Upper Limit on the Tau-Neutrino Mass

S. Abachi, C. Akerlof, P. Baringer, I. Beltrami,[a] D. Blockus, G. Bonvicini, B. Brabson, B. G. Bylsma,
J. Chapman, B. Cork, R. DeBonte, M. Derrick, D. Errede, K. K. Gan, S. W. Gray,[b] N. Harnew,[c]
C. Jung, P. Kesten,[d] D. Koltick, P. Kooijman, F. J. Loeffler, J. S. Loos, E. H. Low, R. L. McIlwain,
D. I. Meyer, D. H. Miller, B. Musgrave, H. Neal, D. Nitz, C. R. Ng, H. Ogren, L. E. Price,
L. K. Rangan, D. R. Rust, J. Schlereth, A. A. Seidl,[e] E. I. Shibata, K. Sugano, R. Thun,
T. Trinko,[e] M. Valdata-Nappi,[f] J. M. Weiss,[g] M. Willutzky, and D. E. Wood[e]

Argonne National Laboratory, Argonne, Illinois 60439
Indiana University, Bloomington, Indiana 47405
Lawrence Berkeley Laboratory, Berkeley, California 94720
University of Michigan, Ann Arbor, Michigan 48109
Purdue University, West Lafayette, Indiana 47907
(Received 10 December 1985)

A sample of τ-lepton decays to $5\pi^{\pm}\nu_{\tau}$ and $5\pi^{\pm}\pi^{0}\nu_{\tau}$, observed in the high-resolution spectrometer at the SLAC $e^{+}e^{-}$ storage ring PEP, has been used to place an upper limit on the mass of the tau neutrino of 84 MeV/c^{2} at the 95% confidence level.

In a previous paper[1] we established that the τ lepton decays to a τ neutrino and $5\pi^{\pm}$ as well as $5\pi^{\pm}\pi^{0}$ by observing five events of each type. This result has been confirmed by Burchat *et al.* (Mark II group) at SLAC.[2] In this Letter the hadronic mass spectra of these decays are used to place an upper limit on the mass of the τ neutrino, which is below the muon mass.

The results come from events collected with the high-resolution spectrometer[3] (HRS) at the $e^{+}e^{-}$ storage ring, PEP. Data corresponding to an integrated luminosity of 185 pb^{-1} were taken at a center-of-mass energy of 29 GeV. The detector provides charged-particle tracking over 90% of the solid angle in a solenoidal magnetic field of 1.6 T. The momenta of tracks at large angles are measured with a relative accuracy of about 1%. Of particular importance to this analysis is the measurement of electromagnetic shower energy with a lead-scintillator calorimeter covering the angular interval $|\cos\Theta| < 0.60$, where Θ is the angle with respect to the beam direction. The forty-module barrel calorimeter system has an energy resolution of $\sigma_{E}/E = 16\%/\sqrt{E}$ (E in gigaelectronvolts) and an angular resolution for showers of 14 mrad along the beam direction and 7 mrad transverse. The outer layers of the tracking system are located immediately in front of the barrel calorimeter and can provide information on the preconversion of photons, particularly in the Cherenkov-counter system.

The events used in this analysis are the same events reported by Ahlen *et al.*[4] where the selection criteria are discussed in detail. The topology of the selected events is five charged tracks in one hemisphere with a single charged track in the opposite hemisphere.

Our limit on the mass of the τ neutrino is obtained by measurement of the total hadronic mass associated with the τ decay since this yields the most accurate determination of the end point of the hadronic mass spectrum. To do so requires a detailed understanding of the neutral energy in the events as well as in possible backgrounds, because the $5\pi^{\pm}\pi^{0}$ events are crucial in establishing the limit.

The main problem in an understanding of the neutral energy deposition is the confusion caused by the $\sim 15\%$ probability for a photon to convert in the Cherenkov-counter system located just in front of the barrel shower-counter system. The 1.6-T magnetic field separates the electron-positron pair yielding two distinct clusters of energy in the calorimeter. This problem was solved by our allowing up to four clusters of energy to be associated with a single π^{0}, and combining closest neighbors to form a single photon. All shower-counter clusters had to be associated with either a charged track or a photon forming the π^{0}; otherwise the event was rejected. Once the clusters had been assigned, the energies of the two photons forming the π^{0} were recalculated, with the mass constrained to that of the π^{0} and the total energy of the π^{0} held fixed. If an ambiguity arose, the lower-mass solution was chosen. Three of the five $5\pi^{\pm}\pi^{0}$ events are consistent with there being a single conversion in the Cherenkov system.

