Study of the Decay $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$

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(Received 21 April 1986)

The branching ratios for $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ and $\tau^- \to \pi^-\pi^-\pi^+(n\pi^0)\nu_\tau$, $n \geq 1$, have been measured to be $0.078 \pm 0.005 \pm 0.008$ and $0.047 \pm 0.005 \pm 0.008$, respectively. The total three-prong tau branching ratio is $0.128 \pm 0.005 \pm 0.008$. Study of the $3\pi^\pm\nu_\tau$ decay indicates that the three pions are predominantly from a $J^P = 1^+$ state which decays through a $\rho^0\pi^\pm$ intermediate state in a relative s wave. The $\rho\pi$ mass spectrum is suggestive of a resonance.

PACS numbers: 13.35.+s, 14.40.Cs, 14.60.Jj

The reaction $e^+e^- \to \tau^+\tau^-$ at energies well above threshold exhibits the distinctive topology of two back-to-back, low-mass and low-multiplicity jets. This provides a clean sample of taus favorable for detailed study of specific decay modes. In this Letter we present an analysis of the decay

$$\tau^- \to \pi^-\pi^-\pi^+\nu_\tau \tag{1}$$

and its charge conjugate. Our data represent a significant improvement in statistics over previous detailed studies of the three-pion final state.[1,2]

In the standard model of weak interactions, this decay probes the $J^P = 1^+$ and 0^- isovector hadronic currents. The $A(1270)$ and possible $\pi(1300)$ resonances[3] are expected to dominate these amplitudes. Much of our present understanding of states with these quantum numbers is derived from phase-shift analyses of hadron-hadron collisions. An analysis of the relatively clean reaction (1) complements the more elaborate hadronic amplitude analyses.

The data for this analysis were taken with the Mark II detector at the Stanford Linear Accelerator Center e^+e^- storage ring PEP, operating at a center-of-mass energy of 29 GeV. The integrated luminosity of this experiment is 205 pb^{-1}, corresponding to the production of 28 000 $\tau^+\tau^-$ events.

The Mark II detector has previously been described in detail[4]; here we summarize the features relevant to this analysis. Charged-particle tracking is accomplished by means of two cylindrical drift chambers concentric with the beam line and immersed in a 2.35-kG solenoidal magnetic field. The inner chamber consists of seven high-resolution axial sense-wire layers, while the outer chamber has ten stereo and six axial layers. The momentum resolution is $\delta p/p \approx [(0.025)^2 + (0.01p)^2]^{1/2}$, where the units of p are GeV/c. Eight lead–liquid-argon calorimeter modules, located outside the magnet coil, cover 64% of 4π and are used for photon detection and electron identification. The energy resolution for photons is $\delta E/E \approx 0.14/\sqrt{E}$ (with E in gigaelectronvolts). No π/K separation is possible at the momenta of pions from tau decay. Thus, our data sample will have some contamination from kaons.

Candidate events are those with four charged tracks, with total charge zero. The tracks are divided into two groups by a plane perpendicular to the highest-momentum track. We select events with three tracks in one group and one track in the other. We reject two-photon events by requiring that the total observed energy (charged plus neutral) exceed $0.25E_{\text{c.m.}}$. Radiative Bhabha events containing an electron pair from photon conversion are removed by our requiring the total energy in the electromagnetic calorimeter to be less than 23 GeV. Events in which the charged tracks in the three-prong group have an effective mass (calculated on the assumption that they are pions) greater than 2 GeV/c^2 or have a total energy and mass kinematically inconsistent with tau decay are rejected. Each of the charged tracks in the three-prong group is required to be well measured by the drift chambers, and must come from the beam-interaction region. An algorithm is used to remove electron pairs from photon conversion and Dalitz-pair electrons.

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These cuts leave a sample of 1420 events from both process (1) and the similar-topology decay

$$\tau^- \rightarrow \pi^-\pi^-\pi^+(n\pi^0)\nu_\tau, \quad n \geqslant 1. \qquad (2)$$

We separate the two classes of events by identifying the photons from the π^0 decay(s) in (2). We consider only photons which deposit at least 0.75 GeV of energy in the calorimeter, and are within 45° of the total momentum vector of the three charged tracks. These criteria leave 890 events without photons. The minimum-energy cut reduces contamination from hadron interactions in the calorimeter which mimic a photon shower. This contamination process has been carefully studied with data from a pion-beam test of the calorimeter. We have used the test data in a simulation of (1) and (2), and adjusted the simulation to match the energy and angular distribution of showers in the tau data. We find that approximately 14% of the events from (1) generate a neutral shower with more than 0.75 GeV, and a photon is correctly identified in 73% of the detected events from (2).

