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STUDY OF τ DECAY MODES WITH MULTIPLE NEUTRAL MESONS IN THE FINAL STATES*

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ABSTRACT

The τ decay modes with multiple neutral mesons in the final states have been studied using the Mark II detector at PEP. The branching ratio for the decay mode $\tau^- \to \pi^- 2\pi^0 \nu_\tau$ is found to be consistent with the theoretical expectation. However, the branching ratio for $\tau^- \to \pi^- 3\pi^0 \nu_\tau$ is found to be inconsistent with the theoretical prediction unless there are other decay modes with multiple neutral mesons in the final states.

The τ lepton has been a subject of extensive study since its discovery in 1975.[1] All measurements[2] indicate that it is a sequential lepton in the standard model of electroweak interactions. However, the measured inclusive one-charged-particle branching ratio is significantly higher[3] than the sum of the measured exclusive one-charged-particle branching ratios. In order to understand the discrepancy we need more precise measurement of branching ratios for decay modes with multiple neutral mesons in the final states. In this Letter, we report a new measurement of the branching ratios for the decays[4] $\tau^- \to \pi^- 2\pi^0 \nu_\tau$, $\tau^- \to \pi^- 3\pi^0 \nu_\tau$, and $\tau^- \to \pi^- \eta \pi^0 \nu_\tau$.

The measurement is based on a data sample collected by the Mark II experiment at the PEP e^+e^- storage ring operated at a center-of-mass energy of 29 GeV. The integrated luminosity for the sample is 220 pb^{-1} and corresponds to 30,000 produced τ-pair events. The Mark II detector has been described in detail elsewhere.[5] Features of the detector relevant for this analysis are the drift-chamber system and the central electromagnetic calorimeter. 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. The system measures charged-particle momenta with a resolution of $\sigma_p/p = [(0.02)^2 + (0.01p)^2]^{1/2}$($p$ in GeV/c) in a 2.3 kG solenoidal magnetic field. The calorimeter consists of eight lead liquid-argon (LA) modules with 14 radiation lengths, covering 65% of the solid angle, and detects electromagnetic showers with an energy resolution of $\sigma_E/E = 0.14/\sqrt{E}$ (E in GeV).

The τ-pair production at PEP energy yields a final state with a clear back-to-back topology, allowing the events to be selected with little background. This analysis used only events that had zero net charge and contained two or four charged particles. The events were divided into two hemispheres by a plane perpendicular to the thrust axis and required to have one charged particle in one hemisphere and one or three charged particles in the other. The total energy of the events was required to be between 7.25 and 25 GeV and the invariant mass of all particles in a hemisphere, including the photons, was required to be less than 2.0 GeV/c^2. Those hemispheres containing one charged particle and three or more photons were considered to be candidates for τ decays with multiple neutral mesons in the final state. To reduce the probability that the photons were due to the charged particles interacting in the magnetic coil or in the LA, the photons were required to have energies of greater than 400 MeV and to be more than 20 cm away from the locations where the charged particles struck the LA.

The number of τ candidates found is listed in Table I. The candidate events were hand-scanned. Two Bhabha candidates with three photons in the one-charged-particle hemispheres were found and removed. No beam-gas interaction or cosmic-ray events were found. The kinematic distributions of the candidate events are consistent with those expected from τ decay. The event sample also contains the expected fractions of electrons and muons opposite the multiple photon candidates. Therefore the sample is of high purity with little background from other e^+e^- reactions.

The detection efficiency for the events was calculated from a Monte Carlo simulation which produced τ-pair events according to the standard electroweak theory, including α^3 QED corrections.[6] Each τ was allowed to decay according to the known branching ratios.[7]

In the Monte Carlo, the simulation of electromagnetic interactions in the LA calorimeter was based on the EGS shower code.[8] The simulation of hadronic interactions in the LA system was based on a library of real pion interaction data extracted from a sample of candidates for the decay $\tau^- \rightarrow \pi^-\pi^+\pi^-\pi^0\nu_\tau$. The candidates were selected from events with one charged particle in one hemisphere and three charged particles in the other. Those hemispheres that contained three charged particles and one or more π^0 candidates were considered to be candidates for $\tau^- \rightarrow \pi^-\pi^+\pi^-\pi^0\nu_\tau$. The two photons from the π^0 candidate with the best χ^2 fit were removed and the remaining photons were treated as from pion interactions and stored in the library. Adjustments were made in the construction of the library to correct for the misidentification of the decay $\tau^- \rightarrow \pi^-\pi^+\pi^-\nu_\tau$ as $\tau^- \rightarrow \pi^-\pi^+\pi^-\pi^0\nu_\tau$ due to pion interactions and for combining a photon from the π^0 decay with a photon produced by pion interactions. The resulting Monte Carlo reproduces the photon candidates in both the $\tau^- \rightarrow \pi^-\pi^+\pi^-\nu_\tau$ and the $\tau^- \rightarrow \pi^-\pi^+\pi^-\pi^0\nu_\tau$ data well. With no further adjustment, the Monte Carlo also reproduces the one-charged-particle data well.

