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Observation of Radiative Leptonic Decay of the Tau Lepton

CLEO Collaboration

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Abstract

Using 4.68 fb^{-1} of e^+e^- annihilation data collected with the CLEO II detector we have studied τ radiative decays $\tau^- \to \nu_\tau \mu^- \overline{\nu}_\mu \gamma$ and $\tau^- \to \nu_\tau e^- \overline{\nu}_e \gamma$. For a 10 MeV minimum photon energy in the τ rest frame, the branching fraction of a τ radiatively decaying to a muon is measured to be $(3.61 \pm 0.16 \pm 0.35) \times 10^{-3}$, and to an electron is $(1.75 \pm 0.06 \pm 0.17) \times 10^{-2}$. The branching fractions are in agreement with the Standard Model theoretical predictions. All quoted results are preliminary.

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Unconventional models for τ decay could lead to behavior inconsistent with the Standard Model in radiative τ decay [1]. In one model τ decay occurs not only through the known s-channel exchange of a W-boson, but also through the s-channel exchange of an unknown X boson. In another model, τ decay occurs only through the exchange of the W-boson but the $\tau-\nu_\tau-$W vertex has anomalous radiative properties. In both cases, the radiative decay behavior of the τ should be altered with respect to the Standard Model expectation.

We search for $\tau^- \rightarrow \nu_\tau \ell^- \overline{\nu}_\ell \gamma$ ($\ell = e$ or μ) using the observed final states: $e^+ + \mu^- \gamma$, $\mu^+ + e^- \gamma$, $h^+ + \mu^- \gamma$, $h^+\pi^0 + \mu^- \gamma$, $h^+ + e^- \gamma$, and $h^+\pi^0 + e^- \gamma$, where h^+ is a charged pion or kaon.[1] The data sample used in this work was acquired from e^+e^- collisions at a center-of-mass energy of $E_{cm} \approx 10.6$ GeV with the CLEO II detector [2] at the Cornell Electron Storage Ring (CESR). The total integrated luminosity of the data is 4.68 fb^{-1}, corresponding to 4.3×10^6 τ pairs.

We select events with exactly two oppositely charged tracks with scaled momentum, $x_\pm = p_\pm/E_{beam}$, satisfying $x_\pm < 0.9$ and with the angle between the two tracks greater than 90°. We require exactly one charged track in each hemisphere as defined by the plane perpendicular to the thrust axis [3]. To suppress beam-gas events, the distance of closest approach of each track to the interaction point must be within 0.5 cm transverse to the beam direction, and 5 cm along it. Hadronic background is suppressed by requiring the total invariant mass of particles in each hemisphere to be less than the τ mass. In computing the invariant mass, we assign the pion mass to the charged hadron. We require the two-track acollinearity in azimuth, $\xi = ||\phi_+ - \phi_-| - \pi|$ where $\phi_+(\phi_-)$ is the azimuthal angle of the positively (negatively) charged track, to satisfy $0.05 < \xi < 1.5$. The scaled missing momentum transverse to the beam, $x_t = p_t/E_{beam}$, and the angle of the missing momentum with regard to the beam line, θ_{miss}, must satisfy $x_t > 0.1$ and $|\cos\theta_{miss}| < 0.8$ for all non-$h\pi^0$ tag modes; for the two $h\pi^0$-tag modes, only $x_t > 0.05$ is required. These criteria effectively reduce potential contamination from non-τ QED events.

Photons are defined as energy clusters in the calorimeter of at least 50 MeV for $|\cos\theta_\gamma| < 0.71$, or 100 MeV when $0.71 < |\cos\theta| < 0.95$ where θ_γ is the polar angle with respect to the beam axis. They are further required to pass a lateral shower shape requirement, which is 99% efficient for isolated photons. No charged particle track can point to within 8 cm of a crystal used in the energy cluster. In the signal lepton hemisphere, we require that there be only one photon, and this photon must be in the region $|\cos\theta_\gamma| < 0.71$. In the tag hemisphere, if the tag is a lepton, then at most one unused photon is allowed; otherwise, at most two unused photons are allowed. Photons from τ radiative leptonic decays tend to be almost collinear with the final state lepton direction, hence we require $\cos\theta_{\mu\gamma} > 0.96$ in the case of muonic decay and $\cos\theta_{e\gamma} > 0.99$ in the case of electronic decay.

