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MEASUREMENTS OF THE DECAYS $\tau^- \to \rho^- \nu_\tau$, $\tau^- \to \pi^- \nu_\tau$ and $\tau^- \to K^{*-}(892)\nu_\tau$ USING THE MARK II DETECTOR AT SPEAR†

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ABSTRACT: Measurements of the branching fractions for the Cabibbo favored decays $\tau^- \to \rho^- \nu_\tau$ and $\tau^- \to \pi^- \nu_\tau$ and the Cabibbo suppressed decay mode $\tau^- \to K^{*-}(892)\nu_\tau$ are presented. The energy dependence of the $\tau^+\tau^-$ production cross section is obtained for the decays $\tau^- \to \rho^- \nu_\tau$ and $\tau^- \to \pi^- \nu_\tau$ and these spectra agree well with the classification of the τ^- as a spin-½ point particle. Fits to the production cross section yield a measurement of $M_\tau = (1787 \pm 10)$ MeV/c^2 for the τ mass. Ninety-five percent confidence upper limits for the forbidden decay $\tau^- \to K^{*-}(1430)\nu_\tau$ and the τ neutrino mass are presented.

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INTRODUCTION

The heavy lepton, τ, is now a well established particle and considerable knowledge about this particle has been obtained — particularly by studying its leptonic decays.[1] The members of the SLAC-LBL MARK II detector group,[2] working at SPEAR, undertook a systematic study of the τ hadronic decay modes in order to test whether the standard weak hadronic current mediates such decays. We present herein measurements of the branching fractions for the decays[3] $\tau^- \to \rho^- \nu_\tau$, $\tau^- \to \pi^- \nu_\tau$ and $\tau^- \to K^{*-}(892)\nu_\tau$ which probe respectively the Cabibbo favored weak hadronic vector current, the Cabibbo favored weak hadronic axial vector current and the Cabibbo suppressed weak hadronic vector current. These data strongly support the notion that the W^- mediates τ decay. The energy dependence of the $\tau^+\tau^-$ production cross section is presented for the decays $\tau^- \to \rho^- \nu_\tau$ and $\tau^- \to \pi^- \nu_\tau$. These data support the assignment of the τ as a spin-½ point particle. From fits to these spectra we obtain a measurement of the τ mass: $M_\tau = (1787 \pm 10)$ MeV/c^2. From an endpoint measurement of the π energy spectrum in the decay $\tau^- \to \pi^- \nu_\tau$ we obtain a 2σ upper limit of 245 MeV/c^2 for the τ neutrino mass.

MEASUREMENT OF THE DECAY $\tau^- \to \rho^- \nu_\tau$

The MARK II solenoidal detector is fully described in the articles listed under ref. 4. The data used for this analysis come from all MARK II running at SPEAR with the exception of the ψ and ψ'.[5] These data span the center-of-mass energy range $3.52 \le E_{c.m.} \le 6.7$ GeV, and correspond to an integrated luminosity of 21,000 nb^{-1} or, using the theoretical $\tau^+\tau^-$ production cross section, 58,000 produced $\tau^+\tau^-$ pairs. In searching for the decay $\tau^- \to \rho^- \nu_\tau$, we attempt to isolate events arising from the decay sequence:

$$e^-e^+ \to \tau^-\tau^+$$
$$\tau^+ \to \ell^+ \nu_\ell \bar{\nu}_\tau$$
$$\tau^- \to \rho^- \nu_\tau$$
$$\rho^- \to \pi^- \pi^0$$
$$\pi^0 \to \gamma\gamma$$

which results in two charged tracks and two photons in the detector. The lepton tag (ℓ^+) helps provide a clean signature for events containing τ's. The selected events have two oppositely charged tracks, one a pion and the other a lepton, and two photons with $E_\gamma \ge 100$ MeV. For the purposes of this analysis a pion is any charged particle which is not positively identified as a kaon, proton, electron or muon. The invariant mass of the two photons ($M_{\gamma\gamma}$) is formed and the photon energies of the π^0 candidates (those for which $80 \le M_{\gamma\gamma} \le 200$ MeV) are adjusted using the π^0 mass as a single constraint. These π^0's are then combined with the charged pion to form the $\pi^\pm\pi^0$ invariant mass [$M(\pi^\pm\pi^0)$] as shown in fig. 1.

