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Study of the $\tau^- \to \pi^-\pi^-\pi^+\pi^0\pi^0\nu_\tau$ and $\tau^- \to 3h^-2h^+\nu_\tau$ decays using the BABAR Detector

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The $\tau^- \to \pi^-\pi^-\pi^+\pi^0\pi^0\nu_\tau$ and $\tau^- \to 3h^-2h^+\nu_\tau$ decays have been studied using the BABAR experiment at the PEP-II e$^+$e$^-$ storage ring. Preliminary branching fractions are given for the $\tau^- \to \pi^-\pi^-\pi^+\pi^0\pi^0\nu_\tau$ and to the sub-channels $\tau^- \to \eta\pi^-\pi^0\nu_\tau$ and $\tau^- \to \omega(782)\pi^-\pi^0\nu_\tau$. A preliminary upper limit is given on the branching fraction for the $\phi(1020)\pi^-\pi^0\nu_\tau$ mode. In addition a preliminary measurement of the branching fraction of the $\tau^- \to 3h^-2h^+\nu_\tau$ decay ($h = \pi, K$) is presented.

1. Introduction

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^-. Most of these studies have involved the decay of the τ to low multiplicity decays. This work presents a preliminary study of the decays of τ^- lepton to $\tau^- \to \pi^-\pi^-\pi^+\pi^0\pi^0\nu_\tau$ and $\tau^- \to 3h^-2h^+\nu_\tau$ using the BABAR detector [2].

This analysis is based on data recorded at the PEP-II asymmetric-energy e^+e^- storage ring operated at the Stanford Linear Accelerator Center. The data sample used in these analyses consist of 110-124 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 [3], 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 [3] and the τ decays are modeled with Tauola [4] according to measured rates [5].

2. Data selection

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 based on the plane perpendicular to the thrust axis, each containing the decay products of a single τ lepton. The analysis procedure selects events with one track in one hemisphere (tag hemisphere) and three or five tracks in the other hemisphere (signal hemisphere).

The 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 with the momentum required to be less than approximately 4 GeV/c^2. Background from non-τ^- events was further reduced in both selection by requirements on the magnitude of the thrust in the event (typically the thrust is required to be greater than 0.92).

2.1. $\tau^- \to \pi^-\pi^-\pi^+\pi^0\pi^0\nu_\tau$ selection

In the $\tau^- \to \pi^-\pi^-\pi^+\pi^0\pi^0\nu_\tau$ selection events were selected with a 1–3 charged-track topology and overall charge balance. To improve resolution, the three signal-side tracks were fitted to a common vertex.

Pairs of energy deposits in the electromagnetic calorimeter of more than 50 MeV which were not associated with any charged particle candidates were used to form π^0 mesons. Additional quality

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cuts were applied to the energy deposits to reject fake neutral candidates. The π^0 mesons were required to have mass in the range from $100\,\mathrm{MeV}/c^2$ to $160\,\mathrm{MeV}/c^2$ and to have energy greater than 215 MeV. These were fitted to the 3-prong vertex with a π^0 mass constraint and kept if the χ^2 of the fit was satisfactory. In cases where two or more π^0 mesons shared energy clusters, the candidate with the lowest value of χ^2 was retained. Events were required to have exactly two π^0 candidates in the 3-prong hemisphere.

To reduce further any remaining backgrounds from $q\bar{q}$ events, the events were required to have observable missing CM energy. Finally particle identification was imposed on the three candidate tracks in the signal hemisphere, requiring them to pass loose selection criteria for pion identification.

2.2. $\tau^- \to 3h^-2h^+\nu_\tau$ selection

The $\tau^- \to 3h^-2h^+\nu_\tau$ decays were selected with a 1-5 charged-track topology. The event was rejected if any of the tracks in the signal hemisphere are identified as an electron or if any pair of oppositely charged tracks was consistent with originating from a photon conversion. The reconstructed mass of the five tracks was 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 GeV and they are not associated with any tracks.

3. Results

3.1. $\tau^- \to \pi^-\pi^-\pi^+\pi^0\pi^0\nu_\tau$

After all cuts and selections, a total of 10600 lepton-tagged events remained, 9900 of which had 5π mass below the τ mass. In this sample, 61 % of events are electron-tagged and 39 % are muon-tagged. The signal purity of the final sample of candidate events was determined in the Monte Carlo to be 82 % in the electron-tagged sample and 83 % in the muon-tagged sample. Some 85 % of the background comes from non-signal τ de-

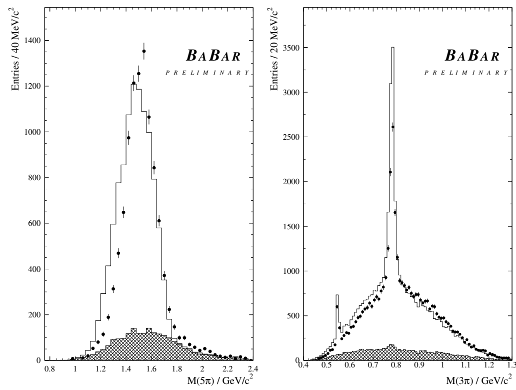

Figure 1. The right figure shows 5π mass spectrum of selected lepton-tagged events with Monte Carlo contributions normalised to the luminosity of the data. The left figure shows 3π mass spectrum for all $\pi^+\pi^-\pi^0$ combinations in the selected lepton-tagged 5π events.

