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Measurement of the Branching Fraction for $\tau^- \to 5\pi^\pm(\pi^0)\nu_\tau$ and an Upper Limit on the ν_τ Mass

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The branching fraction for $\tau^- \to 5\pi^\pm(\pi^0)\nu_\tau$ is measured from data accumulated with the Mark II detector at PEP. Four events are observed with an estimated hadronic background of $(0.03^{+0.04}_{-0.02})$ events and a background from $\tau^- \to 3\pi^\pm\pi^0\nu_\tau$ of $(0.05^{+0.07}_{-0.04})$ events. This results in a measured branching fraction of $(0.16 \pm 0.08 \pm 0.04)$%. The candidate events are used to establish an upper limit of 125 MeV/c^2 on the ν_τ mass at the 95% confidence level.

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Until recently, there has been no evidence for the decay of the τ to five charged particles. Upper limits on the branching fraction at the 95% confidence level have been published by Fernandez *et al.* (0.17%),[1] Blocker *et al.* (0.5%),[2] Althoff *et al.* (0.7%),[3] Behrend *et al.* (0.9%),[4] and Aihara *et al.* (0.3% at the 90% confidence level).[5] Beltrami *et al.* reported the first evidence for the observation of $\tau^- \to 5\pi^\pm(\pi^0)\nu_\tau$.[6] They measure a branching fraction of (0.13 ± 0.04)%. In this Letter, we report evidence for the decay of the τ to five charged particles. We use the $5\pi^\pm$ invariant-mass spectrum to establish an upper limit on the ν_τ mass. Previous limits have been determined from the invariant mass of the $K^-K^+\pi^-$ system in the decay $\tau^- \to K^-K^+\pi^-\nu_\tau$,[7] the invariant mass of the four pions in the decay $\tau^- \to 3\pi^\pm\pi^0\nu_\tau$,[8] the electron spectrum in the decay $\tau^- \to e^-\bar{\nu}_e\nu_\tau$,[9] and the pion spectrum in the decay $\tau^- \to \pi^-\nu_\tau$.[10]

The data sample for our measurements corresponds to an integrated luminosity of 207 pb^{-1} produced at a center-of-mass energy of 29 GeV. The data were accumulated with the Mark II detector[11] at the e^+e^- storage ring PEP. Multilayer cylindrical drift chambers in a 2.3-kG solenoidal magnetic field measure charged-particle momenta with a resolution of $\sigma_p/p = [(0.02)^2 + (0.01p)^2]^{1/2}$ where p is the momentum in GeV/c. The drift-chamber system consists of an inner high-resolution drift chamber with seven concentric layers of sense wires and an outer drift chamber with sixteen layers of sense wires. Eight lead liquid-argon (LA) calorimeter modules, covering 65% of the solid angle, detect electromagnetic showers with an energy resolution of $\sigma_E/E = 0.14E^{-1/2}$ where E is the energy in gigaelectronvolts. Layers of iron hadron absorber separated by proportional tubes detect muons over 45% of the solid angle.

The candidate events have six charged tracks with zero net charge and a total detected energy (charged plus neutral) of more than 25% of the center-of-mass energy. Each charged track is required to have at least eight (out of a maximum of 23) drift-chamber signals, to approach the beam position within 10 cm along the beam direction, and to have a good track fit (χ^2 per degree of freedom ≤ 5). Each event is divided into two jets by a plane perpendicular to the thrust axis. Candidate events are those which contain one charged particle in one jet and five charged particles in the other.

The single charged track on the one-prong side of the event is required to have $|\cos\theta| < 0.8$ and not be identified as an electron by the LA calorimeters. The latter restriction rejects events of the type $e^+e^- \to e^+e^- +$ hadrons in which the e^+ or e^- is detected. In addition, events are rejected if there are more than two neutral energy clusters on the one-prong side or if the invariant mass of the one charged particle (assumed to be a π) plus neutrals is greater than 1.2 GeV/c^2. There are 42 events which satisfy the above criteria.

