 4.52 GeV center of mass energy only four events were found and 17 were expected.

The SLAC-LBL group tried to check this result by searching for events with a pion whose momentum was greater than half the beam energy along with one other charged particle and no detected photons.[23] This search was performed at center of mass energies above 6 GeV. The results, shown in Fig. 7, are in good agreement with predicted τ decay modes and show a large express over what would be predicted if the $\tau \to \pi\nu$ mode was absent. The pion momentum spectrum is almost flat with energy; such a spectrum would be rather untypical of a hadronic process. Using a jet model to estimate and correct for the hadronic background, we obtain a branching fraction of (9.3 ± 3.9)% for $\tau \to \pi\nu$, in excellent agreement with the theoretical prediction. The error is due primarily to the uncertainty in the hadronic subtraction.

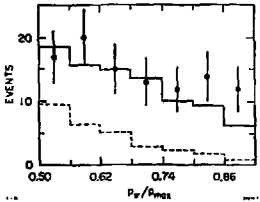

Fig. 7. The ratio of the pion momentum to its maximum value for τ decay for events with a pion, another charged particle and no detected photons. The solid and dashed curves are the spectra expected if the τ decays normally (as indicated in Table IV) and if the τ → πν mode is absent. The data are from the SLAC-LBL experiment.[23]

The DELCO group has measured τ → πν more cleanly by looking for a pion, electron, and no photons.[4] After background subtraction they observe 10.7 events and expect 11.8. As a check that they are not misidentifying muons or missing photons, they observe 10 eμ events and expect 10, and they observe 3.3 eπ events with photons and expect 2.7. DELCO obtains a branching fraction of (8.3 ± 3.0)% for the τ → πν mode.

The τ → πν mode requires more detailed study, but given the results of the SLAC-LBL and DELCO experiments, there is no longer good reason to suspect that it is anomalous.

C. Rare Decay Modes

There have been numerous searches for τ decay modes which should not exist in the standard model.[7,24,25] There is no evidence for any of these modes and the upper limits are given in Table V. Of particular interest is the low upper limit on the τ decay to three charged leptons. Horn and Ross have shown that this implies the existence of the ν_τ in $SU(2) \otimes U(1)$ gauge theories.[26]

III. τ MASS

The DELCO experiment has measured the τ mass precisely by measuring the ex cross section in the threshold region.[12] The data shown in Fig. 8 indicate that the τ mass is 1782^{+2}_{-7} MeV/c^2.

The precision of this result is such as to make all other measurements only of historical interest. This less than glorious history is shown in Fig. 9. The SLAC-LBL mass determinations used properties of the eμ events, such as momentum spectra, collinearly angular distributions, and transverse momentum spectra, to measure the mass.[27,6] The PLUTO group was the first experiment to try to use the energy dependence of the cross section to measure the mass.[28] The breakthrough came with the observation from the DASP group of ψ' decays to τ pairs.[8] The DELCO experiment quickly confirmed this result and homed in on the threshold.

Table V. Upper limits on rare τ decay modes. "x" stands for any charged particle and "ℓ" stands for any charged lepton.

Mode	Experiment	Upper limit(%)	Confidence level(%)	Reference
3x	PLUTO	1.0	95	24
3ℓ	SLAC-LBL	0.6	90	25
ℓ + charged particles	PLUTO	4.0	90	7
ℓ + photons	PLUTO	12.0	90	7
e^- + γ	SLAC-LBL	2.6	90	25
μ^- + γ	SLAC-LBL	1.3	90	25

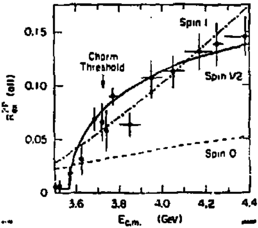

Fig. 8. The ratio of ex events to μ pair production as a function of center of mass energy. The solid curve is a best fit to the spin 1/2 τ pair production cross section. The dashed and dot-dashed curves represent the expected threshold behavior for spin 0 and spin 1 particle production. The data are from the DELCO experiment.[12]

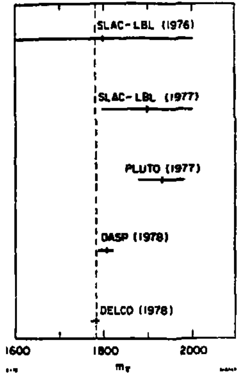

Fig. 9. Measurements of the τ mass.[27,6,28,8,12]

Fig. 10. The scaled lepton momentum in eμ events. r=0 represents the experimental cutoff of 650 MeV/c and r=1 represents the maximum momentum allowed for τ decay. The solid curves show the expected spectra for different mass ν_τ's with V-A τ-ν_τ coupling. The dashed curve shows the expected spectrum for a massless ν_τ with V+A τ-ν_τ coupling. The data are from the SLAC-LBL experiment.[6]

IV. ν_τ MASS

If the ν_τ had a mass, it would soften the charged lepton momentum spectrum as shown in Fig. 10.[29] All experimental measurements are consistent with a massless ν_τ.[6,28,4] The upper limits on the ν_τ mass are given in Table VI.