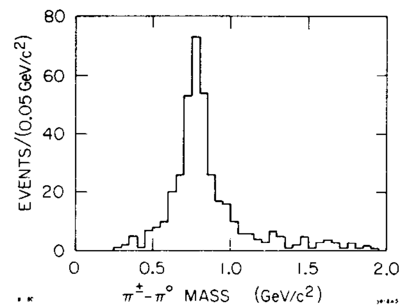


fig. 1. The $\pi^{\pm}\pi^{0}$ invariant mass spectrum for $\ell^{\pm}\pi^{\mp}\pi^{0}$ events.

An impressive $\rho^{\pm}$ signal is seen with very little background. Defining the signal region as $M(\pi^{\pm}\pi^{0}) \leq 1.25$ GeV/c^2 there are 215 ρe events and 137 $\rho\mu$ events. There are fewer $\rho\mu$ events because of the 700 MeV/c threshold of the muon tagging system. Background contributions of 12% due to hadronic events and 14% due to the decays $\tau \to A_1\nu_\tau$ and $\tau \to (4\pi)\nu_\tau$ are removed. In order to obtain $B(\tau^- \to \rho^-\nu_\tau)$ we need to know $B(\tau^- \to \ell^-\nu_\ell\bar{\nu}_\tau)$. This has been measured using 294 events containing an electron, a muon and no photons ($e\mu$ events). A small (12%) correction is made to these events for backgrounds arising from QED and hadronic processes. A Monte Carlo simulation program has been used to generate the detection efficiencies $\varepsilon_{\rho e} = 3.4\%$, $\varepsilon_{\rho\mu} = 2.1\%$ and $\varepsilon_{e\mu} = 7.1\%$. Combining these efficiencies with the number of corrected events and the number of produced $\tau^+\tau^-$ pairs yields:

$$B\left(\tau^- \to \rho^-\nu_\tau\right)\, B\left(\tau^+ \to e^+\bar{\nu}_\tau\nu_e\right) = 0.034 \pm 0.004 \pm 0.007 \quad (1)$$

$$B\left(\tau^- \to \rho^-\nu_\tau\right)\, B\left(\tau^+ \to \mu^+\bar{\nu}_\tau\nu_\mu\right) = 0.041 \pm 0.005 \pm 0.007 \quad (2)$$

$$B\left(\tau^- \to e^-\nu_\tau\bar{\nu}_e\right)\, B\left(\tau^+ \to \mu^+\bar{\nu}_\tau\nu_\mu\right) = 0.030 \pm 0.002 \pm 0.007 \quad (3)$$

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

Assuming μ-e universality in τ decays (3) can be combined with (1) and (2) to yield

$$B\left(\tau^- \to \rho^-\nu_\tau\right) = (21.6 \pm 1.8 \pm 3.2)\% \quad .$$

The branching fraction $B(\tau^- \to \rho^-\nu_\tau)$ can be calculated[6] using the conserved vector current hypothesis and a measurement of $e^+e^- \to \rho^0$. Tsai has recently[7] updated his calculations of 1971 and obtains $B(\tau^- \to \rho^-\nu_\tau) = 21.5 \pm 1.5$ where the uncertainty in $B(\tau^- \to \rho^-\nu_\tau)$ arises from the experimental uncertainty in $\Gamma(e^+e^- \to \rho^0)$. This calculation of $B(\tau^- \to \rho^-\nu_\tau)$ agrees well with the experimental result.

We have measured the energy dependence of the $\tau^+\tau^-$ production cross section ($\sigma_{\tau\bar{\tau}}$) by studying the quantity $\sigma_{\tau\bar{\tau}}B_\rho(B_e + B_\mu)/\sigma_{\mu\mu}$, where $\sigma_{\mu\mu}$ is the point cross section. Figure 2 shows a plot of this quantity as a function of center-of-mass energy. A fit to this data yields a measure of

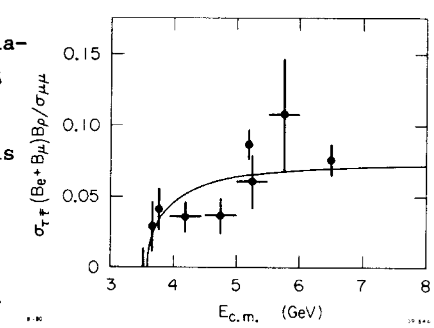


fig. 2. The $\tau\bar{\tau}$ production cross section, normalized to the μ-pair cross section, as a function of $E_{c.m.}$.