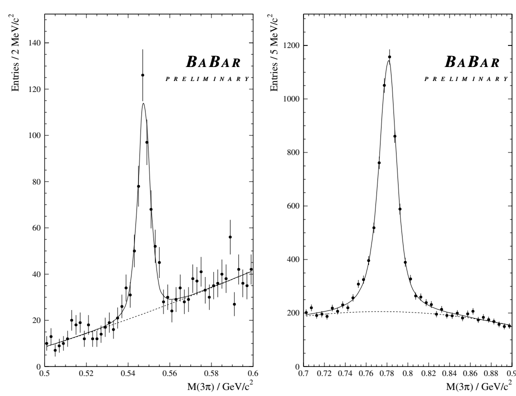

Figure 2. The 3π mass spectra in the η (left), and ω (right) mass regions. The points show the data, the solid lines show the signal+background fits, and the dotted lines show the fitted background only.

cays, mostly decays to three charged pions and either one or three neutral pions. The rest arises from $q\bar{q}$ events. The overall event selection efficiency was found to be 0.65 % for the electron-tagged sample. Comparisons of generator-level Monte Carlo event samples with the final selected samples after full detector simulation and analysis showed that the detection efficiency does not vary significantly with any important physical variables such as the 5π mass, the decay angular distributions or the $\pi^+\pi^-\pi^0$ Dalitz plot variables.

The 5π mass spectra is shown in Fig. 1 after all event selection cuts for the lepton-tagged sample. The preliminary result for the $\tau^- \to \pi^-\pi^-\pi^+\pi^0\pi^0\nu_\tau$ branching fraction is $(4.51 \pm 0.07 \pm 0.56) \times 10^{-3}$. The 12% systematic error in the $\tau^- \to \pi^-\pi^-\pi^+\pi^0\pi^0\nu_\tau$ branching fraction is dominated by the background estimate (9.3%), the efficiency for selecting π^0 (6.5%) and the efficiency for selecting charge pions (3.0%). This result is to be compared with previous measurements of $(4.8 \pm 0.4 \pm 0.4) \times 10^{-3}$ (CLEO [7]) and $(5.0 \pm 0.7 \pm 0.7) \times 10^{-3}$ (ALEPH [8]).

The mass spectrum for all four $\pi^+\pi^-\pi^0$ combinations from the selected events[1] is shown in Fig. 1. There are clear signals from the η and $\omega(782)$ mesons but no evidence for a signal from the $\phi(1020)$ meson. Fig. 1 shows that the Monte Carlo simulates well the intensity of the η peak while overestimating the contribution from the $\omega(782)$. The general shape of the combinatorial mass spectrum tends to lower masses in the Monte Carlo than in the data.

To obtain rates for each of the η and ω subchannels, separate fits to signal plus polynomial backgrounds are made to the $\pi^+\pi^-\pi^0$ mass spectra in the data, the combined Monte Carlo background, and the Monte Carlo signal samples. The expected shapes of the meson peaks are determined by convoluting Breit Wigner line shapes with mass resolution functions obtained from the Monte Carlo[2]. In the fits to the η and ω signals in the data, the peak masses and normalisations are allowed to vary, but the shapes are fixed (see Fig. 2). In fitting to obtain a limit on the ϕ rate, the mass is fixed to the Particle Data Group (PDG) value [5], corrected by a small mass offset found in both the η and ω fits to the data. Contributions to the systematic errors from uncertainties in the meson widths are determined by varying these widths by their PDG uncertainties, refolding with detector resolution to make new shape functions and then refitting to the mass spectra.

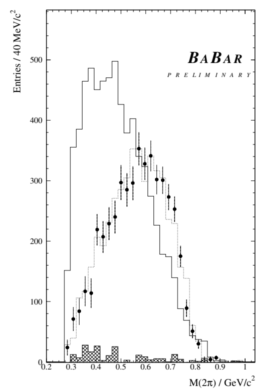

Figure 3. The $\pi^-\pi^0$ mass spectra for lepton-tagged events for the $\pi^-\pi^0$ system recoiling against the ω meson. The plot shows the peak-minus-background data spectrum (points), the ω-weighted data spectrum (dotted histogram), the peak-minus-background total Monte Carlo spectrum (solid histogram) and the non-signal background Monte Carlo spectrum (hatched histogram).

