

Observation of τ -Lepton Decay to Five Charged Particles

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The production of τ -lepton pairs in e^+e^- collisions at 29 GeV has been used to study the inclusive τ decay into five charged particles. Ten events are observed in the high-resolution spectrometer giving a branching ratio of $B(\tau \rightarrow 5\pi^\pm + n\gamma + \nu_\tau) = (1.3 \pm 0.4) \times 10^{-3}$. Five of the events contain photons which are consistent with coming from a single π^0 . With this interpretation we measure $B(\tau \rightarrow 5\pi^\pm + \nu_\tau)$, $B(\tau \rightarrow 5\pi^\pm + \pi^0 + \nu_\tau) = (6.7 \pm 3.0) \times 10^{-4}$. The branching-ratio upper limit for the decay mode $\tau \rightarrow K^0 + 3\pi^\pm + n\gamma + \nu_\tau$ is found, at 90% confidence level, to be 2.7×10^{-3} .

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The observed properties of the τ lepton are consistent with it being a sequential lepton.¹ Because the τ is more massive than many of the SU(3) mesons such as π , K , ρ , K^* , A_1 , and ρ' , etc., the production of these particles through the weak charged bosons in τ decay can be studied. There have been a number of theoretical calculations of the hadronic decay modes and in general the data agree well with these predictions.² The decay of the τ to five charged particles has not previously been observed, although several groups have reported branching-ratio limits of a fraction of a percent.³ This high-multiplicity decay mode is especially interesting since the hadronic state is nearly equal to the mass of the τ lepton itself. In this case it is expected that the resonance nature of the quarks will have a small effect on the matrix element, allow-

ing a better understanding of the underlying fundamental decay processes.⁴

The results presented in this paper are based on data collected with the high-resolution spectrometer (HRS)⁵ at the e^+e^- storage ring PEP. The data correspond to an integrated luminosity of 176 pb^{-1} taken at a center-of-mass energy of 29 GeV. Features of the detector relevant for this analysis include charged-particle tracking over 90% of the solid angle in a solenoidal magnetic field of 16.2 kG, and measurement of electromagnetic shower energy with lead-scintillator calorimeters covering the angular intervals $|\cos\theta| < 0.60$ (barrel) and $0.70 < |\cos\theta| < 0.96$ (end caps), where θ is the angle with respect to the beam direction. The excellent momentum resolution means that tracks at large angles are measured to a relative er-

ror of better than 1%. The forty-module barrel shower-counter system has an energy resolution of $\sigma_E/E = 16\%/\sqrt{E}$ (E in gigaelectronvolts). The energy resolution for the forty-module end-cap system is $\sigma_E/E = 20\%/\sqrt{E}$.

The initial selection criteria used to isolate a sample of τ decay to five charged particles were similar to those used to obtain the events corresponding to the one- and three-charged-particle branching ratios reported in another paper.⁶ For the present analysis the topology of the selected events was five charged tracks in one hemisphere with a single charged track in the opposite hemisphere. The total net charge of the event was required to be zero. Because the single-charged-particle branching ratio of the τ is 86.9%, demanding a single charged track in the hemisphere opposite to that of the five prongs greatly reduces the background from hadronic events while reducing the signal only slightly. In order to reduce backgrounds from beam-gas interactions and from two-photon interactions the scalar sum of the charged momenta was required to be greater than 7.25 GeV/ c and the angle between the total momentum vectors in the two hemispheres had to be greater than 135 degrees. The effective mass of the five particles, each considered a pion, is shown in Fig. 1. A peak is seen in the τ mass region.

