# Measurement of $\tau$ Decays Involving $\eta$ Mesons

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The decay $\tau^- \to \nu_\tau \pi^- \pi^0 \eta$ has been observed for the first time using the CLEO-II detector at the Cornell Electron Storage Ring. The measured branching ratio $(0.17 \pm 0.02 \pm 0.02)\%$, agrees with the CVC (conserved vector current) prediction based on $e^+e^- \to \pi^+\pi^-\eta$ data. Upper limits on the branching ratios for other $\tau$ decays to final states including $\eta$ mesons are improved by an order of magnitude compared to previous measurements.

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Although branching ratios for $\tau$ decay to multipion final states are large [1], decays involving the $\eta$ meson have not yet been observed. Since these decays violate $G$ parity in the standard vector current process, they would be expected to be quite small. However, following Wess and Zumino [2], one can construct an effective Lagrangian involving three meson currents, the so-called chiral anomaly term. This changes the parity of the three-meson final state, permitting decays with an $\eta$ and at least two other mesons in the final state without isospin suppression. Among such decays, the decay $\tau^- \to \nu_\tau \pi^- \pi^0 \eta$ is expected to dominate [3]; using the CVC (conserved vector current) hypothesis and measurements of $\sigma(e^+e^- \to \pi^+\pi^-\eta)$ for $\sqrt{s} < m_\tau$ [4], one predicts $B(\tau^- \to \nu_\tau \pi^- \pi^0 \eta) = (0.13 \pm 0.02)\%$. Effective Lagrangian calculations [5,6] are consistent with this CVC prediction but have large uncertainties. The decay $\tau^- \to \nu_\tau \pi^- \eta$, with only two mesons, cannot proceed through the Wess-Zumino term; it violates isospin conservation [7] and is predicted [6] to have $B(\tau^- \to \nu_\tau \pi^- \eta) \approx 1.5 \times 10^{-5}$. $G$ parity is not relevant to the decay $\tau^- \to \nu_\tau K^- \eta$, but it is Cabibbo and phase-space suppressed, with a predicted branching ratio [8] of $(1.2\text{–}1.6) \times 10^{-4}$. All other $\tau$ decays involving $\eta$ mesons are severely phase-space suppressed and are expected [6] to occur with branching ratios $\sim 10^{-6}$ or less.

We have searched for $\tau$ decays involving $\eta$ mesons using the CLEO-II detector at the Cornell Electron Storage Ring (CESR). The data sample used in this analysis was collected on and near the $\Upsilon(4S)$ resonance ($\sqrt{s} \approx 10.6$ GeV); the integrated luminosity is $\mathcal{L} = 893 \pm 14$ pb$^{-1}$, corresponding to $8 \times 10^5$ produced $e^+e^- \to \tau^+\tau^-$ events. CLEO-II is a general purpose magnetic detector which is described in detail elsewhere [9]. An electromagnetic calorimeter consisting of 7800 CsI(Tl) crystals detects photons with high efficiency and excellent energy and angular resolution which are crucial for $\eta$ reconstruction.

We select $\tau^+\tau^-$ pairs in the 1-1 and 1-3 charged track topologies with zero total charge. Tracks on the 1-prong side must be separated from all other tracks by at least 90° (120°) for the 1-1 (1-3) samples. To suppress $e^+e^- \to e^+e^-(\gamma)$ and $e^+e^- \to \mu^+\mu^-(\gamma)$ events, no track is allowed to have momentum above 85% of the beam energy. Backgrounds from $e^+e^- \to e^+e^- X$ (two-photon) and $e^+e^- \to q\bar{q}$ (hadronic) interactions are reduced by requiring the missing mass [10] to be between 0.5 and 6.5 GeV/$c^2$. We define two partially overlapping hemispheres by the direction of the single prong(s) and the vector sum of the 3-prong tracks. Neutral energy is uniquely associated with a hemisphere by rejecting events for which neutral clusters, defined as localized calorimeter deposits with energy above 60 MeV, lie within or outside both hemispheres. The invariant mass of all charged tracks and neutral clusters in each hemisphere must be less than the $\tau$ mass.