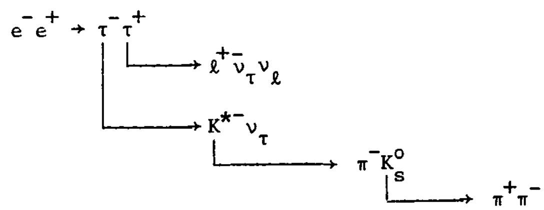
the τ mass:

$$M_\tau = (1790 \pm 40)\ \mathrm{MeV}/c^2$$

which is in good agreement with other experimental determinations.[1)]

MEASUREMENT OF THE BRANCHING FRACTION FOR $\tau^- \to K^{*-}(892)\nu_\tau$

For the study of the decay $\tau^- \to K^{*-}(892)\nu_\tau$ we have used all the MARK II data with $E_{c.m.} > 4.2$ GeV, which corresponds to an integrated luminosity of $14{,}600\ \mathrm{nb}^{-1}$ or 40,200 produced $\tau^+\tau^-$ pairs.[8)] The energy threshold of 4.2 GeV is chosen to avoid those regions where production of D mesons could constitute a significant background. The decay $\tau^- \to K^{*-}\nu_\tau$ is identified via the topology:



which results in four charged particles and no photons in the detector. Events are required to have four charged particles, two positive and two negative, and no photons with $E_\gamma \geq 100$ MeV. Two of the charged particles are required to form a secondary vertex, distant from the primary vertex by at least 1 cm, and have a mass consistent with the K^0_s. We further require that one of the particles at the primary vertex be a lepton; the other is hitherto referred to as a $\pi^\pm$. Figure 3 shows the $K^0_s\pi^\pm$ invariant mass spectrum for the events selected as described above. A clear excess of events is present at the $K^*(892)$ mass and we attribute these $K^*(892)$-lepton coincidences to the decay topology outlined at the beginning of this section. From the eleven events in the five bins from 825-950 MeV/c^2 we have subtracted a background of two events obtained from the ten surrounding bins. The resulting signal is 9.0 ± 3.6 events. Of the eleven events, seven have an electron tag and four a muon tag which is consistent with the relative electron/muon tagging efficiency of 1.6. The momentum spectrum of the leptons is "hard"— nine out of eleven leptons have momenta above 700 MeV/c. This momentum spectrum and that of the K^*'s is well reproduced by the Monte Carlo simulation program assuming a $\tau^+\tau^-$ production process.

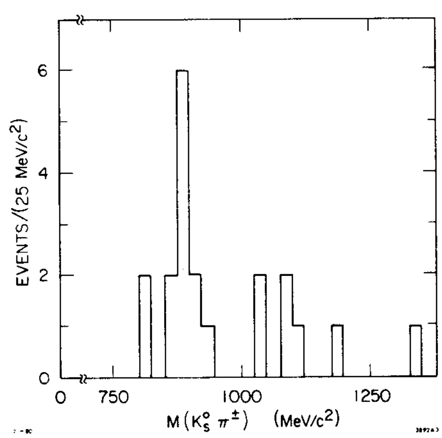


fig. 3. $K^0_S\pi^\pm$ invariant mass spectrum for $K^0_S\pi^\pm\ell^\mp$ events.

Since D mesons are both a source of leptons and strange particles it is important to eliminate them as a source of the K^*-ℓ- no photon events. Charm events have a relatively high charged and neutral multiplicity and this, combined with the good solid angle coverage of the MARK II detector, make it very difficult for charmed events to populate the low multiplicity $K_S^o\pi^\pm\ell^\mp$ topology. A Monte Carlo program has been used to estimate the D background. Charmed particle production contributes at most 0.1 events to the $K^{*\pm}\ell^\mp$ sample. The leptons which come from semileptonic D decays, as simulated by the Monte Carlo program, have a momentum spectrum which is much "softer" than that observed in the $K^*\ell$ events. Almost all these leptons would have momenta below 700 MeV/c, in strong contrast to the data.

The detection efficiencies for the K^*-electron and K^*-muon events are 2.1% and 1.3%, respectively. These efficiencies are combined with the number of produced $\tau^+\tau^-$ pairs and the number of signal events to yield

$$B\left(\tau^- \to K^{*-}(892)\nu_\tau\right)\ B\left(\tau^+ \to \ell^+\nu_\ell\bar{\nu}_\tau\right) = 0.0031 \pm 0.0013 \quad .$$

Using the MARK II measurement[5] of

$$B\left(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau\right) = (18.5 \pm 1.5)\%$$

and assuming electron-muon universality in τ decays, we obtain

$$B\left(\tau^- \to K^{*-}(892)\nu_\tau\right) = (1.7 \pm 0.7)\% \quad .$$

We observe no $K^{*\pm}\ell^\mp$ events in the region of the $K^*(1430)$ which allows us to set a 2σ upper limit $B\left(\tau^- \to K^{*-}(1430)\nu_\tau\right) < 0.9\%$. This decay is, of course, forbidden in any V/A theory.

