First Observation of the Decay tau- -> k- eta tau-neutrino

CLEO Collaboration

First Observation of the Decay $\tau^- \to K^- \eta \nu_\tau$

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Abstract

The decay $\tau^- \to K^- \eta \nu_\tau$ has been observed with the CLEO II detector. The η meson is reconstructed using two decay channels, $\eta \to \gamma\gamma$ and $\pi^+\pi^-\pi^0$. The measured branching fraction is $B(\tau^- \to K^- \eta \nu_\tau) = (2.6 \pm 0.5 \pm 0.5) \times 10^{-4}$, somewhat higher than the theoretical estimates. An improved upper limit for the second-class-current decay $\tau^- \to \pi^- \eta \nu_\tau$ is set, $B(\tau^- \to \pi^- \eta \nu_\tau) < 1.4 \times 10^{-4}$ at 95% CL, consistent with the theoretical expectations.

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The decays of the τ lepton involving η mesons are of particular interest since they are suppressed in comparison with all-pion decays. The decay $\tau^- \to \pi^- \eta \nu_\tau$ [1] violates G-parity conservation and proceeds via a second class current. The standard model predicts a branching fraction of $(1.2 - 1.5) \times 10^{-5}$ [2,3] for this decay mode. Due to SU(3) symmetry breaking, there is no G-parity constraint on the analogous Cabibbo-suppressed decay, $\tau^- \to K^- \eta \nu_\tau$, so this branching fraction is expected to be larger by an order of magnitude, $(1.2 - 1.6) \times 10^{-4}$ [2,4]. Previously, CLEO II measured the branching fraction of the first τ decay involving η mesons, $B(\tau^- \to \pi^- \eta \pi^0 \nu_\tau) = (1.7 \pm 0.2 \pm 0.2) \times 10^{-3}$ [5], and set the following upper limits, $B(\tau^- \to \pi^- \eta \nu_\tau) < 3.4 \times 10^{-4}$ and $B(\tau^- \to K^- \eta \nu_\tau) < 4.7 \times 10^{-4}$ at 95% CL. Using a four times larger data sample we report in this Letter the first measurement of the decay $\tau^- \to K^- \eta \nu_\tau$ and an improved upper limit for $\tau^- \to \pi^- \eta \nu_\tau$.

The data used in this analysis were collected with the CLEO II detector [6] from $e^+ e^-$ collisions at the Cornell Electron-positron Storage Ring (CESR) at a center-of-mass energy $E_{cm} \sim 10.6$ GeV. The total integrated luminosity of the sample is $3.5 fb^{-1}$, corresponding to the production of 3.2×10^6 $\tau^+ \tau^-$ events. CLEO II is a solenoidal spectrometer with a solid angle coverage of 95% of 4π steradians for charged particles and 98% of 4π steradians for photons. The momenta of charged particles are measured with three cylindrical drift chambers located between 5 and 90 cm from the $e^+ e^-$ interaction point (IP), with a total of 67 layers. The specific ionization (dE/dx) of charged particles is measured using the outer 51 layers. The chambers are surrounded by a scintillation time-of-flight (TOF) system and a CsI calorimeter with 7800 crystals. These detector systems are installed inside a 1.5 T superconducting solenoidal magnet, surrounded by proportional tube chambers with iron absorber for muon identification. For hadrons, the TOF system provides K/π separation of $> 2\sigma$ (standard deviation) for particle momenta below 1.07 GeV/c. The dE/dx measurement provides K/π separation of $> 2\sigma$ for particle momenta below 0.75 GeV/c; for the relativistic rise region above 2.0 GeV/c, it provides $\sim 1.8\sigma$ K/π separation.