Because the backgrounds can have an important effect in the establishment of a limit on the τ-neutrino mass, they have been studied in detail. The background from hadronic annihilation events was measured with use of the events that have five charged particles in one jet recoiling against N particles ($N = 3, 5, 7, \ldots$) in the opposite jet. Events containing an internal or external photon conversion were rejected. Only two $(5, N)$ events satisfied the requirement that the effective mass in the five-prong hemi-

sphere, including the photons converting in the shower counters, be less than 1.9 GeV/c^2. One of these events has all the properties of a $(5,3)$ τ pair, consistent with the expectation of 1.5 such events in the data sample. The estimate based on the remaining event must be scaled down by a factor of 8.3, which is the ratio of the $(5,N)$ events to the $(5,1)$ events in the hadronic sample. Finally, by the requirement that the effective mass of the charged particle plus any observed photons in the one-prong hemisphere be less than 1.6 GeV/c^2, the estimate of the hadronic background is reduced an additional 60% to 0.05 event.

The other background contribution is from three-prong τ decays, with accompanying π^0's or γ's that produce an electron-positron pair by conversion before the inner drift chamber. These processes have been estimated by use of a Monte Carlo τ-event simulator incorporating the Berends and Kleiss[5] lepton generator with α^3 QED corrections. With use of the selections reported earlier,[1] the expected background is 0.05 ± 0.03 event.

The absolute mass scale of the spectrometer has been checked by studies of the hadronic annihilation events, particularly the D^0 and $D^\pm$ mesons which have masses near that of the τ. The simulated and observed events[4] have masses that agree to within a few MeV/c^2. The mass differences between our measured values and the world averages[6] agree to within our statistical errors of ± 4 MeV/c^2.

The mass resolution of each event was found by repeated simulation starting each time with the observed event randomly rotated about the beam axis. The full detector simulator was used which includes the effects of multiple scattering, particle decay, photon conversion, neutral energy fluctuations, leakage, and the intrinsic resolution of the detector elements. The parameters used in the calorimeter simulation were tuned to agree with the electromagnetic showers observed at PEP. The output from the simulator passed through the tracking routines and all other analysis routines in the same manner as the experimental data. The simulation was checked by our comparing it with the observed D^0 and $D^\pm$ signals,[4] with the result that the simulated and observed widths agree to within a few MeV/c^2. The resolution functions of the τ events fit well to Gaussian shapes, with non-Gaussian tails typically contributing less than 2%.

The mass acceptance is flat in the range of these data because the combination of the high magnetic field and two-meter-long track lengths ensures excellent spatial separation of the charged tracks from τ decay.

The properties of the event sample are listed in Table I and the hadronic mass distribution is shown in Fig. 1. These events have masses approaching the τ-lepton mass[6] of 1784 ± 3 MeV/c^2 and, in fact, the three highest-mass $5\pi^\pm\pi^0$ events populate the region above $M_\tau - M_\mu$. 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 $M_{\nu_\tau} = M_\tau - M_{\text{hadrons}}$. The mass resolution of the HRS would allow an ultimate sensitivity of M_{ν_τ} of order 10 MeV/c^2 were statistics not a limitation.

Also listed in Table I are the properties of the events in the hemisphere containing the single charged track; each track is categorized as (1) electron, (2) $K/\pi/\mu$ for tracks that have no accompanying neutral energy in that hemisphere, and (3) $K/\pi + \gamma$'s for any track with accompanying neutral energy. By category, one electron, two $K/\pi/\mu$, and seven $K/\pi + \gamma$'s events are observed where 2.1, 3.8, and 4.1 are expected.[6]

TABLE I. Properties of the events.