The background contamination in the data sample is summarized in Table I. The background from the reaction $e^+e^- \to e^+e^-\tau^+\tau^-$ was estimated using a Monte Carlo technique. The background from the process $e^+e^- \to q\bar{q}$ was estimated from the data by the use of two jet hadronic events with the assumption that the two jets fragment independently.[9)]

The observed photon multiplicity spectrum was corrected for the background contamination and unfolded with an efficiency matrix to measure the branching ratios for the decays $\tau^- \to \pi^- 2\pi^0\nu_\tau$, $\tau^- \to \pi^- 3\pi^0\nu_\tau$, and $\tau^- \to \pi^- \eta\pi^0\nu_\tau$, denoted as $B_{2\pi^0}$, $B_{3\pi^0}$, and $B_{\eta\pi^0}$. The efficiency matrix gives the probability that a particular decay mode is detected with a certain photon multiplicity and is calculated using the Monte Carlo (see Table II). A maximum likelihood technique was used in the branching ratio unfold, assuming Poisson statistics. If we assume that there are no decay modes containing η's, the fit yields $B_{2\pi^0} = (6.7 \pm 0.5)\%$ and $B_{3\pi^0} = (2.2 \pm 0.4)\%$, with χ^2 of 6.9 for 4 degrees of freedom. A somewhat better fit is obtained if we allow for the decay mode $\tau^- \to \pi^-\eta\pi^0\nu_\tau$ in the fit[10)]: $B_{2\pi^0} = (6.2 \pm 0.6)\%$, $B_{3\pi^0} = (0.0\pm^{1.4}_{0.0})\%$, and $B_{\eta\pi^0} = (4.2\pm^{0.7}_{1.2})\%$, with χ^2 of 3.8 for 3 degrees of freedom. Although $\tau^- \to \pi^-\eta\pi^0\nu_\tau$ is expected to be the dominant decay mode containing η mesons, assuming the existence of other η decay modes also gives satisfactory fits, as expected. With various assumptions on possible η decay modes, $B_{2\pi^0}$ varies from 6.2 to 8.0% and $B_{3\pi^0}$ varies from 0.0 to 0.3%.

The main sources of systematic error are the uncertainties in the detection efficiencies and in the simulation of fake photons produced in pion interactions. These systematic errors were estimated by varying the energy and isolation distance requirements on the photons. To investigate possible systematic errors in calculating the detection efficiencies for multiple photons in a LA module, we also analyzed a sub-sample of data where the photon occupancy per module was limited to be three or less.[11] Results of these investigations on systematic errors are summarized in Table III. Also included in the table are the systematic errors that arise from the uncertainty in the migration background due to the uncertainty in the branching ratio for the decay $\tau^- \to \pi^-\pi^0\nu_\tau$, from the uncertainties in the backgrounds from the reactions $e^+e^- \to q\bar{q}$ and $e^+e^- \to e^+e^-\tau^+\tau^-$ (assuming an error of 100%), and from the 5% uncertainty in the luminosity measurement. Combining these systematic errors in quadrature yields the final results: $B_{2\pi^0} = (6.2 \pm 0.6 \pm 1.2)\%$, $B_{3\pi^0} = (0.0 \pm^{1.4}_{0.0} \pm^{1.1}_{0.0})\%$, and $B_{\eta\pi^0} = (4.2 \pm^{0.7}_{1.2} \pm 1.6)\%$.

The results can be compared with other reported measurements. The CELLO group[12] ignored the η contributions and reported a measurement of $B_{2\pi^0} = (6.0 \pm 3.0 \pm 1.8)\%$ and $B_{3\pi^0} = (3.0 \pm 2.2 \pm 1.5)\%$. The TPC group[13] reported a weighted sum measurement of $B_{2\pi^0} + 1.6\ B_{3\pi^0} + 1.1\ B_{\eta\pi^0} = (13.9 \pm 2.0 \pm 1.9)\%$. Our new results are consistent with all the measurements.[14]

The results can also be compared with the theoretical expectations. $B_{2\pi^0}$ is related to the branching ratio for $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ by isospin conservation, which imposes the limit $B_{2\pi^0} \leq B_{\pi^+\pi^-}$. The world average measurement[7] of $B_{\pi^+\pi^-}$ is $(7.1 \pm 0.5)\%$. The theoretical prediction[15] for $B_{3\pi^0}$ is $\simeq 1.0\%$ based on the conserved-vector-current (CVC) hypothesis. The measurements of $B_{2\pi^0}$ and $B_{3\pi^0}$ are therefore consistent with the theoretical expectations. There is no theoretical prediction for $B_{\eta\pi^0}$.