We reconstruct the η meson using the $\gamma\gamma$ and $\pi^+ \pi^- \pi^0$ decay channels. The $\tau^+ \tau^-$ candidate events must contain two or four charged tracks and have zero net charge. To reject beam-gas events, the distance of closest approach of each charged track to the IP must be within 0.5 cm transverse to the beam and 5 cm along the beam direction. We divide each event into two hemispheres (tag vs. signal) using the plane perpendicular to the thrust axis, calculated using both charged tracks and photons. The photons are defined as energy clusters in the calorimeter with at least 60 MeV in the barrel, $|\cos\theta| < 0.80$, and 100 MeV in the endcap, $0.80 < |\cos\theta| < 0.95$. The opening angle between the total momentum vectors of the two τ decay products must be greater than 120°. The tag hemisphere must contain only one charged particle, and in the events with $\eta \to \gamma\gamma$, its momentum (p_{tag}) must be greater than 1.0 GeV/c. The hadronic background is suppressed by a requirement on the total invariant mass of the particles in the tag and signal hemispheres to be less than 1.2 and 1.7 GeV, respectively. Backgrounds from two-photon production, Bhabha scattering and hadronic events are suppressed by the requirements on the total visible energy, $0.25 < E_{tot}/E_{cm} < 0.85$, and on the measured net transverse momentum of the event, $p_\perp > 0.5$ GeV/c. All charged particles and photons are included in the calculation of the kinematic variables. For the decay $\tau^- \to \pi^- \eta \nu_\tau$, we reconstruct the η meson using the $\gamma\gamma$ decay channel only and select the events with a lepton tag in order to further suppress the hadronic background. An electron candidate must have an energy deposition in the calorime-

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ter consistent with its measured momentum. A muon candidate must penetrate more than three absorption lengths of iron.

The kaon and pion candidates in the signal hemisphere are restricted to be in the central part of the detector, $|\cos\theta| < 0.81$. Particle identification is based on a confidence level ratio which is constructed from the confidence levels for π and K hypotheses, $\mathcal{C}_\pi$ and $\mathcal{C}_K$. The confidence level ratio for K is

$$R_K = \frac{\mathcal{C}_K}{\mathcal{C}_\pi + \mathcal{C}_K},$$

and similarly for π ($R_\pi = 1 - R_K$). The confidence level is computed from the χ^2 probability for a particle hypothesis using a combination of the TOF and dE/dx information. We use a sample of kaons from $D^{*+} \to D^0\pi^+ \to K^-\pi^+\pi^+$ and pions from K_S decays in hadronic events to study the optimum method of combining the information as a function of momentum. For the momentum ranges 0.2 to 1.0 and 1.3 to 1.7 GeV/c, we require the track to have good dE/dx information; we also use the TOF information if available. In the momentum region 1.0 to 1.3 GeV/c, where π and K have similar dE/dx energy losses, we use TOF information only. For high momentum tracks, 1.7 to 4.5 GeV/c, we use dE/dx information only. A K candidate is then defined as a particle with $R_K > 0.5$, otherwise the particle is considered a pion. Above 1 GeV/c where 80% of the kaons from the decay $\tau^- \to K^-\eta\nu_\tau$ populate, the R_K requirement gives an identification efficiency of $\sim$80% and a misidentification efficiency of $\sim$20%.

The η mesons are reconstructed using photons in the barrel. If there are more than two photons with energy above 100 MeV, including the endcap, the event is rejected. For the $\pi^+\pi^-\pi^0$ decay channel, the invariant mass of the photon pair is constrained to the π^0 mass. For the $\gamma\gamma$ channel, the requirements on the photons are more stringent in order to suppress the background. Each photon must have an energy above 150 MeV and a lateral profile of energy deposition consistent with that expected of a photon. In addition, we do not use showers that are likely fragments of nearby showers. A signal photon may not combine with any other photon to form a π^0 ($|M_{\gamma\gamma} - M_{\pi^0}| < 20$ MeV).

For the $\gamma\gamma$ channel, the invariant mass spectrum of the two photons accompanying the kaon candidate is shown in Fig. 1(a). The mass spectrum is normalized with respect to the mass resolution, $S_{\gamma\gamma} = \frac{M_{\gamma\gamma} - M_\eta}{\sigma_{\gamma\gamma}}$. The mass resolution ($\sigma_{\gamma\gamma}$) is calculated from the shower angle and energy resolution. An η signal is observed. The curve is a fit to the data using a Gaussian with a low mass tail over a polynomial background. An η signal is also observed in the $\pi^+\pi^-\pi^0$ channel as shown in Fig. 1(b). For the decay $\tau^- \to \pi^-\eta\nu_\tau$, no η signal is evident as shown in Fig. 1(c). All fits have the η width constrained to the Monte Carlo expectation. For the $\pi\eta$ analysis, the η mass is also constrained to the Monte Carlo prediction since there is no η signal in the data.