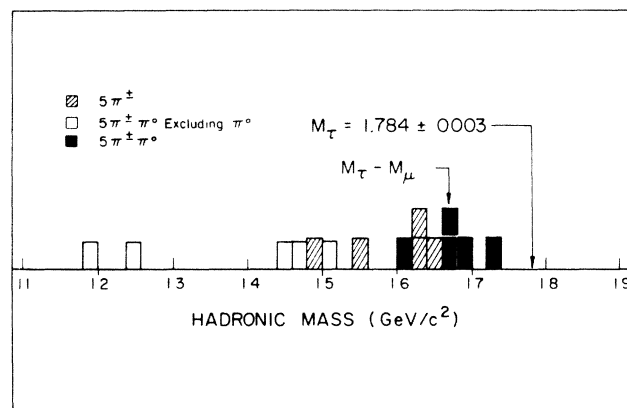|	Mass (MeV/c^2)	σ_M (MeV/c^2)	Single-track momentum (GeV/c)	Single-track particle type
		$\tau \to \nu_\tau 5\pi^\pm$		
1	1494	13	1.3	$K/\pi/\mu$
2	1575	13	6.0	$K/\pi + n\gamma$
3	1625	12	1.6	$K/\pi + n\gamma$
4	1630	14	1.7	$K/\pi + n\gamma$
5	1653	17	1.2	$K/\pi + n\gamma$
		$\tau \to \nu_\tau 5\pi^\pm\pi^0$		
1	1619	15	4.0	$K/\pi + n\gamma$
2	1668	57	1.8	$K/\pi + n\gamma$
3	1684	54	3.8	$K/\pi + n\gamma$
4	1695	18	5.8	$K/\pi/\mu$
5	1727	41	2.1	e

FIG. 1. The hadronic invariant mass of the events $\tau \to 5\pi^\pm\pi^0\nu_\tau$ and $\tau \to 5\pi^\pm\nu_\tau$. The $5\pi^\pm\pi^0\nu_\tau$ events have been plotted twice, once excluding the π^0 to show the effect of adding the π^0 to the mass calculation.

To determine the upper limit for M_{ν_τ}, the $5\pi^\pm$ and $5^\pm\pi^0$ mass distributions have been fitted with use of a maximum-likelihood technique. The mass resolution of each event represents the uncertainty in the mass calculation using the measured kinematic variables. 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 the 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 going unobserved, so that the $5\pi^\pm$-event sample includes an estimated 0.45 ± 0.15 event of the $5\pi^\pm\pi^0$ final state. Since inclusion of the missing π^0 would increase the effective mass of the $5\pi^\pm$ events and because the exact way in which unobserved energy should be added to the events is uncertain, this effect is ignored when we set the upper limit to the neutrino mass.

We have taken into account the 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, 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, one possibility would be a radial excitation of the $A_1(1270)$ resonance, the A_1', which should be more massive and have a larger width than the ~ 300 MeV/c^2 reported for the A_1. These properties
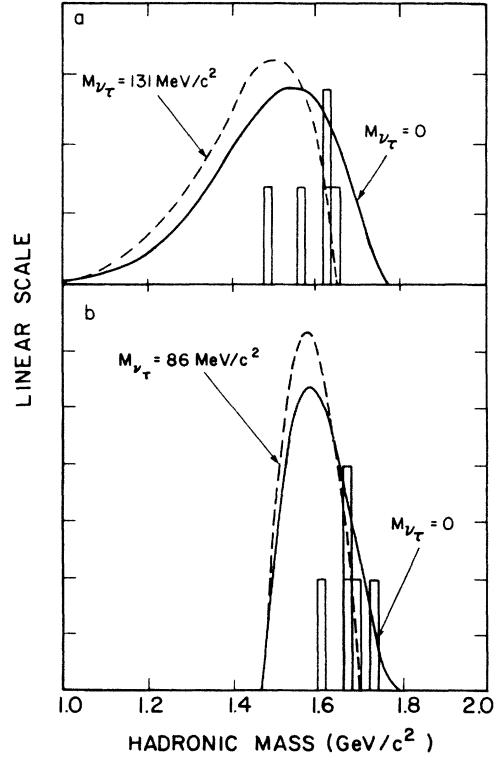

FIG. 2. (a) The hadronic invariant mass of the five events $\tau \rightarrow 5\pi^\pm\nu_\tau$. The solid line is phase space times the weak matrix element for the best fit $M_{\nu_\tau} = 0$. (b) The hadronic invariant mass of the five events $\tau \rightarrow 5\pi^\pm\pi^0\nu_\tau$. The solid line shown is the best fit, $M_{\nu_\tau} = 0$, based on the data of Cosme et al. (Ref. 9). The dashed lines show the 95%-confidence-level limits on M_{ν_τ}.

