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Study of the $\tau^- \rightarrow 3h^-2h^+\nu_\tau$ Decay

The *BABAR* Collaboration

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Abstract

A preliminary measurement of the branching fraction of the $\tau^- \rightarrow 3h^-2h^+\nu_\tau$ decay ($h = \pi, K$) with the *BABAR* detector is found to be $(8.52 \pm 0.09 \pm 0.40) \times 10^{-4}$, where the first error is statistical and the second is systematic. The data show evidence that the ρ resonance plays a strong role in the decay of the τ lepton to five charged hadrons.

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The semi-leptonic decays of the τ lepton are an ideal area for studying strong interaction effects (for example, see Ref. [1]). The decay mode $\tau^- \to X^- \nu_\tau$ probes the matrix element of the left-handed current between the vacuum and the hadronic state X^- [2]. Most of these studies have involved the decay of the τ to one or three charged particles and any number of π^0 mesons whereas decays of the τ to five charged particles have been limited by the small number of observed events [3]. This paper presents a preliminary measurement of the $\tau^- \to 3h^- 2h^+ \nu_\tau$ decay ($h = \pi, K$) from a sample of over 15,000 such decays.[6]

This analysis is based on data recorded by the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- storage ring operated at the Stanford Linear Accelerator Center. The data sample consists of 110.7 fb^{-1} recorded at center-of-mass energy ($\sqrt{s}$) of 10.58 GeV and 10.54 GeV between 1999 and 2003. With an expected cross section for τ-pair production at the luminosity-weighted $\sqrt{s}$ of $\sigma_{\tau\tau} = (0.89 \pm 0.02)$ nb [4], this data sample contains approximately 200 million τ decays. Monte Carlo simulation is used to evaluate the background contamination and selection efficiency. The τ pair events are simulated with the KK2f Monte Carlo event generator [4] and the τ decays were modeled with Tauola [5] according to measured rates [3].

The *BABAR* detector is described in detail in [6]. Charged particle momenta are measured with a five-layer double-sided silicon vertex tracker and a 40-layer drift chamber inside a 1.5-T superconducting solenoidal magnet. A calorimeter consisting of 6580 CsI(Tl) crystals is used to measure electromagnetic-shower energy, a ring-imaging Cherenkov detector is used to identify charged hadrons, and an instrumented magnetic flux return (IFR) is used to identify muons.

The τ pairs are produced back-to-back in the e^+e^- CM frame. As a result it is convenient to divide the event into two hemispheres, each containing the decay products of a single τ lepton. The analysis procedure selects events with one track in one hemisphere (tag hemisphere) and five tracks in the other hemisphere (signal hemisphere). The track in the tag hemisphere is required to be an electron or muon to reduce background from non-τ events.

The event is divided into two hemispheres in the CM frame based on the plane perpendicular to the thrust axis. The thrust is calculated with the use of the tracks in the event. The number of tracks in each hemisphere is used to determine the topology of the event. The tracks are required to have a minimum transverse momentum with respect to the beam of less than 0.1 GeV/c, a distance of closest approach to the production point in the transverse plane to the beam axis (DOCA_{XY}) of less than 1.5 cm and the absolute value of the distance of closest approach in the z-plane of less than 10 cm.

The background from non-τ sources (in particular, Bhabha scattering and two-photon production) is reduced with the use of the magnitude of the thrust of the event and the ratio p_T/E_{missing} where p_T is the transverse component of the vector sum of the momenta of all the tracks in the event and E_{missing} is the missing energy in the event. The p_T/E_{missing} variable is very effective in reducing the background from two-photon production which tend to have low p_T and high E_{missing}. The thrust (T) is required to be in the range between 0.92 and 0.99. Events are retained if they satisfy the following criteria

$$
\begin{array}{llr}
(p_T/E_{\mathrm{missing}} > 0.3 & \text{and} & 0.92 < T < 0.93) \text{ or} \\
(p_T/E_{\mathrm{missing}} > 0.2 & \text{and} & 0.93 < T < 0.94) \text{ or} \\
(p_T/E_{\mathrm{missing}} > 0.1 & \text{and} & 0.94 < T < 0.95).
\end{array}
$$

[6]Charge conjugation is assumed throughout this paper. In addition, a five charged particle state is not considered a $\tau^- \to 3h^- 2h^+ \nu_\tau$ decay if it was the result of a K^0_S decay. No attempt has been made in this work to distinguish charged pions and kaons.