We reconstruct $\eta$ mesons using the three dominant $\eta$ decay modes: $\gamma\gamma$, $\pi^+\pi^-\pi^0$, and $3\pi^0$. For $\pi^0$ reconstruction, we use two neutral clusters which have an invariant mass $m_{\pi^0} - 3.5\sigma_{\pi^0} < m_{\gamma\gamma} < m_{\pi^0} + 2.5\sigma_{\pi^0}$, where the asymmetric cuts account for the low mass tail in $m_{\gamma\gamma}$ [9] and $\sigma_{\pi^0}$ is the $\pi^0$ mass resolution calculated from the vector momenta of the two photons. Reconstruction of $\eta \to \gamma\gamma$ is similar but uses only clusters with energy above 100 MeV and within $3\sigma_\eta$ of $m_\eta - 0.5\sigma_\eta$. To improve the $\eta$ mass resolution, $\pi^0$'s used in reconstruction of $\eta$ mesons are constrained to the nominal $\pi^0$ mass. For most searches, both $\pi^0$ and $\eta$ reconstruction use only clusters with $|\cos\theta_\gamma| < 0.85$, where $\theta_\gamma$ is the angle of the neutral cluster with respect to the beam axis. We select events with reconstructed $\eta$ mesons in a "signal" hemisphere and no other neutral clusters in this hemisphere which are "unassociated" with $\pi^0$ or other $\eta$ candidates. The other "tagging" hemisphere has requirements of varying strictness depending on the background level for each search decay mode. A "loose" tag has no further requirements on the number of charged tracks or neutral clusters. A "generic 1-prong" tag requires a single charged track, no more than two $\pi^0$'s, and no unassociated neutral clusters. A "lepton" tag requires an identified electron or muon with no unassociated neutral clusters. Electrons are identified by selecting charged particles with energy deposition in the calorimeter within 10% of the momentum; muons are identified by selecting tracks which project to hits in the portion of the muon detectors located behind three or more absorption lengths of iron.

We now describe in turn the searches for six $\tau$ decay modes. We find evidence for the dominant decay $\tau^- \to \nu_\tau \pi^- \pi^0 \eta$ in all three $\eta$ decay modes using the generic 1-prong tag. For the $\gamma\gamma$ channel there are four photons in the signal hemisphere. In Fig. 1 $(m_{\gamma\gamma} - m_{\pi^0})/\sigma_{\pi^0}$ is plotted versus $(m_{\gamma\gamma} - m_\eta)/\sigma_\eta$, where the lower and

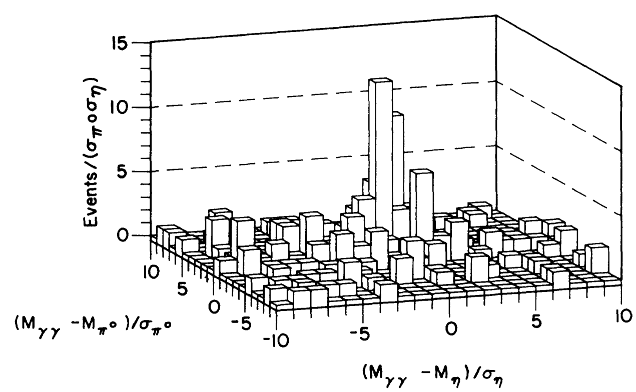


FIG. 1. Distribution of invariant mass of lower mass $\gamma\gamma$ pair vs invariant mass of the other $\gamma\gamma$ pair in 1-prong $\tau$ decays. Masses are expressed in standard deviations from the nominal $\pi^0$ and $\eta$ masses. The average $\pi^0$ ($\eta$) rms mass resolution is 6 (12) MeV/$c^2$.