As a verification of the $K\eta$ signal, we show in Fig. 2 the R_K distribution for events in the η signal region for $\eta \to \gamma\gamma$ (sideband subtracted). There is an enhancement at $R_K = 0$ and 1.0 as expected. The distribution is well described by the Monte Carlo simulation. The enhancement at high R_K is dominated by the $K\eta$ decay while at low R_K it is saturated by the hadronic background.

The detection efficiencies for the candidate events are calculated using a Monte Carlo simulation. The KORALB program is used to generate $\tau^+\tau^-$ pairs according to the standard electroweak theory, including α^3 radiative corrections [7]. The decay $\tau^- \to K^-\eta\nu_\tau$
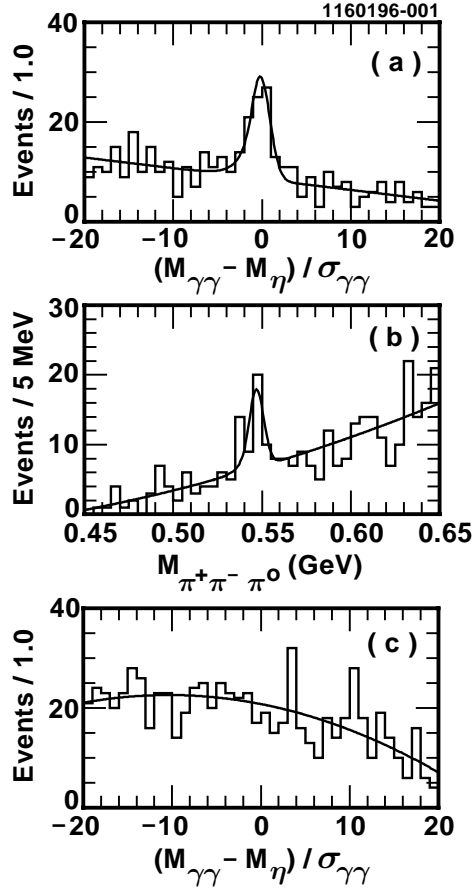
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FIG. 1. The invariant mass spectrum of the η candidates. Each η candidate is accompanied by a kaon candidate in (a) and (b) and by a pion candidate in (c). The mass is expressed in standard deviations from the nominal η mass in (a) and (c). Each curve shows a fit to the mass spectrum (see text).
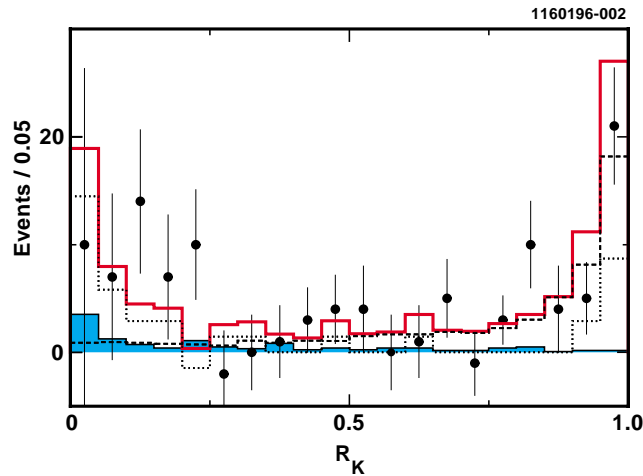

FIG. 2. The observed R_K spectrum of the charged particle in the hemisphere containing an η meson after sideband subtraction. The histogram shows the Monte Carlo expectation which is a sum of the predictions for $\tau^- \to K^- \eta \nu_\tau$ (dashed), $\tau^- \to \pi^- \pi^0 \eta \nu_\tau$ (shaded), and $e^+ e^- \to q\bar{q}$ (dotted).