In order to measure the hadronic background to this signal, the full data sample was searched for events with five charged tracks in one hemisphere and any odd number of charged tracks (excluding the single-track events) in the opposite hemisphere. All the other selection criteria were identical to those used to select the τ sample. The resulting five-prong mass dis-

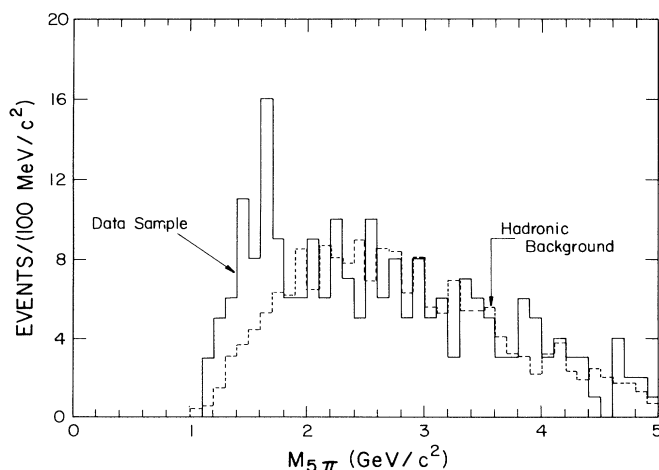


FIG. 1. The invariant mass of the five charged particles for the τ candidate events (solid line) and hadronic background events (dashed line). The hadronic background has 8.3 times the statistics of the τ event sample.

tribution is shown in the dashed histogram of Fig. 1. The hadronic-background distribution has been normalized to the τ sample in the mass region above 2 GeV/ c^2 where the two distributions have the same shape. The hadronic-background histogram is also in excellent agreement with the prediction of a Monte Carlo simulation of the hadronic events.

To separate the signal and the hadronic background in the events with effective mass below 2 GeV/ c^2 , we take advantage of the fact that, in the limit of first-order QED, τ -pair production leads to a unique momentum for each lepton. The thrust axis of the event is taken to be the direction of the produced τ pairs. The momentum, P^* , defined as the sum of all the charged hadronic decay products of the τ , in the τ rest frame, is measured by performing a Lorentz boost. For τ events, P^* is expected to be small because the mass difference between the hadronic decay products and the τ is small. As seen in Fig. 1, there are no events with mass below 1 GeV/ c^2 . This largest mass difference for τ events corresponds to the largest expected P^* of ≈ 600 MeV/ c .

In addition to these criteria, the angle between the thrust axis of the event and the beam direction was required to satisfy $|\cos\theta| < 0.55$. This requirement selected events in the central region of the detector, avoiding regions not fully instrumented. The P^* distributions for the τ candidate events and for the hadronic data are shown in Fig. 2. There is a clear signal of eighteen events in the region $P^* < 600$ MeV/ c , of which 3.0 are estimated to be of hadronic origin.

The hadronic background is further reduced by the following: (1) We required that the combined mass of the charged particle and photons in the hemisphere opposite to that of the five-prong jet be less than 1.5

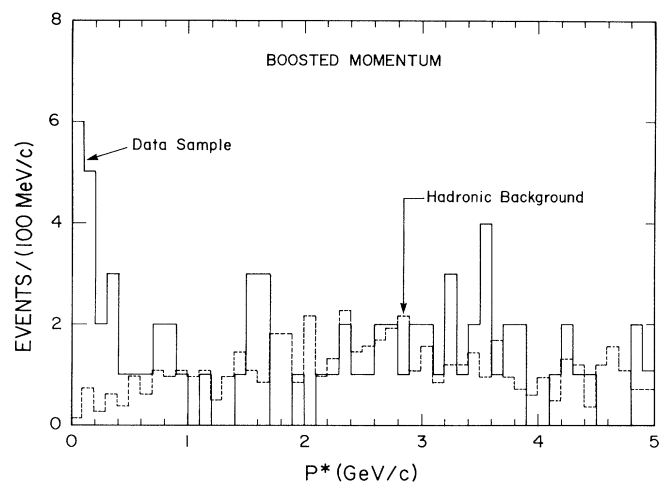


FIG. 2. The measured momentum P^* in the τ rest frame for the τ candidate events (solid line) and the hadronic background (dashed line).

