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Nature of the τ - ν_τ - W Coupling

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The electron momentum spectrum observed in the decay $\tau \rightarrow \nu_\tau e \bar{\nu}_e$ is in good agreement with the $V-A$ hypothesis. The measured value of the Michel parameter, $\rho = 0.72 \pm 0.15$, excludes a $V+A$ current and disfavors pure V or A currents. The spectrum allows us to set an upper limit of $250 \text{ MeV}/c^2$ (95% confidence level) for the τ neutrino mass. Finally, by measuring the τ -lifetime upper limit of $2.3 \times 10^{-12} \text{ sec}$ (95% confidence level), we show that the square of the coupling constant at the τ - ν_τ - W vertex is at least 12% of full weak strength.

In this paper we explore three characteristics of the τ - ν_τ - W coupling (represented by the left-hand vertex of the Feynman diagram in Fig. 1): (a) the space-time structure of the coupling, (b) the upper limit on the mass of the associated neutrino, and (c) the lower limit on the strength of the coupling.

The hypothesis that the τ couples to the standard intermediate vector boson is supported by the good agreement, in all cases, between experimental and theoretical branching-ratio determinations.¹ It is therefore natural to assume that the coupling at the e - ν_e vertex in the decay τ^-

$\rightarrow \nu_\tau e^- \bar{\nu}_e$ is $V-A$ and to use the electron energy spectrum to measure the V, A structure of the τ - ν_τ vertex. The most general coupling is a linear combination of V and A amplitudes, but, for a massless ν_τ , the anticipated couplings are pure $V-A$ or $V+A$, which correspond, respectively, to a left-handed ν_τ and a right-handed ν_τ .

The shape of the electron spectrum in the τ rest frame is determined by the one-parameter Michel formula:

$$N(z) dz \propto z^2 [1 - z + \frac{2}{3} \rho(4z - 3) + r(z)] dz,$$

where z is the electron energy relative to its

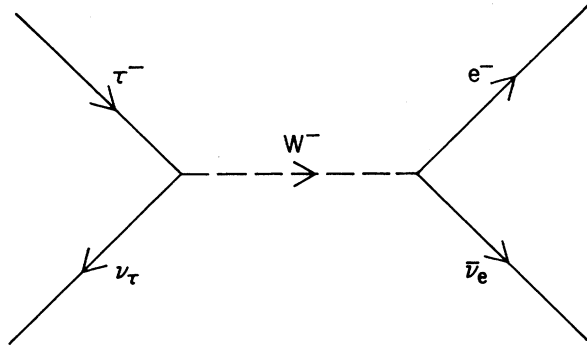


FIG. 1. The Feynman diagram for the decay $\tau^- \rightarrow \nu_\tau e^- \bar{\nu}_e$.

maximum possible value. A $V-A$ coupling is characterized by a Michel parameter, $\rho=0.75$, whereas $V+A$ requires $\rho=0$. Other combinations are represented by intermediate values, e.g., $\rho=0.375$ corresponds to pure V or A . The electron spectra in the τ rest frame as functions of ρ are indicated in Fig. 2. The function $r(z)$ accounts for radiative corrections² to the standard spectral formula and its form is different for $V-A$ and $V+A$ couplings. Radiative effects lead to a significant softening of the uncorrected electron spectra.

The experimental electron spectrum is obtained from a sample of 594 events of the type $e^+e^- \rightarrow e^\pm X^\mp$ ($X \neq e$) taken by the DELCO detector at SPEAR in the center-of-mass energy range $3.57 \leq E_{c.m.} \leq 7.4$ GeV. The apparatus³ and the selection criteria for these events⁴ have been described in previous publications. Several further cuts are imposed to ensure a reliable momentum measurement and reduce backgrounds. The electron track is required to have a spark in the outer wire spark chambers and its momentum must be below the beam energy and above 0.3 GeV/ c (in order to avoid uncertainties in Cherenkov-counter detection efficiency). Finally, the value of $(|\vec{P}_e| + |\vec{P}_X| + |\vec{P}_e + \vec{P}_X|)/E_{c.m.}$ must be less than 0.85 , where \vec{P}_e (\vec{P}_X) is the momentum of the e (X) particle. These cuts result in a very clean sample of τ decays, e.g., the background from misidentified radiative e^+e^- events is about 1%. Charm backgrounds are minimized by excluding data obtained at the $\psi''(3770)$, and the residual contribution is estimated to be 27 ± 15 events.