A detailed calculation by Tsai[6] yields

$$B\left(\tau \to K^*\nu_\tau\right) = \tan^2\theta_c\ B\left(\tau \to \rho\nu_\tau\right)\ F\left(M_\tau, M_{K^*}, M_\rho\right) \quad .$$

The function F accounts for phase space effects and is numerically equal to 0.93. Using the value $B(\tau^- \to \rho^-\nu_\tau) = (21.5 \pm 1.8)\%$ quoted earlier, $\tan^2\theta_c = 0.05$ and $M_\tau = 1.782$ GeV/c^2, theory would predict $B(\tau^- \to K^{*-}\nu_\tau) = (1.0 \pm 0.1)\%$ in good agreement with the data.

MEASUREMENT OF THE DECAY $\tau^- \to \pi^-\nu_\tau$

The data used for this study are identical to that used for the analysis of $\tau^- \to \rho^-\nu_\tau$.[5] We attempt to isolate events which are consistent with the decay sequence

$$e^+e^- \to \tau^+\tau^-, \quad \tau^- \to x^- + \nu\text{'s}, \quad \tau^+ \to \pi^+\nu_\tau$$

which results in two charged particles and no photons in the detector. (The notation x^- indicates any charged particle). The selected events have two oppositely charged tracks, acoplanar by at least 20^o, no photons in the liquid argon barrel modules ($E_\gamma > 100$ MeV) and no hits in the PWC endcap. In addition at least one of the charged particles is required to be a positively identified π. This means that the track must be headed towards the muon system, have sufficient momentum (P) to enter the muon system (i.e. $P > 700$ MeV/c) and not be flagged as a muon. In addition this candidate π must not be an electron (liquid argon), a kaon (TOF) or a proton (TOF). There are 2150 such events. The major source of background comes from the decay $\tau^- \to \rho^- \nu_\tau \to \pi^- \pi^o \nu_\tau$ where both the photons from the π^o decay escape detection by the MARK II. We remove this background using the Monte Carlo simulation program and our measured value of $B(\tau^- \to \rho^- \nu_\tau)$. This constitutes a 25% subtraction. A further subtraction of 22% accounts for feeddown from hadronic events and backgrounds from QED processes. The Monte Carlo simulation program is used to obtain the efficiencies for detecting the $\pi x(x = e, \mu$ or $\pi)$ events. These are combined with the number of corrected events, the number of produced $\tau^+\tau^-$ pairs and $B(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau)$ presented earlier to yield:

$$B\left(\tau^- \to \pi^- \nu_\tau\right) = (11.7 \pm 0.4 \pm 1.8)\% \quad .$$

The theoretical prediction[6] *for* $B(\tau^- \to \pi^- \nu_\tau)$ *is obtained from the known rate for* $\pi^- \to \mu^- \nu_\mu$. The precise prediction of $B(\tau^- \to \pi^- \nu_\tau)/B(\tau^- \to e^- \bar{\nu}_e \nu_\tau) = 0.59$ is obtained. For our measured value of $B(\tau^- \to e^- \bar{\nu}_e \nu_\tau)$ one obtaines the prediction $B(\tau^- \to \pi^- \nu_\tau) = 10.4\%$ in good agreement with our measurement.

Using the background subtracted data we have measured the energy dependence of the production cross section ($\sigma_{\tau\bar{\tau}}$) by studying the quantity $\sigma_{\tau\bar{\tau}} B_\pi / \sigma_{\mu\mu}$. Figure 4 shows a plot of this quantity as a function of center-of-mass energy. The solid curve is the prediction for a spin-½ point particle. A fit to this data yields the τ mass:

$$M_\tau = (1800 \pm 40) \text{ MeV/c}^2 \quad .$$

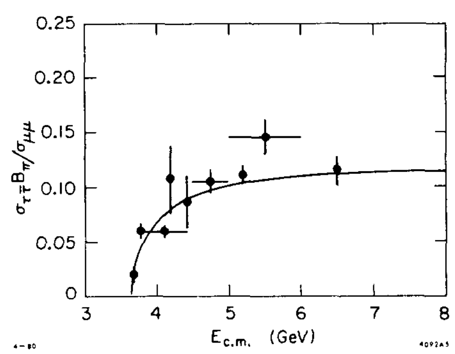


fig. 4. The $\tau\bar{\tau}$ production cross section, *normalized to the* μ-*pair* cross section is shown as a function of $E_{c.m.}$. These data points come from the study of the decay $\tau^- \to \pi^- \nu_\tau$.