A major source of background at this point is the decay $\tau^- \to 3\pi^\pm\pi^0\nu_\tau$ in which the π^0 undergoes a Dalitz decay or one of the photons from the π^0 converts to an e^+e^- pair. Events with e^+e^- pairs are removed with a pair-finding algorithm which searches for oppositely charged tracks which meet the geometrical criteria for a conversion or Dalitz pair. In addition, each of the five tracks is required to have at least one signal in the inner drift chamber, to have a distance of closest approach to the event vertex of less than 4 mm, and to not be identified as an electron by the LA calorimeters. There are fifteen events which survive the above cuts.

A Monte Carlo simulation of $\tau^- \rightarrow 3\pi^\pm \pi^0 \nu_\tau$, equivalent to 20 times the data with an assumed branching fraction for $\tau^- \rightarrow 3\pi^\pm \pi^0 \nu_\tau$ of 6%, is used to determine the efficiency of the above criteria for removing events with e^+e^- pairs. One Monte Carlo event passes our cuts resulting in a background estimate for $\tau^- \rightarrow 3\pi^\pm \pi^0 \nu_\tau$ of $(0.05^{+0.07}_{-0.04})$ events in the final event sample.

To separate hadronic events from τ decays the following analysis is performed. We define neutral tracks to be clusters of electromagnetic energy in the LA of more than 200 MeV which are more than 20 cm away from the closest charged track. The latter restriction is to ensure that the energy cluster is not due to a charged-particle interaction in the coil or the LA calorimeter. Each charged track (assumed to be a π) and neutral track on the five-prong side of the event is boosted along the thrust axis of the event into the rest frame of a τ moving with the beam energy in the laboratory frame. The magnitude of the vector sum of the particle momenta in this frame, which we call p^*, represents the magnitude of the momentum carried off by the neutrino in real $\tau^- \rightarrow 5\pi^\pm(\pi^0)\nu_\tau$ decays assuming no initial- or final-state radiation. Monte Carlo simulations of $\tau^- \rightarrow 5\pi^\pm(\pi^0)\nu_\tau$ are used to determine that 85% of the signal events which pass the cuts to this point have p^* less than 500 MeV/c. Figure 1 shows the distribution of m_5, the invariant mass of the five-prong side including neutrals, vs p^* for the events with $p^* \leq 6.5$ GeV/c^2. The four events in Fig. 1 with $p^* \leq 500$ MeV/c are taken to be the signal for $\tau^- \rightarrow 5\pi^\pm(\pi^0)\nu_\tau$. The invariant masses, m_5, calculated mass errors, and descriptions of the one-prong sides are given in Table I for these four events.

TABLE I. Candidate events for $\tau^- \rightarrow 5\pi^\pm(\pi^0)\nu_\tau$. m_5 is the invariant mass of the five-prong side of the event including neutral tracks. σ_m is the calculated mass resolution for that event. The third column lists the number of neutral energy clusters found on the five-prong side of the event. The fourth column contains a description of the one-prong side of the event. The designation π/μ indicates that the particle was not identifed as an electron and did not pass through the muon-detection system.

m_5 (GeV/c^2)	σ_m (MeV/c^2)	Neutrals	One-prong side
1.751	44	0	0.4 GeV/c π/μ
1.646	35	0	2.8 GeV/c π/μ, two neutrals
1.522	60	0	4.0 GeV/c μ
1.510	51	1	1.1 GeV/c π/μ

The background from hadronic events is estimated from a sample of events with five charged particles in one jet and four or more charged particles in the other. There are 458 such events in our data sample. Figure 2 shows the distribution of m_5 vs p^* for the hadronic-background sample. One event has $p^* \leq 500$ MeV/c. By normalizing this one event to the total number of events in the hadronic sample and multiplying this fraction by the number of events with $p^* \geq 500$ MeV/c in the τ candidate sample, we estimate a hadronic background of $(0.03^{+0.04}_{-0.02})$ events in the τ-candidate

