Upper Limit on the ν_τ Mass

C. Matteuzzi, G. S. Abrams, C. de la Vaissiere,[a] D. Amidei, A. R. Baden, A. M. Boyarski, J. Boyer, M. Breidenbach, P. Burchat, F. Butler, D. L. Burke, J. M. Dorfan, G. J. Feldman, G. Gidal, L. Gladney, M. S. Gold, G. Goldhaber, L. Golding, G. Hanson, D. Herrup, R. J. Hollebeek, W. R. Innes, J. A. Jaros, I. Juricic, J. A. Kadyk, A. J. Lankford, R. R. Larsen, B. W. LeClaire, M. Levi,[b] N. S. Lockyer, V. Lüth, M. E. Nelson,[c] R. A. Ong, M. L. Perl, B. Richter, M. C. Ross, P. C. Rowson, T. Schaad, H. Schellman, D. Schlatter,[b] P. D. Sheldon, W. B. Schmidke, G. H. Trilling, D. Wood, J. M. Yelton, and C. Zaiser

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, and Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720, and Department of Physics, Harvard University, Cambridge, Massachusetts 02138

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We have set an upper limit on the ν_τ mass from a study of the four-pion invariant-mass distribution in the decay $\tau \to 3\pi^\pm\pi^0\nu_\tau$. We obtain the limit $m_{\nu_\tau} < 164$ MeV/c^2 at 95% confidence level.

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Previous upper limits on the ν_τ mass of 250 MeV/c^2 have been determined from a study of the electron spectrum[1] from the decay $\tau \to e\nu_e\nu_\tau$ and from a study of the pion spectrum[2] from the decay $\tau \to \pi\nu_\tau$. In this Letter we report a new upper limit based on a study of the four-pion invariant-mass spectrum in the decay $\tau \to 3\pi^\pm\pi^0\nu_\tau$. This decay mode is more sensitive to the ν_τ mass since the invariant mass of the four-pion state approaches the τ mass.[3]

The data described in this Letter were taken with the Mark II detector at the e^+e^- storage ring PEP (Stanford Linear Accelerator Center) at a center-of-mass energy of 29 GeV. This detector has been described elsewhere.[4] We briefly describe the apparatus relevant to this analysis. The detector contains two charged-particle tracking devices, a high-precision drift chamber, known as the vertex chamber,[5] and a large drift chamber. The vertex chamber has seven layers of axial drift cells divided into an inner band of four layers at an average radius of 11 cm and an outer band of three layers at an average radius of 31 cm. The main drift chamber consists of sixteen layers of sense wires at radii between 41 and 145 cm. Both tracking chambers are immersed in a 2.3 kG solenoidal magnetic field. For high-momentum charged particles, the rms momentum resolution, σ_p/p, is approximately $0.01p$, where p is measured in GeV/c.

The central electromagnetic calorimetry is provided by eight rectangular lead–liquid-argon modules which surround the magnet coil. These modules are approximately 14 radiation lengths thick and provide an energy resolution of $14\%/\sqrt{E}$, where E is the energy measured in GeV.

The integrated luminosity of the data used in this analysis was 158 pb^{-1} and corresponds to a sample of 16 300 produced $\tau^+\tau^-$ pairs.

We selected events as $\tau^+\tau^-$ candidates if they had a total detected energy larger than 8 GeV and exactly four charged particles with zero total charge. Each event was divided into two hemispheres by a plane perpendicular to the thrust axis and was required to have three charged particles in one hemisphere recoiling against a single charged particle in the other. The acollinearity angle, defined as the angle between the total momenta of the particles in each hemisphere, had to be smaller than 50°. To select well measured events, we required each charged track to have signals in at least fourteen layers of the two drift chambers, and to approach the vertex within 2 cm in the plane transverse to the beam direction and within 15 cm along the beam direction. We also required the total energy of the three charged particles to be less than 15 GeV. Events with a low-mass pair of tracks, one of which was identified as an electron, were rejected since this pair was most likely from a π^0 Dalitz decay or from a photon which converted close to the interaction point. Electrons were identified[6] by the calorimeters when the electron energy was greater than 1 GeV and by the time-of-flight counters when the electron energy was less than 350 MeV.

Each photon accompanying the τ decay that contained three charged particles was required to be detected well inside the fiducial volume of the calorimeter modules, to have a measured energy greater than 250 MeV, and to be separated by at least 20 cm in the calorimeter from all charged tracks with energy deposit in the liquid argon smaller than the minimum ionizing energy. To discriminate further against backgrounds due to charged-particle interactions in the calorimeters, photons with measured energies less than 600 MeV were required to have a ratio of energy deposited in the rear layers to that deposited in the front layers of less than 1.5. Additional requirements were applied if the photon shared energy with other particles in one or two of the calorimeter coordinates.

Those events having only two photons obeying the previous criteria were retained. A fit to the π^0 mass was performed by adjusting the photon energies.

Figure 1 shows the $\gamma\gamma$ invariant-mass distributions after the above event selection requirements. There is a clear π^0 signal with little background. There were 61 events in which the fit had a confidence level larger than 10% and these were retained. The fitted values for the photon energies were subsequently used in the calculation of the four-pion invariant mass.