Identified electrons are required to have scaled momenta $x_\pm > 0.1$ and $|\cos\theta| < 0.71$. The ratio of energy deposited in the calorimeter to track momenta for electron candidates must satisfy $E_\pm/p_\pm > 0.85$. The drift chamber specific-ionization (dE/dx) for electron candidates must be no lower than two standard deviations below that expected for an electron. To exclude events in which a photon hides in the track's calorimeter shower, the criteria further

[1]Charge conjugate states are included in this analysis.

require $E_\pm/p_\pm < 1.1$. Muon criteria demand that the track has $|\cos\theta| < 0.71$ and deposit $E_\pm < 0.3$ GeV in the calorimeter, consistent with a minimum-ionizing particle, and that there be hits in the muon detection system matched to the projected trajectory of the track. A muon candidate must also penetrate at least three hadronic interaction lengths for $p_\pm < 2.0$ GeV/c and five interaction lengths for $p_\pm > 2.0$ GeV/c, corresponding to the first and second superlayers of the muon chambers. The tag h is operationally defined as a charged track not identified as a lepton, with $p_\pm > 0.5$ GeV/c and $|\cos\theta_h| < 0.90$. The $h\pi^0$ tag is defined as a reconstructed π^0 plus a charged track not identified as a lepton, and the charged track must satisfy $p_\pm > 0.3$ GeV/c and $|\cos\theta| < 0.90$. A π^0 is reconstructed using two crystal showers in the tag hemisphere that satisfy the photon criteria, except that only one of the showers is required to meet the lateral shower shape requirement. We require that the invariant mass of the two photons satisfy $120 < m_{\gamma\gamma} < 145$ MeV. We exclude events in which an extra π^0 is found.

Additional criteria are applied to suppress mode-specific backgrounds. To reduce contamination from radiative QED processes $e^+e^- \to e^+e^-\gamma$ and $\mu^+\mu^-\gamma$, the total energy of an event must satisfy $E_{tot} < 7.5$ GeV for $h+\mu\gamma$ and $h+e\gamma$ modes. In the $h+e\gamma$ mode, to further reduce background from $e^+e^-e^+e^-(\gamma)$ we restrict the h to satisfy $|\cos\theta_h| < 0.71$ and require the total energy of an event to be greater than 2.8 GeV. In the three electronic radiative decay modes, in order to reduce significant background from external bremsstrahlung, we require the distance of closest approach of the electron's track to the interaction point to be within 0.8 mm transverse to the beam. We further require the distance between the photon candidate shower and the electron shower in the crystal calorimeter to be greater than 250 mm, in order to separate the occasionally overlapping showers.

The detection efficiencies and backgrounds are investigated with a Monte Carlo technique. We use the KORALB/TAUOLA [4] and PHOTOS [5] MC packages to model the production and decay of τ pairs. The detector response is simulated using the GEANT program [6]. Generic Monte Carlo-produced τ-pair decay events are used to study the kinematic distributions of the signal candidates and the backgrounds from τ-pair decay sources. The $\cos\theta_{\ell\gamma}$ and E_γ distributions from selected events for both muonic and electronic decay are shown in Fig. 1. The figure shows that data and luminosity normalized Monte Carlo expectation agree quite well. Using Monte Carlo-produced τ-pairs in which one τ decays radiatively into a lepton and neutrinos and the another τ decays generically, we determine the total detection efficiencies to be $(3.28\pm0.06)\%$ for radiative muonic decay and $(2.02\pm0.03)\%$ for radiative electronic decay.

The backgrounds from τ-pair decay sources relative to signals are shown with the $\cos\theta_{\ell\gamma}$ distributions in Fig. 2. In the muonic decay case, the significant backgrounds are ISR/FSR (initial state and final state radiation), track misidentification (mostly other particles misidentified as a muon) and neutral showers faking photons. In the electronic decay case, the electron external bremsstrahlung process is the only significant background; backgrounds such as other particles misidentified as the electron are relatively small. Figure 2 also shows that a photon from τ radiative decay to a lepton tends to have a very small angle with respect to the final state lepton. Further from the lepton, background photons not related to the τ leptonic decay completely dominate.