higher $m_{\gamma\gamma}$ values are used for the three $\eta\pi^0$ candidate combinations for each event. A two-dimensional fit to this distribution yields $77 \pm 12$ signal events. For $\eta \to \pi^+\pi^-\pi^0$, we remove the $\cos\theta_\gamma$ requirement and cut on the invariant mass of one $\gamma\gamma$ combination to identify the $\pi^0$. The $\pi^+\pi^-\pi^0$ invariant mass is plotted versus the invariant mass of the other $\gamma\gamma$ combination for all $\pi^+\pi^-\pi^0$ combinations. A two-dimensional fit to this distribution yields $29 \pm 9$ events. The projection onto the $m_{\pi^+\pi^-\pi^0}$ axis is shown in Fig. 2(a). For the $\eta \to \pi^0\pi^0\pi^0$ decay, we relax the neutral energy cut to 30 MeV and find the combination of eight photons into four $\pi^0$'s which minimizes $\chi^2 \equiv \sum_{i=1}^{i=4}[(m_{\gamma\gamma i} - m_{\pi^0})/\sigma_{\pi^0_i}]^2$. According to the Monte Carlo simulation, a correct pairing of photons is achieved in about 90% of all events. In Fig. 2(b) we plot $m_{\pi^0\pi^0\pi^0}$ for each of the four combinations for each event. From a fit by a Gaussian signal and polynomial background shape, we find a signal of $19 \pm 6$ events. This is the first observation of the decay $\tau^- \to \nu_\tau \pi^- 4\pi^0$. The average efficiency for reconstruction of $\tau^- \to \nu_\tau \pi^- \pi^0 \eta$ events for the three $\eta$ decay modes is found from Monte Carlo simulation [11] to be 0.10, 0.06, and 0.02, respectively [12]. The branching ratio obtained from all three $\eta$ decay modes is [13] $B(\tau^- \to \nu_\tau \pi^- \pi^0 \eta) = (0.17 \pm 0.02 \pm 0.20)\%$. The first error is statistical and the second error is systematic (see discussion below). We have checked that all of the charged pions accompanying the $\eta$ meson are indeed consistent with the ionization for pions. This branching ratio is in good agreement with the CVC prediction, $(0.13 \pm 0.02)\%$. With this data sample, the invariant mass distribution of the $\pi^-\pi^0\eta$ system, shown in Fig. 3, is not distinguishable from phase space alone.

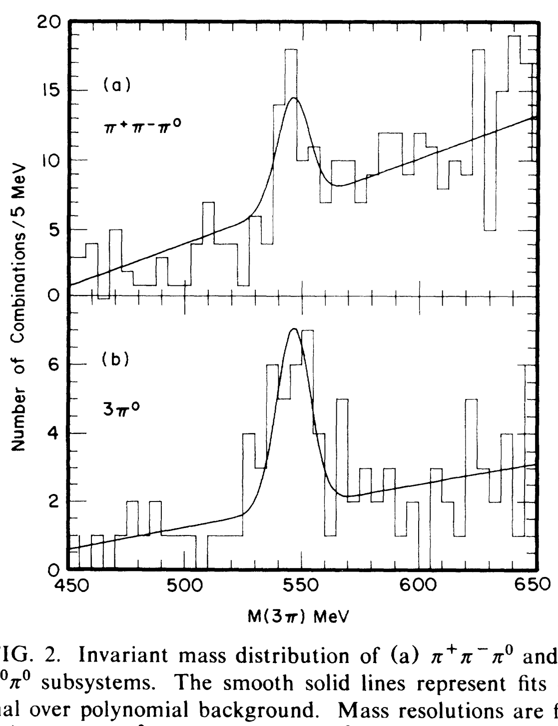


FIG. 2. Invariant mass distribution of (a) $\pi^+\pi^-\pi^0$ and (b) $\pi^0\pi^0\pi^0$ subsystems. The smooth solid lines represent fits of $\eta$ signal over polynomial background. Mass resolutions are fixed at (a) 6.9 MeV/$c^2$ and (b) 7.3 MeV/$c^2$.