The total energy of the $3\pi^{\pm}\pi^0$ state was required to be greater than 8 GeV for $m_{4\pi} < 1.5$ GeV/c^2 and greater than 10 GeV for $m_{4\pi} > 1.5$ GeV/c^2. This requirement loses 7% of the τ events, while rejecting 50% of the hadronic background. Figure 2 shows the invariant-mass distribution for the 58 events which survived all of the event selection criteria. There are no events between 2.0 and 2.5 GeV/c^2. The background in Fig. 2 from hadronic

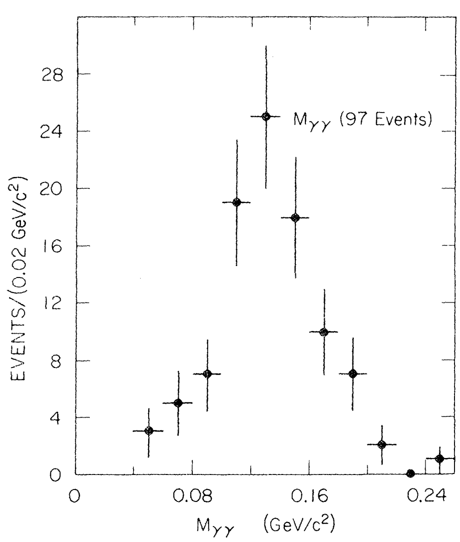

FIG. 1. γ-γ invariant-mass distribution for the $3\pi^{\pm}\pi^0$ candidates before requiring that the confidence level for a fit to the π^0 hypothesis be greater than 10%.

events was determined from a Monte Carlo simulation to be 3% in the total sample, and (10 ± 10)% in the region $m_{4\pi} > 1.5$ GeV/c^2. The resolution in invariant mass was determined from the Monte Carlo simulation as a function of $m_{4\pi}$. Its average value is 53 ± 5 MeV/c^2 in the range $m_{4\pi} > 1.5$ GeV/c^2.

The upper range of the $m_{4\pi}$ spectrum, $m_{4\pi} > 1.5$ GeV/c^2, was compared to the expected behavior [7] for different values of the ν_τ mass and different assumptions about the four-pion state. Only the upper part of the $m_{4\pi}$ spectrum is sensitive to the ν_τ mass. The value of 1.5 GeV/c^2 was chosen because it gives the best compromise between sufficient sensitivity and adequate statistics. A maximum-likelihood method was applied to determine an upper limit from the fifteen events in the $m_{4\pi} > 1.5$ GeV/c^2 region. The hadronic background was taken to be distributed uniformly over the invariant-mass range, as suggested by the Monte Carlo simulation.

If the $\tau \to 3\pi^{\pm}\pi^0\nu_\tau$ decay is assumed to have a pure phase-space distribution, the upper limit on the ν_τ mass is 155 MeV/c^2 at the 95% confidence level. If, as is more likely, the four-pion state is assumed to be dominated by a ρ' resonance[8] of mass 1570 MeV/c^2 and width 510 MeV/c^2, the limit is also 155 MeV/c^2. The results are not very sensitive to the various assumptions about the four-pion state since, in all cases, the $m_{4\pi}$ spectrum close to the τ mass is largely determined by the available phase space. The solid curve in Fig. 2 shows the calculated spectrum with the ρ' hypothesis and with $m_{\nu_\tau} = 0$. It is in good agreement with the data.

We checked the stability of the results by varying some of the parameters involved in the fit. If the experimental resolution in invariant mass is 20%

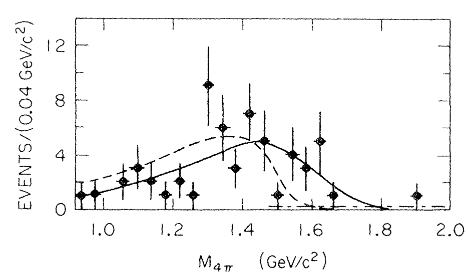

FIG. 2. $3\pi^{\pm}\pi^0$ invariant-mass distribution for the selected decays. The curves are drawn for $m_{\nu_\tau} = 0$ (solid) and 250 MeV/c^2 (dashed) and with the assumption that the four-pion state is dominated by a ρ' resonance of mass 1570 MeV/c^2 and width 510 MeV/c^2. The dash-dotted line represents the hadronic background.

worse than we have assumed, then the limit increases by 8%. If the fraction of background is increased from 10% to 30%, then the limit also becomes 8% worse. If the range of the invariant-mass spectrum used in the fit is enlarged to $m_{4\pi} > 1.3$ GeV/c^2 instead of $m_{4\pi} > 1.5$ GeV/c^2, nothing is added to the sensitivity and the limit does not change.

When we take into account the systematic uncertainties in our knowledge of the hadronic background, our experimental resoltuion, and the mass and width of the ρ' resonance, we obtain an upper limit on the mass of the τ neutrino of 164 MeV/c^2 at 95% confidence level.

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[(a)]Present address: Laboratoire de Physique Nucléaire et Hautes Energies, Université Pierre et Marie Curie, F-75230 Paris, France.

[(b)]Present address: CERN, CH-1211 Geneva 23, Switzerland.

[(c)]Present address: California Institute of Technology, Pasadena, Cal. 91125.

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[3]For comparison, the upper limit on the ν_μ mass is 0.500 MeV/c^2 at the 90% confidence level [H. B. Anderhub *et al.*, Phys. Lett. **114B**, 76 (1982)], and the ν_e mass has been measured to lie between 14 and 46 eV/c^2 at 99% confidence level {V. A. Lyubimov *et al.*, Zh. Eksp. Teor. Fiz. **81**, 1158 (1981) [Sov. Phy. JETP **54**, 616 (1982)]}.

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