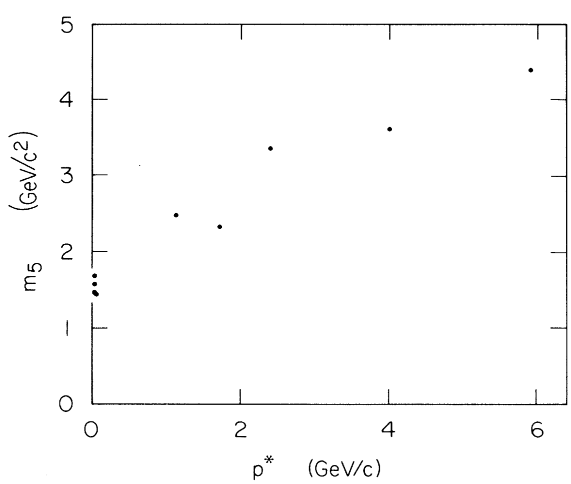

FIG. 1. Invariant mass of the five-prong side of the event vs p^*. The candidate events for $\tau^- \rightarrow 5\pi^\pm(\pi^0)\nu_\tau$ are those with $p^* \leq 500$ MeV/c.

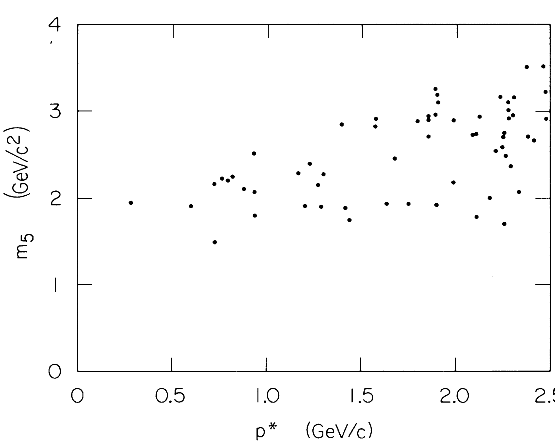

FIG. 2. Invariant mass of the five-prong side of the event vs p^* for the hadronic-background sample.

event sample with $p^* \leq 500$ MeV/c. We have checked that the distribution of m_5 vs p^* for the hadronic sample is independent of the mass of the opposite jet, and is therefore applicable to the τ-sample background.

The efficiency for a five-prong decay of the τ to pass all our cuts is estimated from a Monte Carlo simulation which produces τ pairs with a cross section known from quantum electrodynamics. Initial-state radiation effects are included. The efficiency is measured for $\tau^- \to 5\pi^\pm \nu_\tau$ and $\tau^- \to 5\pi^\pm \pi^0 \nu_\tau$ with the final state distributed purely according to phase space or produced by a resonance of mass 1500 MeV/c^2 and width 500 MeV/c^2. The measured efficiency is not very dependent on the decay mechanism of the final state but is dependent on the number of particles in the final state. The efficiency is about 40% higher for $\tau^- \to 5\pi^\pm \nu_\tau$ because there is a larger opening angle between the charged tracks in the laboratory frame. In the decay $\tau^- \to 5\pi^\pm \pi^0 \nu_\tau$, at least one neutral energy cluster is detected 50% of the time. One of the four candidate events for $\tau^- \to 5\pi^\pm (\pi^0) \nu_\tau$ has a neutral energy cluster. Therefore, to estimate efficiency we assume that half of our events are $5\pi^\pm$ and half $5\pi^\pm \pi^0$, with final states distributed according to phase space. The branching fraction for $\tau^- \to 5\pi^\pm (\pi^0) \nu_\tau$ is then measured to be $(0.16 \pm 0.08 \pm 0.04)\%$. The first error is statistical and the second is an estimate of the systematic error due to the dependence of the efficiency on the number of particles in the final state and the uncertainty in the charged-particle track-reconstruction efficiency.