The dominant non-$\tau$ sources of $\eta$'s are expected to be from two-photon and hadronic production. The former is estimated to be negligible by relaxing the missing mass requirement and looking at the distribution of transverse momentum, which is very peaked for two-photon background. We estimate a hadronic background of $(1 \pm 7)\%$ from the lack of events in the $\pi^-\pi^0\eta$ invariant mass distribution (Fig. 3) with $m > m_\tau$. The fraction of hadronic background with $m < m_\tau$ is estimated from a loose tag sample with a requirement of $m > m_\tau$ on the *tag* side. We also consider four tag subsamples of the data: identified electron ($e$), identified muon ($\mu$), unidentified charged track and no neutrals ($\pi$), and charged track and single $\pi^0(\rho)$. Monte Carlo simulation indicates that non-$\tau$ background in the leptonic-tag subsamples is negligible. The branching ratios measured for these four subsamples are $(0.22 \pm 0.05)\%$, $(0.14 \pm 0.04)\%$, $(0.15 \pm 0.04)\%$, and $(0.18 \pm 0.05)\%$, respectively (statistical errors only). We conclude that there is no evidence for significant non-$\tau$ backgrounds in our sample.

To estimate systematic effects in the efficiency calculation, we have varied the selection criteria and the parameters in the Monte Carlo simulation. We also divide our event sample according to the $\eta$ decay modes used since their efficiencies vary by a factor of 5. For $\eta$ decays to $\gamma\gamma$, $\pi^+\pi^-\pi^0$, and $\pi^0\pi^0\pi^0$, we find $B(\tau^- \to \nu_\tau \pi^- \pi^0 \eta) = (0.16 \pm 0.02)\%$, $(0.16 \pm 0.05)\%$, and $(0.23 \pm 0.08)\%$, respectively (statistical errors only). An additional tagging efficiency uncertainty, arising from uncertainty in the $\tau$ branching ratios, is estimated conservatively from Ref. [1]. To estimate systematic errors due to the signal fit procedure, we have varied the fitting procedure and parameters of the fit.

A total systematic error of 14% is calculated by sum-

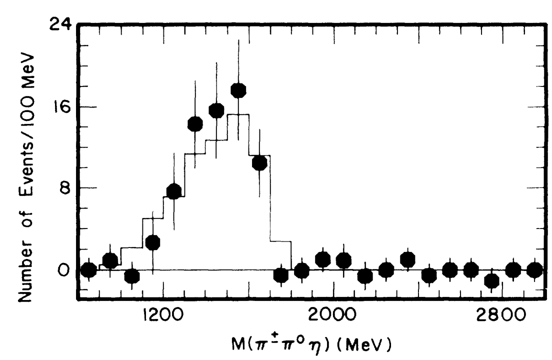


FIG. 3. Invariant mass distribution of $\pi^-\pi^0\eta$ system. Sidebands of the $\eta$ signal have been subtracted to eliminate combinatorial background. We have used only the $\eta \to \gamma\gamma$ subsample since it has the least combinatorial background. Points with error bars represent the data and the histogram shows the distribution obtained for Monte Carlo events generated according to phase space alone.

TABLE I. Summary of measurements in this paper with a comparison of previous measurements [1] and theoretical expectations. Branching ratios are in units of $10^{-4}$ and upper limits are at 95% confidence level.

| Decay mode | This analysis | Previous results | Theoretical prediction |
|---|---|---|---|
| $\tau \to \nu\pi\pi^0\eta$ | $17\pm2\pm2$ | $<110$ | $13\pm2$ (Ref. [4]) |
| $\tau \to \nu\pi\eta$ | $<3.4$ | $<90$ | 0.15 (Ref. [6]) |
| $\tau \to \nu K\eta$ | $<4.7$ | | 1.2–1.6 (Ref. [8]) |
| $\tau \to \nu\pi\pi^0\pi^0\eta$ | $<4.3$ | $<120$ | 0.012 (Ref. [6]) |
| $\tau \to \nu\pi\eta\eta$ | $<1.1$ | $<83$ | 0.00001 (Ref. [6]) |
| $\tau \to \nu\pi\pi^0\eta\eta$ | $<2.0$ | $<90$ | |

ming in quadrature contributions from luminosity (1.5%), $\tau\tau$ cross section (1%), backgrounds (7%), efficiency (8%), signal fit (6%), and tagging branching ratios (7%).

