Study of the $\tau^- \to 3h^- 2h^+ \nu_\tau$ decay

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The branching fraction of the $\tau^- \to 3h^- 2h^+ \nu_\tau$ decay ($h = \pi, K$) is measured with the *BABAR* detector to be $(8.56 \pm 0.05 \pm 0.42) \times 10^{-4}$, where the first error is statistical and the second systematic. The observed structure of this decay is significantly different from the phase space prediction, with the ρ resonance playing a strong role. The decay $\tau^- \to f_1(1285)\pi^- \nu_\tau$, with the $f_1(1285)$ meson decaying to four charged pions, is observed and the branching fraction is measured to be $(3.9 \pm 0.7 \pm 0.5) \times 10^{-4}$.

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The high-statistics sample of τ pair events collected by the *BABAR* Collaboration allows detailed studies of rare decays of the τ lepton. This paper presents a measurement of the $\tau^- \to 3h^- 2h^+ \nu_\tau$ decay ($h = \pi, K$) from a sample of over 34 000 such decays [1]. The large data set allows a first look into the decay mechanism and the search for resonant structure of the $\tau^- \to 3h^- 2h^+ \nu_\tau$ decay mode. The best previous measurement of the $\tau^- \to 3h^- 2h^+ \nu_\tau$ branching fraction is $(7.7 \pm 0.5 \pm 0.9) \times 10^{-4}$, based on 295 events by the CLEO experiment [2].

Tau decays to one and three charged hadrons have been used to test the standard model, measure the masses of the τ^- and ν_τ, study the properties of low-mass resonances, test *CP* violation in the lepton sector, and search for new physics. Moreover, the semileptonic decays of the τ lepton are ideal for studying strong interaction effects (for example, see Ref. [3]) as they probe the matrix element of the left-handed current between the vacuum and the hadronic state [4]. The results presented in this paper suggest that further studies will be possible with $\tau^- \to 3h^- 2h^+ \nu_\tau$ decays.

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 232.1 fb^{-1} recorded at center-of-mass energies ($\sqrt{s}$) of 10.58 GeV and 10.54 GeV between 1999 and 2004. With a luminosity-weighted cross section for τ-pair production of $\sigma_{\tau\tau} = (0.89 \pm 0.02)$ nb [5], this data sample contains approximately 400×10^6 τ decays. Monte Carlo simulation is used to evaluate the background contamination and selection efficiency. The τ pair production is simulated with the KK2f Monte Carlo event generator [5] and the τ decays modeled with Tauola [6] according to measured rates [7].

The *BABAR* detector is described in detail in Ref. [8]. 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 CsI(Tl) crystals is used to measure electromagnetic-shower energies, and an instrumented magnetic flux return (IFR) is used to identify muons.

Since τ pairs are produced back to back in the e^+e^--center-of-mass frame, the event is divided into two hemispheres in the center-of-mass frame based on the plane perpendicular to the thrust axis from the tracks in the event. Each hemisphere is assumed to contain 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). All tracks are taken as pions unless identified as an electron or muon. The total event charge is required to be zero.

Charged particles are required to have momentum greater than 0.1 GeV/c in the plane transverse to the beam axis. The distance of the point of closest approach of the track to the beam axis must be less than 1.5 cm (d_{XY}). In addition, the z coordinate (along the beam axis) of the point of closest approach of the track must be within 10 cm of the z coordinate of the production point.

The background from non-τ sources (in particular, Bhabha scattering and two-photon production) is reduced by requiring the magnitude of the thrust (T) of the event to be between 0.92 and 0.99. The ratio $\mathrm{p_T}/E_{\text{missing}}$ is also used to reduce the background from two-photon production, which tends to have low p_T and high E_{missing}. The p_T is the transverse component of the vector sum of the momenta of all the charged particles in the event and E_{missing} is the missing energy in the event. Events are retained if they satisfy the following criteria:

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

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

Furthermore, 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 and that the momentum of the track in the center-of-mass frame be less than 4 GeV/c. Electrons are identified with the use of the ratio of energy measured by the calorimeter to track momentum (E/p), the ionization loss in the tracking system (dE/dx), and the shape of the shower in the calorimeter. Muons are identified by hits in the IFR and energy deposits in the calorimeter consistent with the minimum energy hypothesis. Residual background from multihadronic events is reduced by requiring that there be at most one electromagnetic calorimeter cluster in the tag hemisphere with energy above 0.05 GeV. Further, the total neutral energy in the tag hemisphere must be less than 1 GeV.

Additional criteria are applied to the five track system in the signal hemisphere to reduce background from photon conversions. The event is rejected if any of the tracks is identified as an electron or if any pair of oppositely charged tracks is consistent with originating from a photon conversion. The invariant mass of the five charged particles is required to be less than 1.8 GeV$/c^2$. All invariant masses shown are calculated assuming that the particles are pions.