would place the A_1' mass near the τ mass with a mass distribution extending well above 1784 MeV/c^2. In this case, 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 the phase space.[7] The results of the maximum-likelihood fit to the data with use of a $5\pi^\pm\nu_\tau$ phase space $(\rho_{5\pi^\pm\nu})$ times the weak matrix element,[8]

$$d\Gamma/dM_{\mathrm{had}} \sim \rho_{5\pi\nu_\tau} M_{\mathrm{had}}[(M_\tau^2 - M_{\mathrm{had}}^2)(M_\tau^2 + 2M_{\mathrm{had}}^2) - M_\nu^2(2M_\tau^2 - M_{\mathrm{had}}^2 - M_\nu^2)], \tag{1}$$

are shown in Fig. 2(a). The best fit, shown as a solid line, yields $M_{\nu_\tau} = 0$. The upper limit, at 95% confidence level, of $M_{\nu_\tau} < 131$ 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 which relates the vector part of the weak interaction to the isovector part of the total annihilation cross section[7] for $e^+e^- \rightarrow 6\pi$. Specifically,[8]

$$\frac{d\Gamma}{dM_{\mathrm{had}}} \sim M_{\mathrm{had}}[(M_\tau^2 - M_{\mathrm{had}}^2)(M_\tau^2 + 2M_{\mathrm{had}}^2) - M_\nu^2(2M_\tau^2 - M_{\mathrm{had}}^2 - M_\nu^2)]$$

$$\times [(M_\tau^2 - M_{\mathrm{had}}^2)^2 - M_\nu^2(2M_\tau^2 + 2M_{\mathrm{had}}^2 - M_\nu^2)]^{1/2} \frac{\sigma_{e^+e^-}^1(M_{\mathrm{had}})}{\sigma_{\mathrm{pt}}(M_{\mathrm{had}})}, \tag{2}$$

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

Measurements of the $e^+e^- \rightarrow 6\pi$ annihilation cross section for center-of-mass energies in the τ mass region

have been reported by Cosme *et al.*[9] 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. With use of a linear fit to the measured 6π cross section in the τ mass region, a 95%-confidence-level upper limit of 86 MeV/c^2 is found for M_{ν_τ}, shown as the dashed line in Fig. 2(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[8] to the data, $M_{\nu_\tau} = 0$, is shown as the solid line in Fig. 2(b).

The combined $5\pi^{\pm}$ and $5\pi^{\pm}\pi^0$ data yield a 95%-confidence-level upper limit of 84 MeV/c^2. This result is in agreement with that of Albrecht *et al.* (ARGUS group)[10] who report a similar limit from $\tau \rightarrow 3\pi^{\pm}\nu_\tau$ decays.

(a)Now at Eidgenössische Technische Hochschule, Zurich, Switzerland.

(b)Now at Laboratory for Nuclear Studies, Cornell University, Ithaca, N.Y. 14853.

(c)Now at CERN, 1211 Geneva 23, Switzerland.

(d)Now at Brandeis University, Waltham, Mass. 02254.

(e)Now at Lockheed Missiles and Space Co., Sunnyvale, Cal. 94086.

(f)Permanent address: Istituto Nazionale di Fisica Nucleare, Pisa, Italy.

(g)Now at SRI International, Menlo Park, Calif. 94025.

[1]I. Beltrami *et al.*, Phys. Rev. Lett. **54**, 1775 (1985).

[2]P. R. Burchat *et al.*, Phys. Rev. Lett. **54**, 2489 (1985).

[3]D. Bender *et al.*, Phys. Rev. D **30**, 515 (1984).

[4]S. Ahlen *et al.*, Phys. Rev. Lett. **51**, 1147 (1983); M. Derrick *et al.*, Phys. Lett. **146B**, 261 (1984); M. Derrick *et al.*, Phys. Rev. Lett. **53**, 1971 (1984).

[5]R. Kleiss, Ph.D. thesis, University of Leiden, 1982 (unpublished); F. A. Berends, R. Kleiss, and S. Jadach, Nucl. Phys. **B202**, 63 (1982).

[6]C. G. Wohl *et al.* (Particle Data Group), Rev. Mod. Phys. **56**, S19 (1984).

[7]The events populate the upper end of the mass regions predicted by the parametrizations of Eqs. (1) and (2). More data are needed to check the possibility of an unexpected intermediate state.

[8]Y. S. Tsai, Phys. Rev. D **4**, 2821 (1971); F. J. Gilman and D. H. Miller, Phys. Rev. D **17**, 1846 (1978).

[9]G. Cosme *et al.*, Nucl. Phys. **B152**, 215 (1979).

[10]H. Albrecht *et al.*, Phys. Lett. **163B**, 404 (1985).