We find no evidence for other $\tau$ decays involving $\eta$ mesons. For modes with a single $\eta$, we use only leptonic tags and the $\eta \to \gamma\gamma$ decay mode. In the search for $\tau^- \to \nu_\tau\pi^-\eta$, we further reduce background by requiring the squared transverse momentum of the event to be greater than 1 $\text{GeV}^2/c^2$. We use this sample to search for the decay $\tau^- \to \nu_\tau K^-\eta$ by additionally requiring the ionization detected in the drift chamber to be within $2\sigma$ of that expected for $K$'s ($\sim$60% of events with $m_{\gamma\gamma}$ near the $\eta$ mass are removed by this cut). The efficiency for these modes is 0.10 and 0.06, respectively. The distributions of $m_{\gamma\gamma}$ are flat in the $\eta$ mass region. From the fits to these distributions, we determine $B(\tau^- \to \nu_\tau\pi^-\eta) < 3.4\times10^{-4}$ and $B(\tau^- \to \nu_\tau K^-\eta) < 4.7\times10^{-4}$ at 95% confidence levels. From a similar search for $\tau^- \to \nu_\tau\pi^-\pi^0\pi^0\eta$ with an analysis efficiency of 0.06, we find a 95% C.L. upper limit branching ratio of $4.3\times10^{-4}$. Systematic errors, estimated as above, are included in all upper limits.

Since decay modes with two $\eta$ mesons have very little background, we use the loose tag, but only the $\eta \to \gamma\gamma$ decay mode. Searches for $\tau^- \to \nu_\tau\pi^-\eta\eta$ and $\tau^- \to \nu_\tau\pi^-\pi^0\eta\eta$ have efficiencies of 0.11 and 0.06, respectively. Since no events are found in the search regions for either decay, we find $B(\tau^- \to \nu_\tau\pi^-\eta\eta) < 1.1\times10^{-4}$ and $B(\tau^- \to \nu_\tau\pi^-\pi^0\eta\eta) < 2.0\times10^{-4}$ at 95% C.L. These and all other results mentioned above are given along with previous measurements [1] and theoretical predictions in Table I.

In summary, we measure for the first time $B(\tau^- \to \nu_\tau\pi^-\pi^0\eta) = (0.17\pm0.02\pm0.02)\%$, in good agreement with the CVC prediction of $(0.13\pm0.02)\%$ and chiral-anomaly, effective Lagrangian calculations. We find no evidence for other $\tau$ decay modes involving $\eta$'s and set upper limits which are more than an order of magnitude below previous limits.

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[10] Missing mass is defined as $[(\sqrt{s}-E_{\text{tot}})^2-\mathbf{p}_{\text{tot}}^2]^{1/2}$, where $E_{\text{tot}}$ and $\mathbf{p}_{\text{tot}}$ are calculated using charged tracks and neutral clusters in the event.

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[12] These numbers, included for illustration, are averaged over tagging decays $e$, $\mu$, $\pi$, and $\rho$ and do not include tagging branching ratios or $\eta$ branching ratios.

[13] The branching ratio is calculated from $B=N/(N_\tau\sum_i B_i\epsilon_i)$, where $N$ is the number of signal events, $N_\tau = 2\sigma(e^+e^- \to \tau^+\tau^-)$, $\mathcal{L}$ is the total number of produced $\tau$'s, and $B_i$ and $\epsilon_i$ are the $\tau$ branching ratio and reconstruction efficiency for decay mode $i$. We calculate branching ratios for each $\eta$ decay mode and then compute weighted averages using statistical errors. For $B_i$ we have used the "fit" values quoted in Ref. [1].