It is also required that there be no π^0 candidates in the signal hemisphere. A π^0 candidate consists of two clusters in the electromagnetic calorimeter that are not associated with any track. Each cluster is required to have an energy of at least 0.050 GeV and the two clusters have a combined invariant mass between 0.115 and 0.150 GeV$/c^2$. In addition, any remaining clusters with energy greater than 0.5 GeV that are not associated to a track are considered a π^0 candidate.

A total of 20 920 and 13 929 events are selected when an electron or muon, respectively, are identified in the tag hemisphere.

The selection efficiency is defined as the number of events with a $\tau^- \to 3h^-2h^+\nu_\tau$ decay in signal hemisphere and a tau leptonic decay in the tag hemisphere divided by the number of τ pair events with a $\tau^- \to 3h^-2h^+\nu_\tau$. The branching fraction of the τ leptonic decay mode [7] is incorporated into the selection efficiency. The efficiencies are $(4.71 \pm 0.05)\%$ and $(3.03 \pm 0.04)\%$ in the electron and muon samples, respectively. The efficiencies are obtained from the Monte Carlo simulation and the quoted uncertainty is the Monte Carlo statistical error.

The background in the selected sample comes from other τ decays and multihadronic events. The background percentages in the electron and the muon tag samples estimated from the Monte Carlo simulation are $(20.6 \pm 2.0)\%$ and $(21.7 \pm 2.1)\%$, respectively. The errors are the combined statistical and systematic uncertainties. The sources of background in the electron tag sample can be broken down into the following categories: $\tau^- \to 3h^-2h^+\pi^0\nu_\tau$ decays (7.2%), τ decays with one or three tracks and at least one π^0 (6.3%), τ decays with a K_S^0 (4.9%), multihadronic events (1.8%, primarily $c\bar{c}$ events), and a residual amount from other τ decays (0.5%). Background from Bhabha scattering and two-photon production is negligible. The relative uncertainties range between 15% and 20% for each background and reflect the statistical precision of the data and Monte Carlo samples used to evaluate the backgrounds. The backgrounds in the muon tag sample are very similar.

In order to validate our Monte Carlo simulation for the background contamination we use experimental data samples where the particular background is enhanced. The uncertainty on the $\tau^- \to 3h^-2h^+\pi^0\nu_\tau$ background is estimated to be 20% by comparing the number of π^0 mesons reconstructed in five charged track sample in the data and Monte Carlo simulation. The background from $\tau^- \to h^-(\geq 1\pi^0)\nu_\tau$ and $\tau^- \to h^-h^-h^+(\geq 1\pi^0)\nu_\tau$ arises when one or both of the photons from the decay of a π^0 converts to an e^+e^- pair or from a $\pi^0 \to e^+e^-\gamma$ decay. The uncertainty on this background is estimated to be 15% from the number of conversions and number of tracks identified as electrons.

Background can also arise from $\tau^- \to \pi^- K_S^0 K_S^0 \nu_\tau$ and $\tau^- \to h^-h^-h^+K_S^0\nu_\tau$ decays, both of which have been observed by other experiments [7]. The background from these decays is determined by fitting the mass distribution of $\pi^+\pi^-$ pairs to obtain an estimate of the number of K_S^0 mesons. The background estimation uses the Monte Carlo prediction for the $\tau^- \to \pi^- K_S^0 K_S^0 \nu_\tau$ decay modes. The $\tau^- \to h^-h^-h^+K_S^0\nu_\tau$ decay mode is not simulated and the background is assumed to be the excess of K_S^0 mesons in the data over the Monte Carlo prediction. The uncertainty in the background from τ decays with K_S^0 mesons was found to be approximately 20% and includes contributions from the statistical uncertainties of the fits to the mass distribution of $\pi^+\pi^-$ pairs and the branching ratios of the background decay modes. In addition, checks were made to ensure that the K_S^0 background was from τ decays and not multihadronic events.

The background from multihadronic events was estimated from the number of events for which the reconstructed mass of the five tracks is above the τ mass, and also from the number of events with more than one electromagnetic cluster in the tag hemisphere. The uncertainty in the multihadronic background is estimated to be 20%.

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

The branching fraction of the $\tau^- \to 3h^-2h^+\nu_\tau$ decay is found to be $(8.53 \pm 0.06 \pm 0.42) \times 10^{-4}$ and $(8.73 \pm 0.07 \pm 0.48) \times 10^{-4}$ for the data selected by the electron and muon tags, respectively. The first uncertainty is the statistical error and the second systematic. The average branching fraction is $(8.56 \pm 0.05 \pm 0.42) \times 10^{-4}$ where the correlation between the systematic errors in the electron and muon tag results is taken into account. Our value of the branching fraction is in good agreement with the Particle Data Group fit value of $(8.2 \pm 0.6) \times 10^{-4}$ [7].

