Brief Reports

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Tau-neutrino mass limit

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Using a data sample corresponding to an integrated luminosity of 300 pb^{-1} collected by the High Resolution Spectrometer, a 95%-confidence-level upper limit of 76 MeV/c^2 is found for the mass of the τ neutrino. The experiment is based on a study of the hadronic mass spectrum in the decays $\tau \to 5\pi^{\pm}\nu_\tau$ and $\tau \to 5\pi^{\pm}\pi^0\nu_\tau$.

Tau-lepton decays to a τ neutrino (ν_τ) and $5\pi^{\pm}$ as well as $5\pi^{\pm}\pi^0$ have been established in previous papers.[1,2] The hadronic mass spectrum of these events was used to place limits on the mass of the τ neutrino.[2,3] This paper reports final results for upper limits on the mass of the τ neutrino based on seven $5\pi^{\pm}$ events and six $5\pi^{\pm}\pi^0$ events obtained from a data sample corresponding to 300 pb^{-1} collected by the High Resolution Spectrometer. At the end point of the hadronic mass spectrum, where the limiting value of the neutrino kinetic energy is zero, the τ-neutrino mass is given by the simple expression $M_{\nu_\tau} = M_\tau - M_{\text{hadrons}}$. However, the actual upper limit for M_{ν_τ} was found by fitting the overall mass distributions of the $5\pi^{\pm}$ and $5\pi^{\pm}\pi^0$ events using a maximum-likelihood technique.

The properties of the detector, the criteria used for event selection and classification, and the cuts needed to eliminate the background have been previously presented.[1,3,4] The selected events have one charged particle in one hemisphere recoiling against five charged particles in the opposite hemisphere. The properties of the 13 events passing the cuts are listed in Table I. These events have

TABLE I. Properties of the events.

	Hadronic mass (M_{had}) (MeV/c^2)	Mass resolution (MeV/c^2)
	$\tau \to 5\pi^{\pm}\nu_\tau$	
1	1486	13
2	1488	8
3	1574	13
4	1608	10
5	1630	12
6	1633	14
7	1645	17
	$\tau \to 5\pi^{\pm}\pi^0\nu_\tau$	
1	1618	15
2	1655	44
3	1666	57
4	1688	54
5	1693	18
6	1731	41

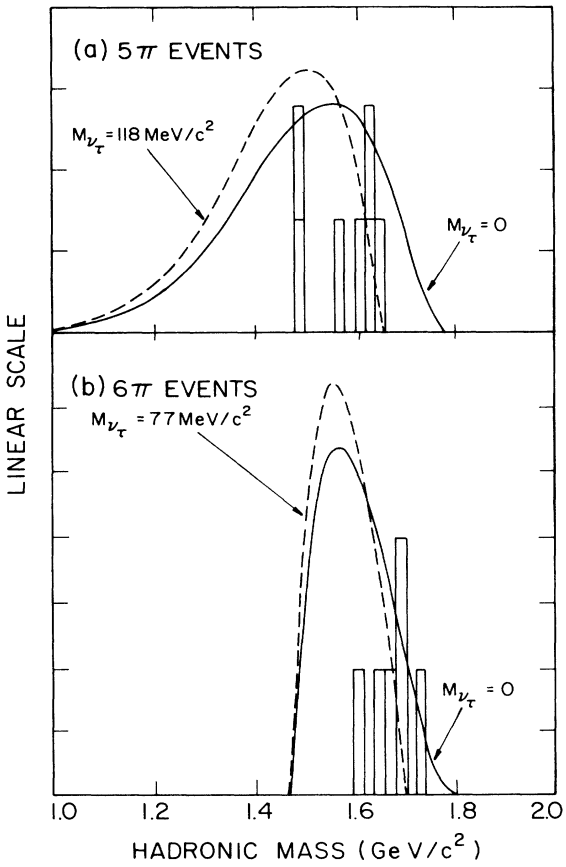

FIG. 1. (a) The hadronic invariant mass of the seven events $\tau \to 5\pi^{\pm}\nu_\tau$. The solid line is phase space times the weak matrix element for the best fit $M_{\nu_\tau}=0$. (b) The hadronic invariant mass of the six events $\tau \to 5\pi^{\pm}\pi^0\nu_\tau$. The solid line shown is the best fit, $M_{\nu_\tau}=0$, based on the data of Cosme *et al.* The dashed lines show the 95%-confidence-level limits on M_{ν_τ}.

masses approaching the τ-lepton mass of 1784 ± 3 MeV/c^2. The mass resolution of each event was determined by repeatedly passing the event through the Monte Carlo simulation of the detector. For events having neutral energy that escapes through cracks in the detector, the true mass can be larger than that measured, but not smaller. From a Monte Carlo event simulator, it is estimated that for the $5\pi^{\pm}\pi^0$ events there is a 0.09 ± 0.03 chance of the accompanying π^0 being unobserved, so that the $5\pi^{\pm}$ event sample includes an estimated 0.6 ± 0.2 events of the $5\pi^{\pm}\pi^0$ final state. We have also taken into account the