There is no requirement on p_T/E_{missing} if the thrust is between 0.95 and 0.99.

Further reduction of the non-τ background is made by requiring that the track in the tag hemisphere be identified as an electron or a muon. Electrons are identified with the use of the ratio of calorimeter energy to track momentum (E/p), the ionization loss in the tracking system ($\mathrm{d}E/\mathrm{d}x$), and the shape of the shower in the calorimeter. Muons are identified with hits in the IFR and small energy deposits in the calorimeter.

The momentum of the lepton in the tag hemisphere in the center-of-mass frame is required to be less than $4\,\mathrm{GeV}/c$ to reduce background from Bhabha scattering and dimuon events. Residual background from multihadronic events is reduced by cutting on the number of clusters in the electromagnetic calorimeter within the tag hemisphere and not associated to the lepton. It is required that there be at most one cluster with energy between 0.05 and 1 GeV.

Additional criteria are applied to the five tracks in the signal hemisphere to reduce background from photon conversions and secondary decays. The event is rejected if any of the tracks in the signal hemisphere is identified as an electron or if any pair of oppositely charged tracks is consistent with originating from a photon conversion. The reconstructed mass of the five tracks is required to be less than $1.8\,\mathrm{GeV}/c^2$.

It is also required that there be no π^0 candidates in the signal hemisphere. The π^0 finding algorithm first searches for two clusters (each of at least 50 MeV) in the electromagnetic calorimeter that reconstructs to the π^0 mass (0.115 - 0.150 GeV/c^2). Any residual clusters are considered π^0 mesons if their energy is greater than $0.5\,\mathrm{GeV}$ and they are not associated with any tracks.

A total of 9668 and 6201 events are selected when an electron or muon are identified in the tag hemisphere, respectively. The background fractions in the electron and the muon tag samples are 0.210 ± 0.016.[7] The efficiencies for selecting the lepton plus $\tau^- \to 3h^-2h^+\nu_\tau$ events are 0.0455 ± 0.0004 and 0.0291 ± 0.0003 in the electron and muon samples, respectively, where the quoted uncertainty is the Monte Carlo statistical error[8].

The background is estimated by Monte Carlo simulation and tested with a dataset where the particular background is enhanced. The sources of background in the electron tag sample[9] can be broken down into the following categories: $\tau^- \to 3h^-2h^+\pi^0\nu_\tau$ decays (6.8%), τ decays with one or three tracks and at least one π^0 (5.7%), τ decays with a K^0_S (5.2%), multihadronic events (2.9%, primarily $c\bar{c}$ events) and a residual amount from other τ decays (0.3%). The relative uncertainties range between 10 and 20% for each background and reflect the statistical precision of the data and Monte Carlo samples used to evaluate the backgrounds. The sources of background in the muon-tag sample are almost the same as for the electron-tag sample.

The $\tau^- \to 3h^-2h^+\pi^0\nu_\tau$ background is validated with the use of the energy of the π^0 found in five-prong events that contain a single π^0 in the signal hemisphere. The background from τ one- and three-prong decays with a π^0 arises when one of the photons converts to an e^+e^- pair or a $\pi^0 \to e^+e^-\gamma$ decay. Decays are removed if there is an identified photon conversion or if any tracks in the event is considered an electron candidate.

The background from τ decays with at least one K^0_S ($\tau^- \to \pi^- K^0_S K^0_S \nu_\tau$ and $\tau^- \to h^-h^-h^+K^0\nu_\tau$

[7]The total background in the electron and muon tag samples are evaluated independently and by coincidence, are identical.

[8]The efficiency is defined to the ratio of the number of selected lepton plus $\tau^- \to 3h^-2h^+\nu_\tau$ events divided by the number of τ-pair events with a $\tau^- \to 3h^-2h^+\nu_\tau$. The branching fraction of the lepton is incorporated into the selection efficiency.

[9]An event is categorized as signal or background by whether or not the decay in the signal hemisphere passes the five-prong selection. An event is considered a signal event if the track in the tag hemisphere is mis-identified as an electron and the decay in the signal hemisphere passes the five-prong selection.

decays) is determined by fitting the mass distribution of $\pi^+\pi^-$ pairs to obtain an estimate of the number of K^0_S mesons. The background estimation takes into account that the $\tau^- \to \pi^- K^0_S K^0_S \nu_\tau$ decays often have two identified K^0_S mesons in a single event. The uncertainty in the background from τ decays with K^0_S mesons was found to be approximately 20% and includes contributions from the fit uncertainty and the branching ratios of the background decay modes. In addition, checks were made to ensure that the K^0_S background was from τ decays and not multihadronic events.