The systematic error includes contributions from the efficiency for reconstructing the six tracks in the event (3.1%), the background in the sample (2.4%), the luminosity and $\tau^+\tau^-$cross section (2.3%), the π^0 finding algorithm (2.0%), and the lepton identification in the tag hemisphere (1.0% for electrons and 2.5% for muons).

The error on the efficiency for reconstructing a track is estimated to be 1.2% for tracks with $p_T < 0.3$ GeV$/c$ and 0.5% for tracks with $p_T > 0.3$ 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 an independent analysis of τ decays into three charged particles and a neutrino. Variation of 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 d_{XY} of the five tracks resulted in a negligible change in the branching fraction.

Variation of the selection criteria produced consistent results for the branching fraction. In addition, the selection efficiency was found to have no dependence on the reconstructed mass of the five tracks.

In Fig. 1, the distribution of the invariant mass of the five charged particles in the signal hemisphere is presented. The discrepancy between Tauola, which uses a phase space distribution for $\tau^- \to 3\pi^- 2\pi^+ \nu_\tau$ [6], and the data is believed to be due to resonant contributions in the $\tau^- \to 3\pi^- 2\pi^+ \nu_\tau$ decay mode. There are three allowed isospin states for this decay mode (see Ref. [9]) and two of these isospin states have particles with quantum numbers of the ρ meson. Figure 2 shows the mass of h^+h^- pair combinations where the shoulder at 0.77 GeV$/c^2$ suggests a strong contribution from the ρ resonance.

No attempt was made to extract the fraction of ρ mesons as no model for resonant structure of the $\tau^- \to 3h^- 2h^+ \nu_\tau$ decay exists. Such a model would need to include the three allowed isospin states and the admixture of the isospin states could be extracted from this data sample as it was done for $\tau^- \to h^- h^- h^+ \nu_\tau$ [10].

The data sample can also be used to study the $\tau^- \to f_1(1285)\pi^- \nu_\tau$ decay, where the $f_1(1285)$ decays into a $2\pi^- 2\pi^+$ final state. In Fig. 3, the invariant mass of the $2h^+ 2h^-$ particle system is plotted for data. The fit to the data uses a second-order polynomial distribution for the background and a Breit-Wigner for the peak region. The Breit-Wigner is convoluted with a Gaussian distribution with a standard deviation corresponding to the expected mass resolution. The background distribution was determined by fitting the region between 1.1 and 1.4 GeV$/c^2$ excluding the $f_1(1285)$ peak (1.25-1.31 GeV$/c^2$).

A total of 1369 ± 232 $\tau^- \to f_1(1285)\pi^- \nu_\tau$ decays are obtained from the fit. The fraction of $\tau^- \to f_1(1285)\pi^- \nu_\tau$ decays found in the $\tau^- \to 3h^- 2h^+ \nu_\tau$ sample is measured to be $(0.050 \pm 0.008 \pm 0.005)$ and the branching fraction of the $\tau^- \to f_1(1285)\pi^- \nu_\tau$ decay is calculated to be $(3.9 \pm 0.7 \pm 0.5) \times 10^{-4}$. The branching fraction for the $f_1(1285) \to 2\pi^- 2\pi^+$ decay used to calculate the $\tau^- \to f_1(1285)\pi^- \nu_\tau$ branching fraction is taken from the Particle Data Group [7]. The first errors are the statistical

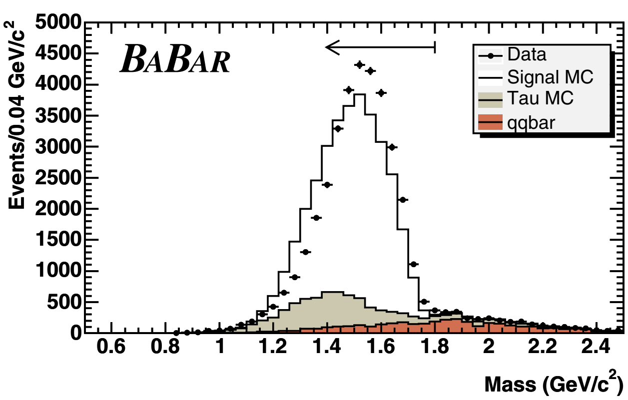

FIG. 1 (color online). Invariant mass of the five charged particles in the signal hemisphere after all other selection criteria (except the mass requirement) are applied. The points are the data and the histogram is the Monte Carlo simulation for both the electron and muon tag samples. The unshaded and two shaded histograms are the signal, tau, and multihadronic background events, respectively. The arrow indicates the selection requirement applied to the samples. The Monte Carlo sample is normalized to the luminosity of the data sample.