We investigate possible contamination from hadronic events by using the Lund simulation [7] and find that it is negligible. We rely upon Monte Carlo simulation of e^+e^- to $\mu^+\mu^-(\gamma)$

[8], $e^+e^-(\gamma)$ [9,10], $e^+e^-\mu^+\mu^-$ [11], $e^+e^-\pi^+\pi^-$ [11], and $e^+e^-e^+e^-$ [12] final states to model backgrounds from these processes. All these background sources are small except in the two h tag modes. In the case of muonic radiative decay with h tag, we find that the two photon process $e^+e^-\mu^+\mu^-$ contributes 0.69% to the selected sample in data and the QED process $\mu^+\mu^-(\gamma)$ contributes another 0.46%. In the electronic decay case, the Monte Carlo predicts 0.42% from the two-photon process $e^+e^-e^+e^-$ and 0.29% from the QED process $e^+e^-(\gamma)$. As these processes are significantly suppressed by the selection criteria and their accurate normalization is difficult to verify, a total relative error of 100% will be assigned in the final systematic errors.

Branching fractions $\mathcal{B}(\tau^- \to \nu_\tau\mu^-\overline{\nu}_\mu\gamma)$ and $\mathcal{B}(\tau^- \to \nu_\tau e^-\overline{\nu}_e\gamma)$ are calculated for $E_\gamma > 50$ MeV in the laboratory frame for each mode and then converted into the τ rest frame for $E^*_\gamma > 10$ MeV by applying a boost factor. The factor ϵ_{boost} is determined from Monte Carlo simulation to be 0.754 ± 0.007 for muonic radiative decay and 0.762 ± 0.003 for electronic radiative decay. The branching fractions from three different tags are combined using a weighted average. The measured branching fractions from data are compared with the theoretical predictions extracted from Monte Carlo simulation. Tables I summarizes the relative results and Table II shows the measured absolute branching fractions.

TABLE I. Branching fractions for $\tau^- \to \nu_\tau\mu^-\overline{\nu}_\mu\gamma$ and $\tau^- \to \nu_\tau e^-\overline{\nu}_e\gamma$ relative to Standard Model Monte Carlo expectation for all tag modes and combined results for $E^*_\gamma > 10$ MeV. Errors are statistical only.

	e tag	μ tag	h tag	$h\pi^0$ tag	Total
$\nu_\tau\mu^-\overline{\nu}_\mu\gamma$	1.00 ± 0.08		0.98 ± 0.07	0.96 ± 0.07	0.98 ± 0.04
$\nu_\tau e^-\overline{\nu}_e\gamma$		0.95 ± 0.06	0.91 ± 0.07	0.97 ± 0.05	0.94 ± 0.03

TABLE II. Measured branching fractions $\mathcal{B}(\tau^- \to \nu_\tau\mu^-\overline{\nu}_\mu\gamma)$ and $\mathcal{B}(\tau^- \to \nu_\tau e^-\overline{\nu}_e\gamma)$ for $E^*_\gamma > 10$ MeV and theoretical predictions extracted from the Monte Carlo. For data, the first error is statistical and the second one is systematic. For Monte Carlo, the error is based on the number of events generated. Also listed is the ratio of $\mathcal{B}(\tau^- \to \nu_\tau e^-\overline{\nu}_e\gamma)$ to $\mathcal{B}(\tau^- \to \nu_\tau\mu^-\overline{\nu}_\mu\gamma)$, $\mathcal{B}_{e\gamma}/\mathcal{B}_{\mu\gamma}$

	data	MC
$\mathcal{B}(\tau^- \to \nu_\tau\mu^-\overline{\nu}_\mu\gamma)$ $(\times 10^{-3})$	$3.61 \pm 0.16 \pm 0.35$	3.68 ± 0.02
$\mathcal{B}(\tau^- \to \nu_\tau e^-\overline{\nu}_e\gamma)$ $(\times 10^{-2})$	$1.75 \pm 0.06 \pm 0.17$	1.86 ± 0.01
$\mathcal{B}_{e\gamma}/\mathcal{B}_{\mu\gamma}$	$4.85 \pm 0.27 \pm 0.57$	5.05 ± 0.04

Systematic error estimates s for $\tau^- \to \nu_\tau\mu^-\overline{\nu}_\mu\gamma$ and $\tau^- \to \nu_\tau e^-\overline{\nu}_e\gamma$ are shown in Table III. The errors in the table are relative to the final branching fraction. For muonic radiative decay, we estimate the error from photon reconstruction by varying the photon selection criteria and also from a separate study of radiative $\mu\mu$ events. The trigger efficiency systematic error is obtained by a comparison of trigger lines between data and Monte Carlo. We evaluate the muon misidentification systematic error by allowing a variation of the hadron to muon misidentification rate of 15% as estimated from a sample of tracks with a lepton recoiling against an $h\pi^0$ system. The energy deposition of hadrons faking muons is not well modeled in the Monte Carlo; therefore, we vary the muon maximum energy requirement to obtain its associated error. The integrated luminosity of the data at CLEO is measured with a relative error of 1%; this results in a relative error of 1.4% on the total number of τ pairs produced in data, assuming a theoretical error of 1% for the τ-pair production cross section [4]. The uncertainty for the track finding efficiency is estimated from a hand scan of Bhabhas selected using shower information only and a study of pion finding efficiency in $\tau^+\tau^-$ events in which one τ decays to lepton and the another τ decays to $3\pi^\pm(\pi^0)$. Other errors are small and we estimate these errors by either using an independent sample or by varying related individual requirements.