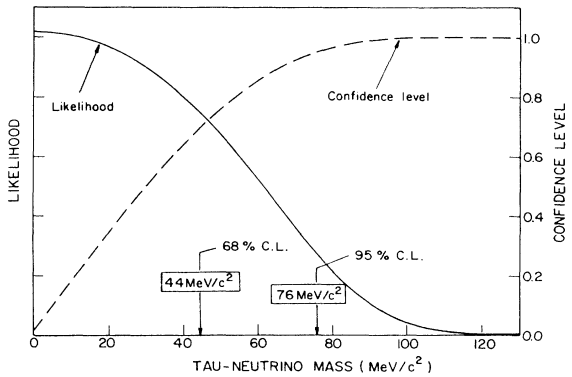

FIG. 2. The likelihood function for the combined $5\pi^{\pm}\nu_\tau$ and $5\pi^{\pm}\pi^0\nu_\tau$ data. The confidence level as a function of τ-neutrino mass is also plotted.

possibility that the $5\pi^{\pm}\pi^0$ events include true $5\pi^{\pm}$ events with a radiative photon incorrectly interpreted as a π^0. In addition, in the $5\pi^{\pm}\pi^0$ sample, the energy of a radiative photon could be incorrectly included in the calculation of the π^0 energy. The probability of each of these effects is 0.006 ± 0.003, and is included in the fitting procedure.

As is the case for the 2π, 3π, and 4π decay modes of the τ (Ref. 5), it is likely that the 5π and 6π decays will proceed through hadronic resonances. Although there is no known resonance that can be associated with the $5\pi^{\pm}$ decays, the exact shape of the resonance is unimportant because the functional form of the hadronic mass distribution near the end point of the spectrum is dominated by the weak-interaction matrix element and the effects of phase space. The results of the maximum-likelihood fit to the data using a $5\pi^{\pm}\nu_\tau$ phase-space ($\rho_{5\pi^{\pm}\nu_\tau}$) factor times the weak matrix element,[6]

$$\frac{d\Gamma}{dM_{\rm had}} \sim \rho_{5\pi^{\pm}\nu_\tau} M_{\rm had}[(M_\tau^2 - M_{\rm had}^2)(M_\tau^2 + 2M_{\rm had}^2) - M_{\nu_\tau}^2(2M_\tau^2 - M_{\rm had}^2 - M_{\nu_\tau}^2)] ,$$

are shown in Fig. 1(a). The best fit is for $M_{\nu_\tau}=0$ and is shown as the solid line. The upper limit, at 95% confidence level, of $M_{\nu_\tau} < 118$ MeV/c^2 is shown by the dashed line.

The shape of the $5\pi^{\pm}\pi^0$ mass spectrum is predicted by the conserved-vector-current hypothesis that relates the vector part of the weak interaction to the isovector part of the total annihilation cross section for $e^+e^- \to 6\pi$. Specifically,[6]

$$\frac{d\Gamma}{dM_{\rm had}} \sim M_{\rm had}[(M_\tau^2 - M_{\rm had}^2)(M_\tau^2 + 2M_{\rm had}^2) - M_{\nu_\tau}^2(2M_\tau^2 - M_{\rm had}^2 - M_{\nu_\tau}^2)] \times [(M_\tau^2 - M_{\rm had}^2)^2 - M_{\nu_\tau}^2(2M_\tau^2 + 2M_{\rm had}^2 - M_{\nu_\tau}^2)]^{1/2} \frac{\sigma^1_{e^+e^-}(M_{\rm had})}{\sigma_{\rm pt}(M_{\rm had})} ,$$

where $\sigma^1_{e^+e^-}$ is the isospin-one part of the cross section and $\sigma_{\rm pt}(M_{\rm had})$ is the point cross section which varies as $1/M_{\rm had}^2$.

Measurements of the $e^+e^- \to 6\pi$ annihilation cross section for center-of-mass energies in the τ mass region have been reported by Cosme *et al.*[7] In these data there is a thresholdlike behavior near 1.5 GeV/c^2. Our observed 6π events all cluster above 1.6 GeV/c^2. Using a linear fit to

the measured 6π cross section in the τ mass region, a 95%-confidence-level upper limit of 77 MeV/c^2 is found for M_{ν_τ}, shown as the dashed line in Fig. 1(b). If the cross section threshold is varied by ± 50 MeV/c^2, the limit changes by less than 1.5 MeV/c^2. The best fit to the data, $M_{\nu_\tau}=0$, is shown as the solid line in Fig. 1(b).

Figure 2 shows the normalized likelihood as a function of τ-neutrino mass for the result coming from the combined $5\pi^{\pm}$ and $5\pi^{\pm}\pi^0$ data. The arrows show the integral of the normalized likelihood at the 68%- and 95%-confidence-level points corresponding to limits of 44 and 76 MeV/c^2, respectively. This result is consistent with that of Albrecht *et al.* (ARGUS group)[8] who report a similar limit from $\tau \to 3\pi^{\pm}\nu_\tau$ decays.

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