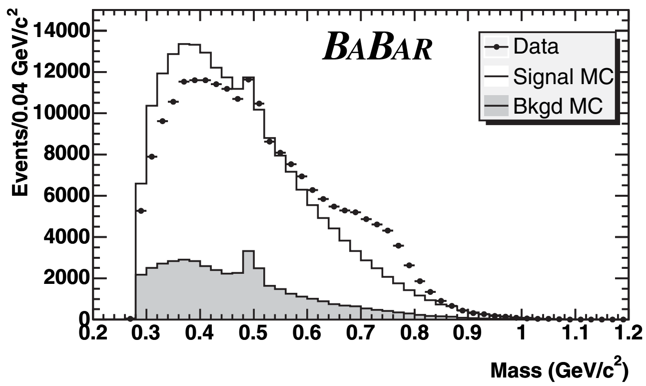

FIG. 2. Reconstructed mass of h^+h^- pairs in the five tracks in the signal hemisphere. The data are shown as points with error bars. The unshaded and shaded histograms are the signal and background predicted by the Monte Carlo simulation. The peak at 0.5 GeV$/c^2$ is due to K^0_S mesons that are not rejected by the selection. There are six entries per event.

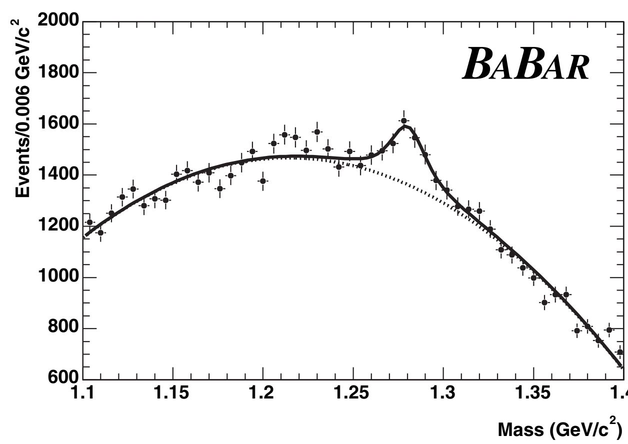

FIG. 3. Reconstructed mass of the $2h^+2h^-$ combinations in the signal hemisphere. The solid line is a fit to the data using a second-order polynomial distribution (dashed line) for the background and a Breit-Wigner convoluted by a Gaussian for the peak region. The data are shown as points with error bars. There are three entries per event.

uncertainties obtained from the fit and the second errors are the systematic uncertainties. The systematic uncertainties include a contribution from the fit (10%) estimated by studying the results of fits using different mass bins, background functions, and detector resolutions. The systematic error on the branching fraction also includes the uncertainty on the branching fractions of the $\tau^- \to 3h^-2h^+\nu_\tau$ (5%) and the $f_1(1285) \to 2\pi^-2\pi^+$ decay modes (6%).

Checks confirmed that the $f_1(1285)$ signal did not arise from multihadronic events. This was done by relaxing the selection criteria in a way which increased the multihadronic background and confirming that the $f_1(1285)$ signal did not increase. In addition, the observation of the $\tau^- \to f_1(1285)\pi^-\nu_\tau$ decay was confirmed by looking at a data sample with a hadron tag.

Our value of the $\tau^- \to f_1(1285)\pi^-\nu_\tau$ branching fraction is in agreement with the result obtained by the CLEO Collaboration, $(5.8 \pm 2.3) \times 10^{-4}$, obtained using the $f_1(1285) \to \eta\pi\pi$ decay mode [11]. It is also consistent with a theoretical prediction of 2.91×10^{-4} [12].

In summary, the *BABAR* Collaboration has measured the $\tau^- \to 3h^-2h^+\nu_\tau$ branching fraction, $B(\tau^- \to 3h^-2h^+\nu_\tau) = (8.56 \pm 0.05 \pm 0.42) \times 10^{-4}$. The mass of the five charged hadron system is not well described by a phase space model. The invariant mass distribution of h^+h^- pairs shows that the ρ meson is produced in the $\tau^- \to 3h^-2h^+\nu_\tau$ decay. The decay $\tau^- \to f_1(1285)\pi^-\nu_\tau$ is confirmed in the $f_1(1285) \to 2\pi^-2\pi^+$ channel and the branching fraction measured is $B(\tau^- \to f_1(1285)\pi^-\nu_\tau) = (3.9 \pm 0.7 \pm 0.5) \times 10^{-4}$.

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[1] 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_S^0 decay.
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