Monte Carlo simulation is used to determine the total acceptance for detection of the two classes of events, and to generate a folding matrix which maps the two decay modes into events with and without detected photons. Out total efficiency for detection of either (1) or (2) is approximately 24%. The Monte Carlo simulation is also used to determine the fraction of background from other tau decays in the all-charged (charged + neutral) sample. Using measured branching ratios,[5] we find that the decay $\tau^- \rightarrow \pi^-\pi^0\nu_\tau$, with a pair from Dalitz decay or photon conversion, contributes 1.4% (5.3%). Similarly, the three-charged-pion final state from the decay $\tau^- \rightarrow K^{*-}\nu_\tau$ contributes 1.9% (0.8%). Finally, we estimate the background from $e^+e^- \rightarrow q\bar{q}$ by studying low-multiplicity hadronic events with three charged tracks in one jet. The ratio of the number of these events which fail the three-prong mass and energy cuts to the number passing the cuts, combined with the number of events in the 3 + 1 sample which fail these cuts, leads to a background estimate of 1.9% (5.6%). Backgrounds from other sources are negligible.

To determine the branching ratios for (1) and (2) we use a subset of approximately half of the full data sample for which the charged-tracking efficiency is best understood. The backgrounds are subtracted, and the folding matrix is used to determine the number of events of each type. We normalize to the total number of $\tau^+\tau^-$ events expected for our integrated luminosity. The luminosity is measured with wide-angle Bhabha events, and we use a cross section for $e^+e^- \rightarrow \tau^+\tau^-(\gamma)$ of 0.136 nb.[6]

We find the branching ratio for decay (1) to be $0.078 \pm 0.005 \pm 0.008$, where the first error is statistical and the second systematic. For decay (2) our result is $0.047 \pm 0.005 \pm 0.008$. These values are in good agreement with previous results.[2,7] The four-pion result is in good agreement with a prediction of 0.049 based on the conserved-vector-current hypothesis.[8] (There is no analogous prediction for the three-pion mode.) We note that these branching ratios contain a small contribution from decays including one or two charged kaons.[9] The dominant source of systematic error is in the separation of events with and without a photon. This error is highly correlated between the two processes: Reducing the branching ratio for (1) increases the ratio for (2) by the same amount. The sum of the two modes is independent of the photon identification. Systematic errors for this sum include uncertainty in the luminosity (4%), error in background (3%), and uncertainty in acceptance (4%). Including the contribution from K^* decay mode,[5] we determine the total three-prong branching ratio for taus to be $0.128 \pm 0.005 \pm 0.008$. This value is in good agreement with previous results.[7,10]

For further analysis of mode (1), we use the entire data sample. Tighter cuts are made on the quality of the tracks to ensure that their directions and momenta are well measured. We are left with a sample of 830 events without an identified photon, including a background of 180 events from process (2). For each distribution studied, we subtract this background using the distribution for events with an identified photon. We ignore the small contamination from other backgrounds. Calculated distributions are corrected for detector efficiency and resolution before comparison with the data.

The spin and parity of the three-pion state can be derived from a Dalitz-plot analysis.[11] In Fig. 1 we

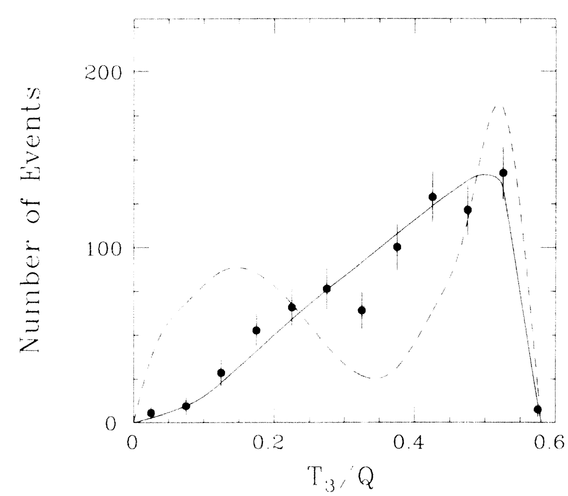

FIG. 1. The distribution of the quantity T_3/Q as defined in the text, with the expected distribution for a 1^+ s wave (solid line). The expectation for 0^- is overlaid for comparison (broken line).