GeV/c^2 . A Monte Carlo simulation of τ decay indicates that only 6% of the τ events are rejected by this cut, whereas 60% of the events in the solid histogram in Fig. 2 with a five-prong mass greater than $2 \text{ GeV}/c^2$ are rejected. (2) We required that the combined mass⁷ of the charged particles and photons in the five-prong hemisphere be less than $3.0 \text{ GeV}/c^2$. Less than 3% of the five-prong τ decays are rejected by this cut while 65% of the hadronic background with a five-prong invariant mass less than $2 \text{ GeV}/c^2$ are rejected. (3) We eliminated all Dalitz pairs and external photon conversions in the vertex region as will be described later. With these selections, the estimated hadronic background is reduced to less than 0.3 event.

To measure the effect of the selection criteria on the 5π and 6π decay modes of the τ , a simple thermodynamic model⁸ of the hadronic decay was used together with the full Monte Carlo τ -event simulator incorporating the Berends and Kleiss⁹ lepton generator with α^3 QED corrections. The predictions for the measured P^* distributions for the two decay modes are shown in Fig. 3. The requirement that P^* be less than $600 \text{ MeV}/c$ was found to accept 91% of these τ events. In this analysis the Monte Carlo events were passed through the same program as was used for the real data.

A second background to the five-charged-particle decay comes from $\tau \rightarrow 3\pi^\pm + \pi^0 + \nu_\tau$, in which one of the photons from the π^0 forms an e^+e^- pair either by a Dalitz conversion or by external conversion in the $\approx 1.5\%$ of a radiation length of material surrounding the interaction point. The estimated number of five-prong events which include an e^+e^- pair is 6.5, found by use of the Monte Carlo simulation.

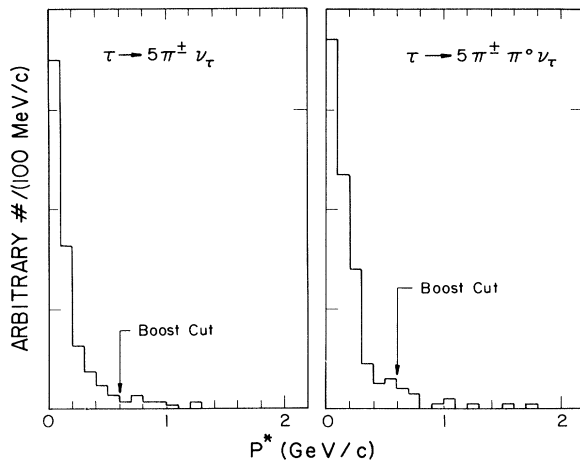


FIG. 3. The Monte Carlo prediction for the measured momentum P^* of the charged hadronic-decay products in the τ rest frame.

There are three properties of these e^+e^- pairs which allows them to be eliminated from the sample. (1) The tracks are low momentum because the original photon has on average half the momentum of its parent neutral pion and each electron has only half the momentum of its parent photon. (2) The effective mass of the pair is low: For Dalitz pairs the probability of forming a mass larger than $85 \text{ MeV}/c^2$ is less than 1%. (3) The showering nature of the electron and positron yields two chances to distinguish at least one member of the pair as being nonhadronic. All events have been removed with neutral pairs (treated as electrons) whose invariant mass is less than $200 \text{ MeV}/c^2$ and which have at least one member that deposits an energy in the barrel shower-counter system within 3σ of the expected value for an electron. If neither member of the pair was energetic enough to hit the barrel shower counter then the event was also eliminated. If one member of the pair was nonshowering, depositing an energy consistent with a minimum-ionizing particle, then the event was accepted. With these criteria, seven of the τ candidate events were found to contain e^+e^- pairs, which is consistent with the Monte Carlo estimate. The remaining conversion background is less than 0.1 event.