The fitting procedure involves Monte Carlo generation of $\tau^+\tau^-$ events according to the experimental $E_{c.m.}$ distribution and corresponding to different values of ρ and ν_τ mass⁵ (denoted m_{ν_τ}).

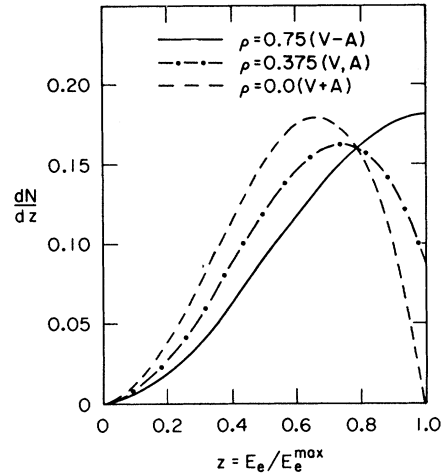


FIG. 2. The electron momentum spectra in the τ rest frame for several values of the Michel parameter ρ . No radiative effects are included.

Radiative corrections are included in the initial and final states. After the simulated data are processed through the standard data-analysis program and the cuts described above are applied, a comparison with the experimental electron spectrum yields χ^2 as a function of ρ and m_{ν_τ} .

Our understanding of errors from measurement and Coulomb scattering has been verified by studies of elastic e^+e^- events in the energy range $3.1 < E_{c.m.} < 7.4$ GeV and from the distribution of the ψ (missing) mass as reconstructed from the soft pions alone in the events $\psi' \rightarrow \psi\pi^+\pi^-$, $\psi \rightarrow e^+e^-$. The former events are mainly sensitive to measurement errors and the latter to Coulomb scattering. The agreement between the Monte Carlo calculation and experimental data is satisfactory.

The experimental data, after subtraction of the charm background, are compared with the distributions expected for pure $V-A$ and $V+A$ hypotheses.⁶ In addition the ρ value giving the lowest χ^2 is determined under the assumption $m_{\nu_\tau}=0$. The data and fitted curves are displayed in Fig. 3, and the numerical results are summarized in Table I. The systematic errors in the measurement of ρ arise from backgrounds due to charm, radiative e^+e^- events, two-photon processes, and misidentified hadronic events in addition to small contributions from errors in momentum measurement and radiative corrections. They result in a systematic error in ρ of ± 0.11 which, when combined with the statistical error, determines that $\rho = 0.72 \pm 0.15$. We con-

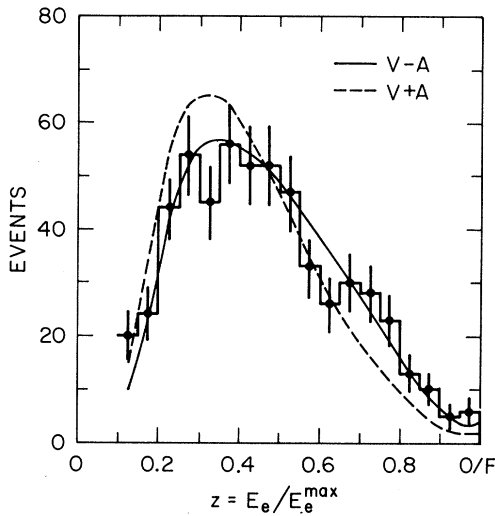


FIG. 3. The electron momentum spectrum expressed as $z = E_e/E_e^{\max}$, in the range $3.57 \leq E_{c.m.} \leq 7.4$ GeV, excluding data taken at the ψ'' (3770). The solid and dashed lines are, respectively, $V-A$ and $V+A$ fits with zero ν_τ mass.

clude that there is good agreement with a $V-A$ coupling whereas $V+A$ is excluded and pure V or pure A is unlikely.

An alternative presentation of the data involves calculating the average value of E_e/E_{beam} which is 0.35 for $V-A$ and 0.3 for $V+A$ and is independent of beam energy⁷ under the conditions of complete electron acceptance, no measurement errors, and no radiative corrections. These effects have been accounted for by means of a Monte Carlo calculation. To avoid excessive sensitivity to a few mismeasured events we reject events with $P_e > P_e^{\max}$ in both the experimental and simulated data. The data and the two extreme hypotheses are displayed in Fig. 4 and indicate agreement in each energy range with a $V-A$ current. The mean value for the complete data sample is $\langle E_e/E_{\text{beam}} \rangle = 0.34 \pm 0.006$ to be compared with the predictions of 0.344 ± 0.002 and 0.307 ± 0.002 for

TABLE I. Results of the fits to the electron momentum spectrum.