show the distribution of the quantity T_3/Q, where T_3 is the kinetic energy of the odd-sign pion in the three-pion center of mass, and Q is the total kinetic energy in this system. In calculating the expected distribution for different hypotheses we use the observed total-mass spectrum and assume $\rho\pi$ dominance; this assumption will be justified below. The data are well represented by a $J^P = 1^+$ distribution with the $\rho\pi$ in a relative s wave. For comparison, the poor agreement with the 0^- hypothesis is shown. The data are compared to incoherent mixtures of the dominant 1^+ s wave and small amounts of the other allowed spin and parity states. Upper limits at the 95% confidence level for these contributions are found to be 18% for the 0^- hypothesis and 29% for the 1^+ d wave. Alternatively, the best-fit population in combination with the 1^+ s wave is $(10 \pm 5)\%$ for 0^-, and $(16 \pm 8)\%$ for the 1^+ d wave.

Figure 2 shows the $\pi^+\pi^-$ mass distribution (two entries per event), with the like-sign distribution subtracted. The solid curve shows the expected distribution for a 1^+ $\rho\pi$ in a relative s wave. The calculation uses the observed total-mass distribution, and includes the effects of interference between the two opposite-sign pion combinations.[12] The slight negative dip in the curve is the result of this interference. The expected distribution for non-$\rho\pi$ is also shown. (By non-$\rho\pi$ we mean three pions in a 1^+ state with no $\pi^+\pi^-$ mass enhancement.) The data are compatible with a pure $\rho\pi$ state; at the 95% confidence level, the upper limit for non-$\rho\pi$ contribution is 21%.

Figure 3 shows a plot of the three-pion total-mass distribution. The data exhibit a sharp rise at $\rho\pi$ threshold and a rapid falloff above 1.3 GeV/c^2. The broken line shows the expectation for decay to a $\rho\pi$ final state, including the leptonic matrix element for tau decay, but with no $\rho\pi$ interaction. While kinematics suffices to interpret the threshold behavior, the data fall off at lower mass than expected for $\rho\pi$ phase space. We have fitted the data by a function of the form

$$\frac{dN}{dm^2} \propto m^{-2}(m_\tau^2 - m^2)^2(m_\tau^2 + 2m^2) \times m\Gamma(m)/[(m^2 - {}^2_0)^2 + m_0^2\Gamma(m)^2]. \quad (3)$$

This parametrization is derived by our factorizing the matrix element and phase space for the entire process into two substeps, including the propagation of a virtual A with complex mass.[13] It assumes that the state is 1^+ and decays through a $\rho\pi$ s wave. The mass-dependent width $\Gamma(m)$ includes the effects of $\rho\pi$ threshold and interference.[12,14] The fit yields the resonance parameters $M_A = m_0 = 1.194 \pm 0.014 \pm 0.010$ GeV/c^2, $\Gamma_A = \Gamma(M_A) = 0.462 \pm 0.056 \pm 0.030$ GeV/c^2. The systematic errors include uncertainty in efficiency, resolution, and background to the distribution, but not uncertainties in the form of (3). The solid curve in Fig. 3 shows that the data are well described by this parametrization, with χ^2 of 10.9 for 14 degrees of freedom.

It is important to note that the parametrization (3) is not unique. There is no reason to exclude arbitrary form factors at both the W-A and the $A\rho\pi$ vertices. A form factor at the first of these would multiply the entire distribution (3), and at the second of these it would multiply $\Gamma(m)$. In (3) we have taken these terms to be constants. We have investigated the effect of form factors on the resonance parameters by includ-