We have performed a measurement of the τ neutrino mass (M_{ν_τ}) using the background subtracted energy spectrum of the π from the decay $\tau^- \to \pi^- \nu_\tau$.[5] This analysis is best done at a fixed center-of-mass energy since the maximum π momentum clearly depends on $E_{c.m.}$. We have chosen $E_{c.m.} = 5.2$ GeV which comprises about a quarter of our total data (approximately 15,000 produced $\tau^+\tau^-$ pairs). Fixing the mass of the τ, the π energy spectrum was fit for the τ neutrino mass.

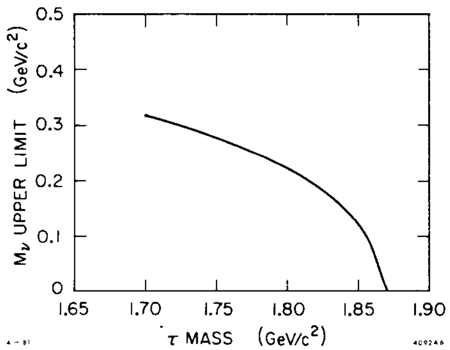


fig. 5. Upper limit (95% confidence level) on the mass of the τ neutrino as a function of the mass of the τ.

Figure 5 shows the 2σ upper limit on M_{ν_τ} as a function of M_τ. For the favored DELCO mass[1] $M_\tau = 1782$ we obtain:

$$M_{\nu_\tau} < 245 \text{ MeV/c}^2 \quad (2\sigma \text{ upper limit})$$

MEASUREMENT OF THE τ MASS

We have performed a combined fit (χ^2 minimization) to the production spectra obtained from the decays $\tau^- \to \rho^- \nu_\tau$ (fig. 3), $\tau^- \to \pi^- \nu$ (fig. 4) and $\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$ (not shown, see ref. 5) which yields

$$M_\tau = (1787 \pm 10) \text{ MeV/c}^2$$

This result is in excellent agreement with other experimental determinations.[1]

CONCLUSIONS

A detailed study of τ hadronic decays indicate that all results agree with the theoretical classification of the τ as a sequential, spin-½ lepton whose decays are mediated by the familiar W boson. The vector and axial vector Cabibbo favored hadronic decays are seen at their expected strengths and in the case of the vector current the Cabibbo suppressed decay $\tau^- \to K^{*-} \nu_\tau$ is seen at its expected strength. A precise determination of the τ mass has been obtained from the hadronic decays as well as a 2σ upper limit on the τ neutrino mass.

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2) Members of the SLAC-LBL collaboration: G. S. Abrams, M. S. Alam, C. A. Blocker, A. M. Boyarski, M. Breidenbach, D. L. Burke, W. C. Carithers, W. Chinowsky, M. W. Coles, S. Cooper, W. E. Dieterle, J. B. Dillon, J. Dorenbosch, M. W. Eaton, G. J. Feldman, M. E. B. Franklin, G. Gidal, G. Goldhaber, G. Hanson, K. G. Hayes, T. Himel, D. G. Hitlin, R. J. Hollebeek, W. R. Innes, J. A. Jaros, P. Jenni, A. D. Johnson, J. A. Kadyk, A. J. Lankford, R. R. Larsen, V. Lüth, R. E. Millikan, M. E. Nelson, C. Y. Pang, J. E. Patrick, M. L. Perl, B. Richter, A. Rousarie, D. L. Scharre, R. H. Schindler, R. F. Schwitters, J. L. Siegrist, J. Strait, H. Taureg, M. Tonutti, G. H. Trilling, E. N. Vella, R. A. Vidal, I. Videau, J. M. Weiss and H. Zaccone.

3) The notation $\tau^- \to \rho^- \nu_\tau$, $\tau^- \to \ell^- \nu_\tau \bar{\nu}_\ell$, $\tau^- \to K^{*-} \nu_\tau$ and $\tau^- \to \pi^- \nu_\tau$ imply also the charge conjugate reactions.

4) The most thorough review of the detector appears in Vera Lüth's talk in the Proc. of the 1979 Int. Symp. on Lepton and Photon Interactions at High Energy, Batavia (1979), p. 78.

5) The results presented in this section are more fully discussed in Craig Blocker's Ph.D. thesis, LBL-10801, April 1980. The results based on about a quarter of this data can be found in G. S. Abrams et al., Phys. Rev. Lett. 43 (1979), 1555 (for the decay $\tau^- \to \rho^- \nu_\tau$).

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8) J. M. Dorfan et al., Phys. Rev. Lett. 46 (1981) 215.