The background from multihadronic events was estimated by selecting events where the reconstructed mass of the five tracks in the signal hemisphere is above the τ mass. In addition, events with more than one cluster in the electromagnetic calorimeter in the tag hemisphere were used to measure the multihadronic background.

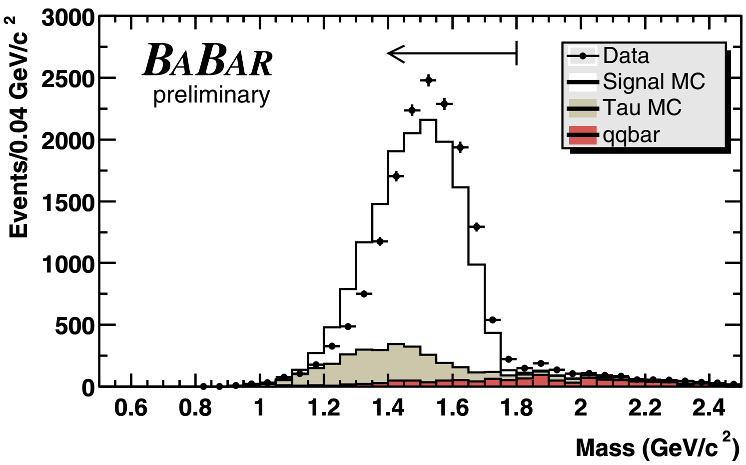

Figure 1: Reconstructed mass of the five tracks in the signal hemisphere after all other selection criteria are applied. The points are the data and the histogram is the Monte Carlo simulation for both the electron and muon tag samples, respectively. The unshaded and shaded histograms are the signal and background events. The arrow indicates the selection requirement applied to the samples. The Monte Carlo simulation is normalized to the luminosity of the data sample.

The branching fraction[10] of the $\tau^- \to 3h^-2h^+\nu_\tau$ decay is found to be $(8.52 \pm 0.09 \pm 0.40) \times 10^{-4}$ and $(8.54 \pm 0.11 \pm 0.45) \times 10^{-4}$ for the data selected by the electron and muon tags, respectively. The first uncertainties is the statistical error and the second systematic.

The systematic error includes contributions from the efficiency for reconstructing the six tracks in the event (3.1%), the luminosity and $\tau^+\tau^-$ cross section (2.3%), the π^0 finding algorithm (2.0%), the background in the five-prong sample (1.5%), and the lepton identification in the tag hemisphere (1.0%). The numbers given above are for the electron tag sample. The systematic uncertainty for the muon tag data is slightly larger. The systematic errors on the branching fraction determined with the electron and muon samples are highly correlated and combining the two results would result

[10] The branching fraction is defined as $B = \frac{N_{sel}}{2N}\frac{1-f_{bkgd}}{\epsilon}$ where N_{sel} is the number of selected events (1-prong lepton tag plus $\tau^- \to 3h^-2h^+\nu_\tau$ candidate), N is the number of tau pair events determined from the cross section and luminosity, f_{bkgd} is the fraction of background, and ϵ is the efficiency for selecting lepton and $\tau^- \to 3h^-2h^+\nu_\tau$ events.

in no improvement in the total uncertainty. As a consequence, the branching fraction obtained with the electron tag is used for the final result.

The error on the efficiency for selecting six tracks is based on studies of the efficiency for reconstructing a single track. The error on the efficiency for reconstructing a track is estimated to be 1.2% for tracks with $p_T < 0.3\,\mathrm{GeV}/c$ and 0.5% for tracks with $p_T > 0.3\,\mathrm{GeV}/c$. The errors were obtained from comparison of efficiencies of the standalone track reconstruction in the silicon vertex tracker and the drift chamber, and confirmed by the an independent analysis of the τ decays into three charged particles and neutrino. The variation of the selection cuts such as the minimum transverse momentum of the track, the number of tracks with hits in the silicon vertex tracker, and the sum of the DOCA_{xy} of the five tracks resulted in a negligible change in the branching fraction.

The systematic error associated with the π^0-finding algorithm used to separate $\tau^- \to 3h^-2h^+\nu_\tau$ and $\tau^- \to 3h^-2h^+\pi^0\nu_\tau$ events was based on the π^0 energy distribution. An excess of data over the Monte Carlo simulation was observed at low π^0 energy and a systematic uncertainty of 2% in the selection efficiency was included to account for this discrepancy.