$(\pi^-\eta\nu_\tau)$ is modeled with the $K^*(1410)$ $(a_0(980))$ resonance assuming a $V - A$ weak interaction. The detector response is simulated using the GEANT program [8]. Detector activity not attributable to the e^+e^- interaction is modeled by embedding random trigger events obtained during data taking into the generated events. The identification and misidentification efficiencies are calibrated as a function of momentum by comparing the efficiencies measured from the D^* and K_S data sample with the Lund Monte Carlo expectations [9].

The hadronic background is estimated from the data, using events in which the invariant mass in one hemisphere is above the τ mass. Two methods are used to estimate the background in $\tau^- \rightarrow K^-\eta\nu_\tau \rightarrow K^-\gamma\gamma\nu_\tau$: (1) The background is estimated from the number of events with high $K\eta$ mass, measured with looser cuts ($p_{tag} > 0.5$ GeV/c, $p_\perp > 0.25$ GeV/c) to increase the data sample. The normalization to the low $K\eta$ mass region is performed using 1 vs. 3 events with a high 3-prong jet mass. The Lund Monte Carlo is used to estimate the loose to standard cuts scaling factor. The calculation yields $N_{bkg} = 9.0 \pm 7.1$ events. (2) In this method we use events with high tag mass. The normalization to low tag mass is performed with the Lund Monte Carlo. The calculation yields $N_{bkg} = 7.9 \pm 4.5$ events. Combining these two statistically independent and consistent results gives $N_{bkg} = 8.2 \pm 3.8$ events [10]. The backgrounds in the other two τ samples are estimated using a similar procedure (Table I).
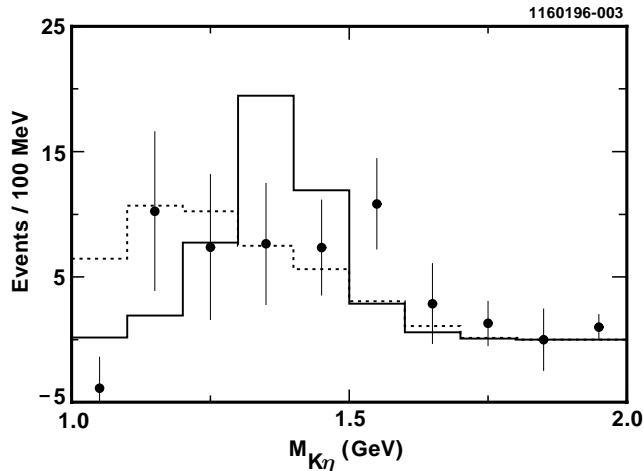

FIG. 3. The $K\eta$ invariant mass spectrum after the subtraction of all backgrounds. The histograms show the Monte Carlo expectations for the $K^*(1410)$ (solid) and phase space (dashed) models assuming a V-A weak interaction. The number of events above the τ mass is consistent with zero.

The background to $\tau^- \rightarrow K^-\eta\nu_\tau$ from two-photon interactions is estimated using the fact that the two-photon events are produced at low $p_\perp$. From the paucity of events at $p_\perp < 0.1$ GeV/c, we set an upper limit [11] of 2% contamination at 95% CL.

We use the measured branching fraction [5] for $\tau^- \rightarrow \pi^-\eta\pi^0\nu_\tau$ to estimate its contribution to the $\tau^- \rightarrow K^-\eta\nu_\tau$ sample. The measured branching fractions for $\tau^- \rightarrow K^-\eta\nu_\tau$ and $\pi^-\eta\nu_\tau$ presented in Table I are used to estimate the cross-feed backgrounds between the two decay modes. The background from $\tau^- \rightarrow K^-\pi^0\eta\nu_\tau$ is neglected since it is expected to be $\sim$0.1% [2] of the signal. The signals, backgrounds, and detection efficiencies are summarized in Table I.

The observed $K\eta$ mass spectrum for $\eta \rightarrow \gamma\gamma$ is compared with the Monte Carlo expec-

tation in Fig. 3. Also shown is the prediction in which the $K^*(1410)$ resonance is replaced by a spectral function determined simply from the $K\eta$ phase space. The data are consistent with both models.

TABLE I. Summary of signals, backgrounds, detection efficiencies, and branching fractions. All errors are statistical.