The three candidate events for $\tau^- \to 5\pi^\pm \nu_\tau$ are then used to establish an upper limit on the ν_τ mass. We do not use the event which has a neutral energy cluster on the five-prong side of the event because the energy resolution of the neutrals is not as good as the momentum resolution of the charged tracks and part of the event may be missing since only one cluster of neutral energy is detected.

For a particular ν_τ mass, the theoretical m_5 distribution is generated according to phase space and $(V-A)$ coupling[12] with $5\pi^\pm$ and no π^0 in the final state. Properly normalized backgrounds are added. The mass spectrum of the hadronic background is assumed to be uniform over the range 1.4 to 2.0 GeV/c^2. The mass spectrum of the background from $\tau^- \to 3\pi^\pm \pi^0 \nu_\tau$ is estimated from Monte Carlo events which survive all of the cuts except the pair cuts.

Figure 3 shows the expected m_5 spectrum for ν_τ mass equal to 0 and 125 MeV/c^2. These distributions include backgrounds and detector efficiencies, but not detector-resolution effects. The invariant masses of the $5\pi^\pm$ events with the calculated mass errors are also shown in the figure. The expected shape of the mass-resolution function is determined with Monte Carlo simulations and agrees well with a Gaussian distribution. For each event, a likelihood is determined from a convolution of the expected m_5 distribution with a Gaussian distribution whose width is the calculated mass error for that event.

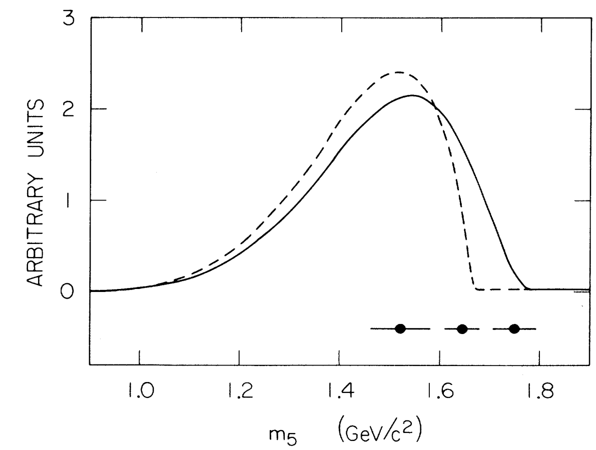

FIG. 3. Expected $5\pi^\pm$ invariant-mass spectrum for ν_τ mass equal to 0 (solid line) and 125 MeV/c^2 (dashed line). The curves do not include mass-resolution effects. The $5\pi^\pm$ invariant masses for the three events in the data are shown at the bottom of the graph with the estimated errors.

If we use our best estimate of the backgrounds and the calculated invariant-mass resolution, the upper limit on the ν_τ mass is 107 MeV/c^2 at the 95% confidence level, with a most likely value at zero. If the invariant-mass resolution is 20% worse than the calculated value, the limit is 117 MeV/c^2. If the backgrounds are double our best estimate, the limit is also 117 MeV/c^2.

Doubling our best estimate of the background and increasing the mass resolution by 20% over the calculated value, we obtain an upper limit of 125 MeV/c^2 on the ν_τ mass at the 95% confidence level. It is obvious from Fig. 3 that our result is heavily dependent on the event with the highest $5\pi^\pm$ invariant mass.

In conclusion, we measure a branching fraction for $\tau^- \to 5\pi^\pm (\pi^0) \nu_\tau$ of $(0.16 \pm 0.08 \pm 0.04)\%$. We use the candidate events for $\tau^- \to 5\pi^\pm \nu_\tau$ to establish an upper limit of 125 MeV/c^2 on the ν_τ mass at the 95% confidence level.

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