The systematic uncertainty for selecting electrons and muons in the tag hemisphere has been conservatively estimated to be 1% and 2.5% respectively. Other consistency checks included varying the selection variables. In addition, the selection efficiency was found to have no dependence on the reconstructed mass of the five tracks in the signal hemisphere.

In Fig. 1, the mass of the five tracks in the signal hemisphere is presented.[11] Tauola uses a phase space distribution for the $\tau^- \to 3\pi^-2\pi^+\nu_\tau$ decay [5].[12] The small samples of $\tau^- \to 3h^-2h^+\nu_\tau$ decays recorded by other experiments prior to this measurement find no disagreement with a phase-space distribution. It is clear from Fig. 1 that a phase-space distribution does not give a good description of the mass of the five tracks. This is not surprising as τ decays with two to four pions in the final state cannot be modeled with a phase-space distribution and one needs to include resonances.

In three-prong τ decays clear evidence could be found for resonant contributions by plotting the mass of $\pi^+\pi^-$ pairs (for example, see Ref. [7]). In Fig. 2 the mass of h^+h^- pair combinations is plotted for all five-prong events in both the electron and muon tag samples. Evidence for the ρ resonance at $0.77\,\mathrm{GeV}/c^2$ in the h^+h^- mass distribution is apparent. The observation of the ρ in $\tau^- \to 3\pi^-2\pi^+\nu_\tau$ decays is not unexpected. There are three allowed isospin states for the $\tau^- \to 3\pi^-2\pi^+\nu_\tau$ decay mode (for example, see Ref. [8]) and two of these isospin states have the same quantum numbers as the ρ resonance.

In summary, the *BABAR* Collaboration has made a preliminary measurement of the $\tau^- \to 3h^-2h^+\nu_\tau$ branching fraction, $B(\tau^- \to 3h^-2h^+\nu_\tau) = (8.52 \pm 0.09 \pm 0.40) \times 10^{-4}$. The invariant mass distribution of h^+h^- pairs suggests that the ρ meson is abundantly produced in the $\tau^- \to 3h^-2h^+\nu_\tau$ decay.

We are grateful for the extraordinary contributions of our PEP-II colleagues in achieving the excellent luminosity and machine conditions that have made this work possible. The success of this project also relies critically on the expertise and dedication of the computing organizations that support *BABAR*. The collaborating institutions wish to thank SLAC for its support and the kind hospitality extended to them. This work is supported by the US Department of Energy and National Science Foundation, the Natural Sciences and Engineering Research Council (Canada), Institute of High Energy Physics (China), the Commissariat à l'Energie Atomique and Institut

[11] All mass distributions shown in this paper are calculated assuming that the particles are pions.

[12] Tauola does not generate any five-prong decays with charged kaons.

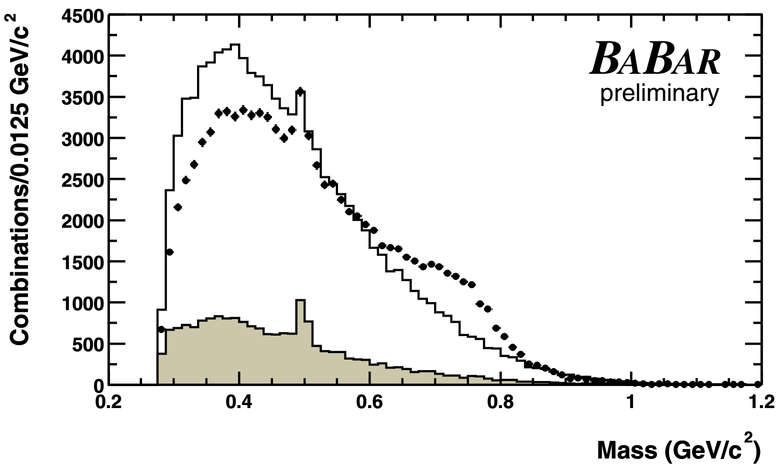

Figure 2: Reconstructed mass of h^+h^- pairs in the five tracks in the signal hemisphere. The data are shown as points with error bars. The unshaded and shaded histograms are the signal and background predicted by the Monte Carlo simulation. The peak at 0.5 GeV/c^2 are K_S^0 mesons which are not rejected by the selection.

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