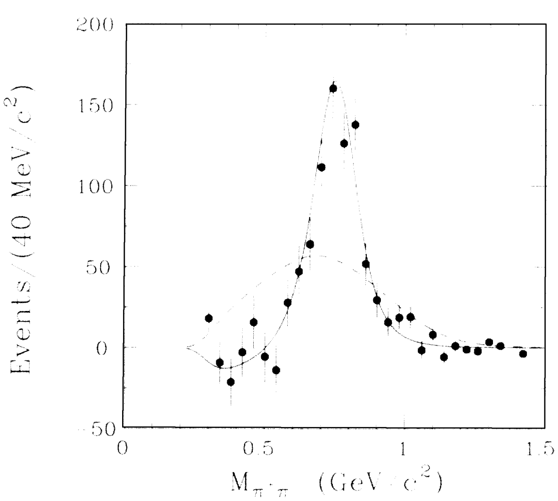

FIG. 2. $\pi^+\pi^-$ mass distribution, with like-sign distribution subtracted. The solid line shows the expected distribution for a $\rho\pi$ intermediate state. The broken line is for non-$\rho\pi$.

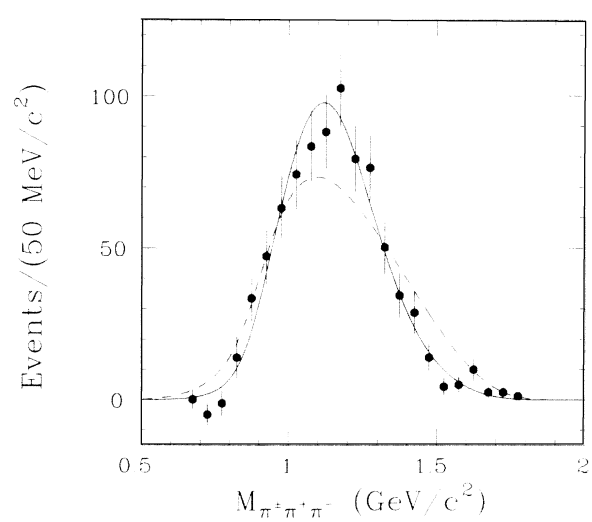

FIG. 3. 3π total-mass distribution. The solid line shows the best fit for a Breit-Wigner $\rho\pi$ resonance with $M = 1.194$ GeV/c^2, $\Gamma = 0.462$ GeV/c^2. The broken line is the expectation for no $\rho\pi$ interaction.

ing various powers of mass in the appropriate terms in the distribution. We find that on inclusion of $m^{\pm 1}$, M_A changes by approximately ∓ 0.03 GeV/c^2 and Γ_A changes by ∓ 0.06 GeV/c^2. Larger variations in the form factors lead to larger changes in the resonance parameters. Thus we conclude that although the resonance parameters extracted by use of (3) differ from the Particle Data Group values for the $A(1270)$, $M_A = 1.275 \pm 0.030$ GeV/c^2 and $\Gamma_A = 0.315 \pm 0.045$ GeV/c^2,[3] this difference may be attributed to ambiguities in the parametrization used for the three-pion mass distribution.[15]

In conclusion, we have measured the three-prong branching ratios for tau decay into three and four pions. Study of the three-pion mode indicates that it is a $J^P = 1^+ \rho\pi$ resonance, decaying in an s wave. There is no evidence for a 0^- contribution to the final state. The resonance seems to be lower in mass and broader than the $A(1270)$ seen in hadronic experiments, but these differences may be attributed to the parametrization of the total-mass distribution.

We wish to thank Y. S. Tsai for useful discussions. This work was supported in part by the U. S. Department of Energy under Contracts No. DE-AC03-76SF00515 and No. DE-AC03-76SF00098.

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[14]$\Gamma(m)$ is basically the phase space for $A \to \rho\pi$, most importantly describing the s-wave threshold for this reaction. There are small corrections for interference which do not significantly affect the resonance parameters but do improve the quality of the fit.

[15]Ruckstuhl *et al.*, Ref. 2, use a parametrization with a coupling constant proportional to m^2, resulting in a form factor proportional to m^4. They also use a slightly different form for the Breit-Wigner resonance, without a variable mass in the numerator. This results in a parametrization which has 3 more powers of of mass than ours. Using their parametrization on our data, we find $M_A = 1.097 \pm 0.013$ GeV/c^2, $\Gamma(M_A) = 0.378 \pm 0.040$ GeV/c^2, where the errors are statistical. Their results are $M_A = 1.056 \pm 0.020 \pm 0.015$ GeV/c^2, $\Gamma(M_A) = 0.476^{+0.132}_{-0.120} \pm 0.054$ GeV/c^2. Thus, our data are in good agreement. Differences in our results are due mainly to parametrization.