We refit the data, taking advantage of the fact that $B_{3\pi^0}$ is predicted to be small, to investigate whether the data actually require the existence of η decay modes. In the refit, we constrain $B_{3\pi^0}$ to be the theoretical prediction of 1.0%

and assume that there are no η decay modes. The result is $B_{2\pi^0} = (8.6 \pm 0.3)\%$ (statistical error only), with χ^2 of 13.1 for 5 degrees of freedom. Therefore $B_{3\pi^0}$ is inconsistent with the theoretical prediction unless there are η decay modes or other decay modes with multiple neutral mesons in the final states.

As a check of the measurements, a sub-sample of four- and six-photon candidates was used to measure $B_{2\pi^0}$ and $B_{3\pi^0}$ directly. In the four-photon sample, only those candidates that satisfied a $2\pi^0$ hypothesis were used, where a π^0 candidate was defined to be a photon pair with $\chi^2 < 8$ for a one-constraint fit to the π^0 mass. No π^0 requirement was imposed on the six-photon sample due to the large combinatorial background. After correcting the sample for detection efficiencies and background contaminations, the results are $B_{2\pi^0} = (4.5 \pm 1.0 \pm 1.2)\%$ and $B_{3\pi^0} = (4.7 \pm 1.0 \pm 1.1)\%$, assuming there are no decay modes containing η's. If we allow for the decay $\tau^- \to \pi^-\eta\pi^0\nu_\tau$, then $B_{2\pi^0} = (4.5 \pm 1.0 \pm 1.2 - 0.95(B_{3\pi^0} - 4.7) - 0.43B_{\eta\pi^0})\%$ and $B_{3\pi^0} = (4.7 \pm 1.0 \pm 1.1 - 0.67B_{\eta\pi^0})\%$. The result for $B_{2\pi^0}$ is consistent with the value expected from isospin conservation. However, the measurement of $B_{3\pi^0}$ is somewhat higher than the CVC prediction unless there are some η contributions. Therefore this direct measurement indicates the existence of η decay modes and is consistent with the results obtained from the unfolding technique.

In conclusion, the branching ratio for the decay mode $\tau^- \to \pi^- 2\pi^0\nu_\tau$ is found to be consistent with the theoretical expectation. However, the branching ratio for $\tau^- \to \pi^- 3\pi^0\nu_\tau$ is found to be inconsistent with the theoretical expectation unless there are other decay modes containing multiple neutral mesons in the final states. Therefore the discrepancy in the one-charged-particle decay branching ratio could be due to the not yet directly observed multiple neutral meson decay modes. Better measurement of the branching ratio for $\tau^- \rightarrow \pi^- 3\pi^0 \nu_\tau$ and the observations of the multiple neutral meson decay modes will help to resolve the discrepancy.

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10. It should be noted that the best fit corresponds to a negative value of $B_{3\pi^0}$. It is evident from the efficiency matrix in Table II that this experiment cannot clearly differentiate the photon multiplicity spectrum of the decay $\tau^- \rightarrow \pi^- 3\pi^0 \nu_\tau$ from that of $\tau^- \rightarrow \pi^- \eta\pi^0\nu_\tau$. This is reflected in the relatively large errors in the unfolded $B_{3\pi^0}$ and $B_{\eta\pi^0}$.

11. We previously reported a precise measurement of the branching ratio for $\tau^- \rightarrow \pi^-\pi^0\nu_\tau$ in J. M. Yelton *et al.*, Phys. Rev. Lett. **56**, 812 (1986). The measurement is in excellent agreement with both the theoretical expectation and the results from other experiments, indicating that the photon detection efficiency is well understood.

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Table I. Number of candidates with three or more photons together with their background contaminations.

Number of photons	3	4	5	6	7
Number of candidates	815	254	41	14	1
Background	Number of events				
$e^+e^- \to q\bar{q}$	8.6	5.3	1.1	0.2	0.0
$e^+e^- \to e^+e^-\tau^+\tau^-$	10.5	4.9	0.0	0.0	0.0

Table II. Efficiency matrix for the branching ratio unfold (in %).

Number of Photons	$\pi^-\pi^0$	$\pi^-2\pi^0$	$\pi^-3\pi^0$	$\pi^-\eta\pi^0$
3	1.2	11.5	11.5	7.8
4	0.1	3.2	8.6	4.5
5	0.0	0.3	2.4	1.4
6	0.0	0.0	0.4	0.3
7	0.0	0.0	0.2	0.1

Table III. Summary of the systematic errors in the branching ratio measurements (in %).

	$B_{2\pi^0}$	$B_{3\pi^0}$	$B_{\eta\pi^0}$
Efficiency and pion interactions	1.0	1.0	1.5
$B_{\pi^0} = (22.2 \pm 1.3)\%$	0.2	0.1	0.1
$e^+e^- \to q\bar{q}$	0.1	0.1	0.1
$e^+e^- \to e^+e^-\tau^+\tau^-$	0.2	0.1	0.1
Luminosity	0.5	0.2	0.2