The preliminary results for the measurements of the branching fractions are: $B(\tau^- \to \eta\pi^-\pi^0\nu_\tau) = (1.71 \pm 0.12 \pm 0.16) \times 10^{-3}$ and $B(\tau^- \to \omega\pi^-\pi^0\nu_\tau) = (3.66 \pm 0.10 \pm 0.31) \times 10^{-3}$. The systematic errors are dominated by the efficiency for finding π^0 and charged pions as well as contributions from Monte Carlo statistics, tracking efficiencies, background and luminosity. The branching fraction measurements are to be compared with the current PDG values [5] of $(1.74 \pm 0.24) \times 10^{-3}$ for $\eta\pi^-\pi^0\nu_\tau$ and $(4.4 \pm 0.5) \times 10^{-3}$

[1] The 5π events used are required to have a reconstructed 5π mass below the τ mass.

[2] The root-mean-square deviation values for the mass resolutions are 5.7 MeV/c^2 for the η, 8.7 MeV/c^2 for the ω and 11.3 MeV/c^2 for the ϕ.

for $\omega\pi^-\pi^0\nu_\tau$.

A similar fit has been made to obtain a limit on the rate for production of the $\phi(1020)$ meson. The dominant systematic error on the ϕ measurement comes from a 46 % contribution from the uncertainty in the rate of ϕ meson production attributable to the non-tau background. The result of the fit was used to obtain a preliminary limit of $B(\tau^- \to \phi\pi^-\pi^0\nu_\tau) < 4.5 \times 10^{-4}$ at the 90 % confidence-level.

The mass spectrum of the $\pi^-\pi^0$ recoiling against the ω has also been studied. This has been reconstructed using a peak-minus-sidebands method. A peak region is defined about the ω mass, and sidebands, each one-half the width of the peak region, are defined above and below this region. As an alternative, events with entries in the ω peak region have been assigned weights according to the expected Dalitz plot distribution for the ω decay, in such a way that signal contributions would contribute an average weight of one per event and non-ω, phase-space-like, events would contribute zero. Figure 3 shows the $\pi^-\pi^0$ mass spectra obtained from the selected lepton-tagged data events for both peak-minus-background selection and for ω-weighting; there is very good agreement between the two methods. The $\pi^-\pi^0$ spectrum is also shown in this figure for Monte Carlo events using the peak-minus-background method. It is clear that the $\pi^-\pi^0$ spectrum from the `Tauola` Monte Carlo peaks at a much lower mass than the data.

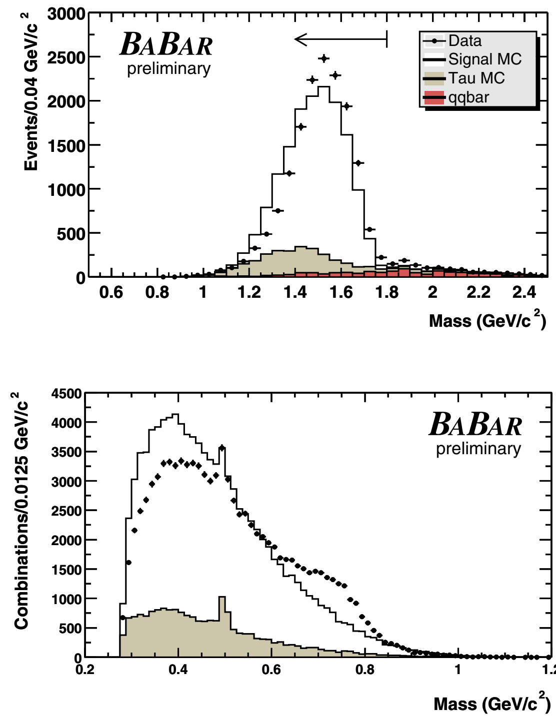

Figure 4. Reconstructed mass of the five tracks in the signal hemisphere (top figure) after all other selection criteria are applied. Reconstructed mass of h^+h^- pairs in the five tracks in the signal hemisphere (bottom figure). The peak at 0.5 GeV/c^2 are K^0_S mesons which are not rejected by the selection. The Monte Carlo simulation is normalized to the luminosity of the data sample.

3.2. $\tau^- \to 3h^-2h^+\nu_\tau$

A total of 9668 and 6201 $\tau^- \to 3h^-2h^+\nu_\tau$ 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 identically 0.210 ± 0.016. 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.

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 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 $c\overline{c}$ 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 branching fraction of the $\tau^- \to 3h^-2h^+\nu_\tau$ decay is found to be $(8.52\pm0.09\pm0.40)\times10^{-4}$ 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.