V. τ SPIN

As long as we assume that the τ does not have a form factor which varies rapidly over the range of a few GeV, all spin assignments except 1/2 are excluded.

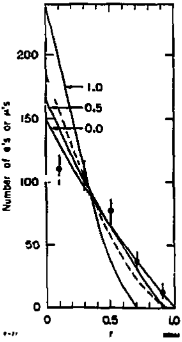

Table VI. Upper limits on ν_τ

Experiment	Upper limit (MeV/c^2)	Confidence level(%)	Reference
SLAC-LBL	600	95	6
PLUTO	540	90	28
DELCO	250	90	4

All integer spins will require a β^3 threshold dependence which is excluded by the DELCO measurements shown in Fig. 8.[12] Half-integer spins greater than 1/2 will lead to much too large a cross section in the 4 to 7 GeV region. Figure 11 shows results of some calculations by Tsai.[30] The solid line, which shows the least divergent spin 3/2 case and agrees with spin 1/2 in the threshold region, lies a factor of two above the data at 4 GeV and an order of magnitude above the data at 6 GeV.

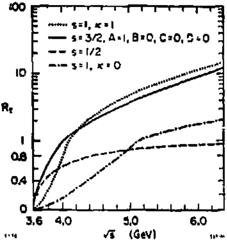

Fig. 11. Energy dependence of the ratio of τ pair production to μ pair production for various τ spins.[30]

VI. τ LIFETIME

The τ lifetime has been studied by examining the closest distance of approach to the interaction region of leptons from τ decays. The upper limits on the τ lifetime are 1.1×10^{-11} sec from the SLAC-LBL experiment[25] and 1.0×10^{-11} sec from the PLUTO experiment,[28] both at the 95% confidence level. For a full strength τ-ν_τ coupling to the weak current the τ lifetime should be about 3×10^{-13} sec. Thus the τ-ν_τ coupling has to be at least 3% of full strength.

VII. τ-ν_τ COUPLING

The lepton momentum spectrum can be used to determine the V,A structure of the τ-ν_τ coupling. V-A gives the hardest spectrum, V+A gives the softest, and pure V or A is halfway in between. The PLUTO experiment favored V-A over V+A slightly.[13] The SLAC-LBL experiment strongly disfavored V+A, giving it a statistical confidence level of at most a few percent.[6]

At this conference we have seen conclusive data from the DELCO experiment completely excluding V+A and even disfavoring pure V or A at the two standard deviation level.[4] The data are shown in Fig. 12. The radiatively corrected Michel parameter is expected to be 0.64 for V-A and -0.17 for V+A. The DELCO measurement is 0.66 ± 0.13.

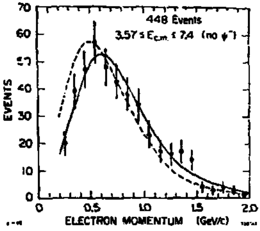

Fig. 12. Electron momentum spectrum for ex events. The solid and dashed curves represent the spectra expected for V-A and V+A τ-ν_τ couplings. The data are from the DELCO experiment.[4]

VIII. WHAT TYPE OF LEPTON IS THE τ?

All of the evidence is consistent with the τ being a sequential lepton decaying to its own massless neutrino with a V-A coupling.

One can ask, however, whether it is possible that the τ^- has the same lepton number as either the e^-, e^+, μ^-, or μ^+; that is, whether it couples to the ν_e, $\bar{\nu}_e$, ν_μ, or $\bar{\nu}_\mu$. The τ^- cannot have the lepton number of either the μ^- or μ^+ or it would be produced in ν interactions. The upper limit on τ-ν_μ coupling is 2.5% of full strength.[31] The τ^- cannot have the lepton number of either the e^+ or μ^+. If it did there would be two identical neutrinos in the final state and B_μ/B_e would be either .5 or 2, in contradiction to the data in Table III.

The one possibility which cannot be excluded at present is that the τ^- has the same quantum number as the e^-. Detailed measurements of ν_e interactions, possibly from beam dump or tagged decay experiments, may be able to address this question in the future.

Of course, there are many more possibilities than the simple ones we have discussed here, and, in general, one must simply compare the predictions of a given model to the range of parameters allowed by the data. It is remarkable, in the three years since the τ discovery, how tight the constraints have become.

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29. We are fortunate that the data agree with both a massless neutrino and a V-A $\tau-\nu$ coupling (see Sec. VII) because this combination gives the hardest lepton momentum spectrum for V and A couplings. Thus upper limits can be set independently on the ν_τ mass and the amount of V-A coupling. It would be difficult, for example, to distinguish the difference between a V-A coupling with a 600 MeV/c^2 ν_τ and a V+A coupling with a massless ν_τ.

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