	$K^-\gamma\gamma$	$K^-\pi^+\pi^-\pi^0$	$\pi^-\gamma\gamma$
η Signal	61 ± 11	24 ± 7	$0^{+5.3}_{-0}$
$q\bar{q}$	8.2 ± 3.8	5.9 ± 3.1	2.7 ± 1.9
$\pi^-\pi^0\eta$	3.2 ± 0.8	3.8 ± 1.0	3.9 ± 0.9
Cross-feed eff (%)	1.3 ± 0.1	0.8 ± 0.1	0.8 ± 0.1
Eff (%)	7.6 ± 0.1	3.9 ± 0.1	3.5 ± 0.1
B (10^{-4})	2.6 ± 0.6	2.5 ± 1.3	$0^{+0.62}_{-0}$

TABLE II. Summary of systematic errors (%).

	$K^-\gamma\gamma$	$K^-\pi^-\pi^+\pi^0$	$\pi^-\gamma\gamma$
$N_{\tau\tau}$	1.4	1.4	1.4
η BR	1.3	2.5	1.3
Identification	2	2	2
Background	9	24	–
Fit	5	8	–
Acceptance	5	7	11
Decay model	13	10	1
MC statistics	2	3	2
Total	18	28	12

There are several sources of systematic errors as shown in Table II. These include the uncertainties in the luminosity, $\tau^+\tau^-$ cross section, branching fractions of $\eta \to \gamma\gamma$ and $\pi^+\pi^-\pi^0$ [12], identification efficiency, background subtraction, fitting procedure, acceptance calculation, decay modeling, as well as the uncertainty due to limited Monte Carlo statistics. The systematic error in the identification efficiency has two components: (i) the statistical uncertainty due to the limited D^* and K_S samples, (ii) the potential difference in the efficiencies between τ and hadronic events. This is estimated from the dependence of the efficiency in the hadronic events on the number of useful dE/dx hits and the isolation of the TOF hits from the other charged tracks. There is also a similar systematic error in the misidentification efficiency. This is included in the systematic error of the background subtraction. Also included are the statistical errors in the background estimate (Table I) and the uncertainties in the branching fractions of the decay modes. The systematic error due to the fitting procedure was estimated by comparing the results for various fit ranges and for different orders of polynomial background. We estimated the systematic error in the acceptance calculation using the well-measured decay channels with the similar topology as the reactions under study, $\tau^- \to h^-\pi^0\nu_\tau$ and $h^-h^-h^+\pi^0\nu_\tau$, where h can either be a π or K. By comparing the measured branching fractions with the world averages [13], we assign a

systematic error of 5% for the $K\gamma\gamma$ mode, 7% for the $K\pi^+\pi^-\pi^0$ mode, and 11% for the $\pi\gamma\gamma$ mode. The systematic error in the decay modeling is estimated by comparing the detection efficiencies for the resonance and phase space models.

The branching fraction for $\tau^- \to K^-\eta\nu_\tau$ is extracted after correcting for the backgrounds and detection efficiencies. The results are $(2.6 \pm 0.6 \pm 0.5) \times 10^{-4}$ and $(2.5 \pm 1.3 \pm 0.7) \times 10^{-4}$ for the $\gamma\gamma$ and $\pi^+\pi^-\pi^0$ channels, where the first error is statistical and the second systematic. Combining these two results yields

$$B(\tau^- \to K^-\eta\nu_\tau) = (2.6 \pm 0.5 \pm 0.5) \times 10^{-4}.$$

The upper limit on $\tau^- \to \pi^-\eta\nu_\tau$ is obtained without correcting for the backgrounds, $B(\tau^- \to \pi^-\eta\nu_\tau) < 1.2 \times 10^{-4}$ at 95% CL. Loosening the limit by one unit of the total systematic error yields

$$B(\tau^- \to \pi^-\eta\nu_\tau) < 1.4 \times 10^{-4} \text{ at } 95\% \text{ CL}.$$

In summary, we have measured, for the first time, the branching fraction of $\tau^- \to K^-\eta\nu_\tau$ and set a more stringent limit on $B(\tau^- \to \pi^-\eta\nu_\tau)$. The measured branching fraction is somewhat higher than the theoretical predictions [2,4] while the upper limit on the second-class-current decay is consistent with theoretical expectations [2,3].

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