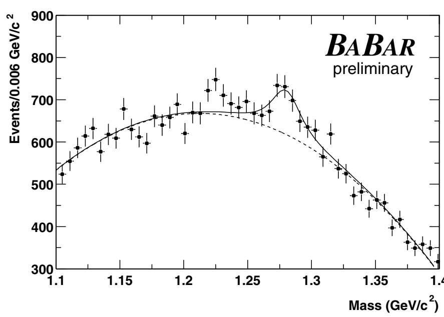

Figure 5. Reconstructed mass of the $2h^+2h^-$ combinations in the signal hemisphere. The solid line is a fit to the data using a second-order polynomial distribution (dashed-line) for the background and a Breit-Wigner convoluted by a Gaussian for the peak region.

In the upper plot of Fig. 4, the mass of the five tracks in the signal hemisphere is presented while the lower plot shows the mass of all h^+h^- pair combinations. Both mass distributions are calculated assuming that the particles are pions. Tauola uses a phase space distribution for the $\tau^- \to 3\pi^-2\pi^+\nu_\tau$ decay [4]. 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. 4 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.

The h^+h^- mass distribution shows 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. [9]) and two of these isospin states have particles whose quantum numbers are the same as the ρ resonance.

The $\tau^- \to 3h^-2h^+\nu_\tau$ decay can also be used to study the $\tau^- \to f_1(1285)\pi^-\nu_\tau$ decay via the $f_1(1285) \to 2\pi^-2\pi^+$ mode. The CLEO Collaboration has observed the $\tau^- \to f_1(1285)\pi^-\nu_\tau$ via the $f_1(1285) \to \eta\pi\pi$ decay mode in one- and three-prong τ decays [10]. The dominant decay modes of the $f_1(1285)$ meson are the $\eta\pi\pi$ mode (52%) and the 4π mode (33% with 11% decaying to $2\pi^+2\pi^-$) [5].

In Fig. 5, the invariant mass of the 4 particle state ($2h^+2h^-$) is plotted for data in both the electron and muon tag samples. The fit to the data uses a second-order polymonial 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 of 4 MeV/c^2 corresponding to the expected mass resolution for a four-particle state. The background distribution was determined by fitting the region outside of the $f_1(1285)$ peak (1.25-1.31 GeV/c^2). The parameters of the background distribution were allowed to vary by 5%, and the mass and width of the peak were constrained to within three standard deviation of the Particle Data Group values [5].

A total of 745 ± 185 $\tau^- \to f_1(1285)\pi^-\nu_\tau$ decays are obtained from the fit. The fraction of 745 ± 185 decays found in the $\tau^- \to 3h^-2h^+\nu_\tau$ sample is measured to be $(0.059 \pm 0.015 \pm 0.006)$ where the first error is the statistical uncertainty obtained from the fit and the second error is the systematic uncertainty. The branching fraction of the $\tau^- \to f_1(1285)\pi^-\nu_\tau$ decay is calculated to be $(4.6 \pm 1.2 \pm 0.7) \times 10^{-4}$. The systematic uncertainty is dominated by the errors on fit procedure (10%), the branching fraction of the $\tau^- \to 3h^-2h^+\nu_\tau$ (5%) and the $f_1(1285) \to 2\pi^-2\pi^+$ decay modes (6%). The result of the fit was studied with different mass bins, background functions and detector resolutions. Checks were made to ensure that the $f_1(1285)$ signal could not arise from multihadronic events.

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

4. Summary

In summary, the *BABAR* Collaboration has made a preliminary measurements of the following τ^- branching fractions:

$\tau^- \to \pi^-\pi^-\pi^+\pi^0\pi^0\nu_\tau$	$(4.51 \pm 0.07 \pm 0.56) \times 10^{-3}$
$\tau^- \to \eta\pi^-\pi^0\nu_\tau$	$(1.71 \pm 0.12 \pm 0.16) \times 10^{-3}$
$\tau^- \to \omega\pi^-\pi^0\nu_\tau$	$(3.66 \pm 0.10 \pm 0.31) \times 10^{-3}$
$\tau^- \to \phi\pi^-\pi^0\nu_\tau$	$< 4.5 \times 10^{-4}$ at 90 % CL
$\tau^- \to 3h^-2h^+\nu_\tau$	$(8.52 \pm 0.09 \pm 0.40) \times 10^{-4}$
$\tau^- \to f_1(1285)\pi^-\nu_\tau$	$(4.6 \pm 1.2 \pm 0.7) \times 10^{-4}$.

The large τ^- data sets have made it possible to make detailed comparisons of the observed mass distributions with the Tauola generator. The results presented show that the current modeling is inadequate.

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