The background from two-photon interactions is small. If the five-prong events are interpreted as originating from two-photon interactions, then the invariant mass of the two-photon system, including neutral energy, ranges over $8 \text{ GeV}/c^2 < W_{\gamma\gamma} < 25 \text{ GeV}/c^2$, and each event has one jet with a transverse momentum that ranges over $10 \text{ GeV}/c < P_T < E_{\text{beam}}/c$. An estimate for the number of two-photon events with these properties can be obtained by use of the differential jet cross section $d\sigma/dp_T^{(\text{jet})}$ for $e^+e^- \rightarrow e^+e^- + \text{jet} + x$ as measured by Bartel *et al.*,¹⁰ extrapolating it to higher transverse momentum as $(P_T^{(\text{jet})})^{-4}$, and scaling the result¹¹ to take into account the very large visible mass observed in our events. This cross section must be further reduced to take into account the requirement that one quark jet fragments into one charged particle and the other into five charged particles. By use of the measured scaling of jet multiplicity,¹² an additional suppression factor of 0.005 is found for the observed events. When the effects of geometric acceptance, the acollinearity cut, and the Lorentz boost which alone suppresses the single-photon hadronic contribution by $\approx 10^{-2}$ are included, the two-photon background is conservatively estimated to be less than 0.1 event.

A possible source for the five-charged-prong signal is the Cabibbo-suppressed decay mode $\tau \rightarrow K^0 + 3\pi^\pm + \nu_\tau$, followed by the decay $K^0 \rightarrow \pi^+\pi^-$. The thermodynamic model was used to simulate this decay together with the Monte Carlo τ -event generator. An overall acceptance of 0.025 was found for this mode

when only five charged tracks were accepted, including the effects of K_L and K_S production. It was then found that the resulting $K_S^0 \rightarrow \pi^+ \pi^-$ decays in the accepted sample had a 0.76 ± 0.12 probability of being correctly identified as a K_S^0 . The inclusive K_S^0 signal from the hadronic data set is found at $496.8 \text{ MeV}/c^2$ with a full width at half height of $9 \text{ MeV}/c^2$. No K_S^0 candidates were found with a $\pi^+ \pi^-$ mass combination between 440 and $560 \text{ MeV}/c^2$ in the five-prong τ -decay sample. To a confidence level of 90%, the upper limit on this mode is then $B(\tau \rightarrow K^0 + 3\pi^\pm + n\gamma + \nu_\tau) < 2.7 \times 10^{-3}$.

All sources of background having been reduced to a negligible level, a signal of ten events remains. The acceptance for these events, including the solid angle, tracking efficiency, and all other cuts, for both the five-charged- π decay of the τ and the decay into five charged π 's accompanied by a single π^0 , is found to be 0.17 ± 0.01 . When all the effects of acceptance are included together with the total number of τ events produced 25×10^3 , an inclusive branching ratio of $B_5 = (1.3 \pm 0.4) \times 10^{-3}$ is found.

A detailed examination of the ten candidate events shows that five of the events are accompanied by neutral energy in the barrel shower counters which is clearly separated from the charged tracks. Three of these five events have two clear clusters of neutral energy while two show a single cluster of neutral energy. If we now include these neutral clusters in a recalculation of the invariant mass for these events and treat the clusters as having originated from the decay of a π^0 , none of the events is found to exceed the τ mass. With this interpretation of the events the resulting branching ratios of the τ are found to be $B(\tau \rightarrow 5\pi^\pm + \nu_\tau) = (6.7 \pm 3.0) \times 10^{-4}$ and $B(\tau \rightarrow 5\pi^\pm + \pi^0 + \nu_\tau) = (6.7 \pm 3.0) \times 10^{-4}$.

In conclusion, we have observed the inclusive five-charged-particle decay of the τ lepton and report the 5π and 6π branching ratios of the τ . It should not escape the attention of the reader that these high-mass hadronic decays of the τ can be used to probe for a

possible mass of the τ neutrino. We plan to report on such a study in a future publication.

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