Hypothesis	ρ	χ^2	No. of degrees of freedom
$V-A$	0.75	15.9	17
$V+A$	0.0	53.7	17
Free fit	0.72 ± 0.10^a	15.8	16

^aStatistical error.

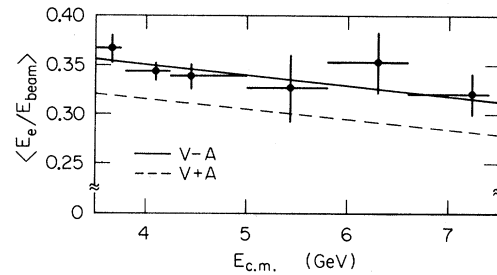


FIG. 4. The average value of E_e/E_{beam} for several ranges of center-of-mass energy (indicated by the horizontal error bars). The energy dependences of the predictions of the $V-A$ and $V+A$ hypotheses (indicated, respectively, by the solid and dashed lines) result from experimental cuts and measurement errors.

$V-A$ and $V+A$, respectively.

The effect of a nonzero ν_τ mass is to soften the electron spectrum and to reduce the apparent value of ρ . Therefore, since our data rule out the $V+A$ hypothesis for all values of m_{ν_τ} , we set the ρ parameter at 0.75 ($V-A$) for this study. From the measured χ^2 variations with $m_{\nu_\tau} \neq 0$, we determine the upper limit, $m_{\nu_\tau} < 250$ MeV/ c^2 (95% confidence level).⁸

We shall now consider the strength of the $\tau-\nu_\tau-W$ coupling. The standard weak-coupling constant results in a τ lifetime, $\tau_0 = 2.7 \times 10^{-13}$ sec (assuming the world-average¹ branching fraction for $\tau \rightarrow \nu_\tau e \nu_e$ of $16.5 \pm 1.5\%$). Although this lifetime is below our experimental sensitivity, a lifetime upper limit determines a lower limit on the coupling strength.

Our procedure is to define for each track in an eX event the possible cone into which the parent τ was emitted. Different directions in that cone have different probabilities depending on the momentum of the daughter particle and the beam energy. The second τ has an identical probability to be emitted in the opposite direction. We thus determine the intersection of the second charged track with each possible τ direction and from it calculate the projected τ flight path (in the plane perpendicular to the beam axis) assuming an origin at the center of the beam. This distance, appropriately weighted by the *a priori* probability, is in turn converted into a probability distribution for observing this event as a function of τ lifetime. The total sample of events yields the overall likelihood function for the lifetime. With systematic errors taken into account the result is $\tau_0 < 2.3 \times 10^{-12}$ sec (95% confidence level),⁹ which implies that the square of the coupling constant

at the τ - ν_τ - W vertex is at least 12% (95% confidence level) of full weak strength.

This upper limit on the τ lifetime can be combined with precise measurements dealing with electron-muon universality to exclude a wide range of descriptions of the ν_τ .¹⁰ An example is the heavy- τ -neutrino model¹¹ in which the τ decays at a reduced rate via small mixings between ν_e , ν_μ , and ν_τ . The tight experimental limits on μ - e universality¹² as well as experiments with ν_μ beams¹³ impose upper bounds on the mixing amplitudes which are too small to allow the τ to decay within the measured lifetime limit.

In conclusion, our measurements are in agreement with the hypothesis of a $V-A$ interaction at the τ - ν_τ vertex. $V+A$ is ruled out and pure V or A is disfavored. The mass of the " ν_τ " produced in $\tau \rightarrow \nu_\tau e \nu_e$ has an upper limit of 250 MeV/ c^2 . The combined results of the τ -lifetime upper limit, electron-muon universality, and neutrino experiments imply that the neutral particle which couples directly to the τ is almost certainly a new neutrino, ν_τ .^{14, 15}

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¹For a recent review of the branching-ratio situation see G. J. Feldman, Rapporteur's talk, in Proceedings of the Nineteenth International Conference on High Energy Physics, Tokyo, Japan, August 1978 (to be published).

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¹⁴Formally, the possibility that τ is an orthoelectron is not excluded despite the low upper limit for the decay $\tau \rightarrow e \gamma$. The absence of clean ν_e beams has prevented neutrino experiments from exploring this possibility. If this were the nature of the τ , then " ν_τ " would be an electron neutrino.

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