The largest background to the decay $\tau^- \to \nu_\tau e^- \overline{\nu}_e \gamma$ comes from electron external bremsstrahlung. This process contributes about 40% of the observed γ's. Its systematic error contribution is estimated from comparisons of data and Monte Carlo simulation for accepted $e^+e^-\gamma$ events from $e^+e^- \to e^+e^-e^+e^-(\gamma)$. The comparison indicates that external bremsstrahlung events in our Monte Carlo simulation are $(11\pm7)\%$ more likely than in data. This result is also confirmed by comparing the number of photon conversion events from π^0 decays between data and Monte Carlo. We estimate a propagated branching fraction error of 6.9% by allowing a variation of as much as 18% for this background. The error from photon reconstruction is estimated by varying the photon selection criteria. Errors from the trigger and tracking simulations are evaluated as in the muonic decay case. All remaining errors are also estimated as in the muonic case.

TABLE III. Summary of systematic errors from different sources for τ muonic and electronic radiative decays.

Source	$\tau^- \to \nu_\tau \mu^- \overline{\nu}_\mu \gamma$	$\tau^- \to \nu_\tau e^- \overline{\nu}_e \gamma$
external bremsstrahlung	$\approx 0.0\%$	6.9%
photon reconstruction	5.9%	4.6%
trigger	5.0%	5.0%
track misidentification	4.4%	1.1%
muon shower energy requirement	3.6%	NA
$N_{\tau\tau}$	1.4%	1.4%
tracking	1.0%	1.0%
non τ sources	0.9%	0.1%
ISR/FSR	0.8%	0.2%
Total	9.8%	9.9%

There have been measurements of τ radiative muonic decay from MARK II [13] and OPAL [14]. The OPAL result is more recent and more precise. OPAL reports a measurement of the branching fraction $\mathcal{B}(\tau^- \to \nu_\tau \mu^- \overline{\nu}_\mu \gamma) = (3.0 \pm 0.4 \pm 0.5) \times 10^{-3}$ for $E^*_\gamma > 20$ MeV. Converting our result for $E^*_\gamma > 10$ MeV to a result for $E^*_\gamma > 20$ MeV gives a measurement of $\mathcal{B}(\tau^- \to \nu_\tau \mu^- \overline{\nu}_\mu \gamma)$=$(3.04 \pm 0.14 \pm 0.30) \times 10^{-3}$, which is in excellent agreement with the OPAL result but with an error smaller by a factor of two. CLEO has previously observed τ radiative electronic decay [15], but this is the first direct measurement of the branching fraction.

As pointed out in refs. [16,17], Lorentz structure parameters in τ decay that are difficult to measure directly in non radiative decays can also be investigated in radiative τ decay. For example, the probability Q^ℓ_R of the τ decaying into a right-handed charged daughter lepton is given by $Q^\ell_R = \frac{1}{2}(1 - \xi')$ (ξ'=1 in the Standard Model). If we could extract the Michel type parameter ξ' by measuring the partial τ radiative decay rate [16], then Q^ℓ_R could be limited. However, the differential τ radiative decay rate is most sensitive to ξ' for photons emitted in the direction opposite to the daughter lepton, an area dominated by photons from other sources. This indicates that we are unable to set useful limits using the experimental method described here.

In summary, we have performed the first measurement of $\mathcal{B}(\tau^- \to \nu_\tau e^- \overline{\nu}_e \gamma)$ and an improved measurement of $\mathcal{B}(\tau^- \to \nu_\tau \mu^- \overline{\nu}_\mu \gamma)$ using the CLEO detector at the CESR electron-positron collider. Within the errors of the measurements we find that the magnitude of the decay rates and the kinematic distributions agree with expectations of conventional electromagnetic and weak interaction theory. We also conclude that it is not currently possible to set useful limits on the parameters proposed in [16,17] using the experimental method described in this letter.

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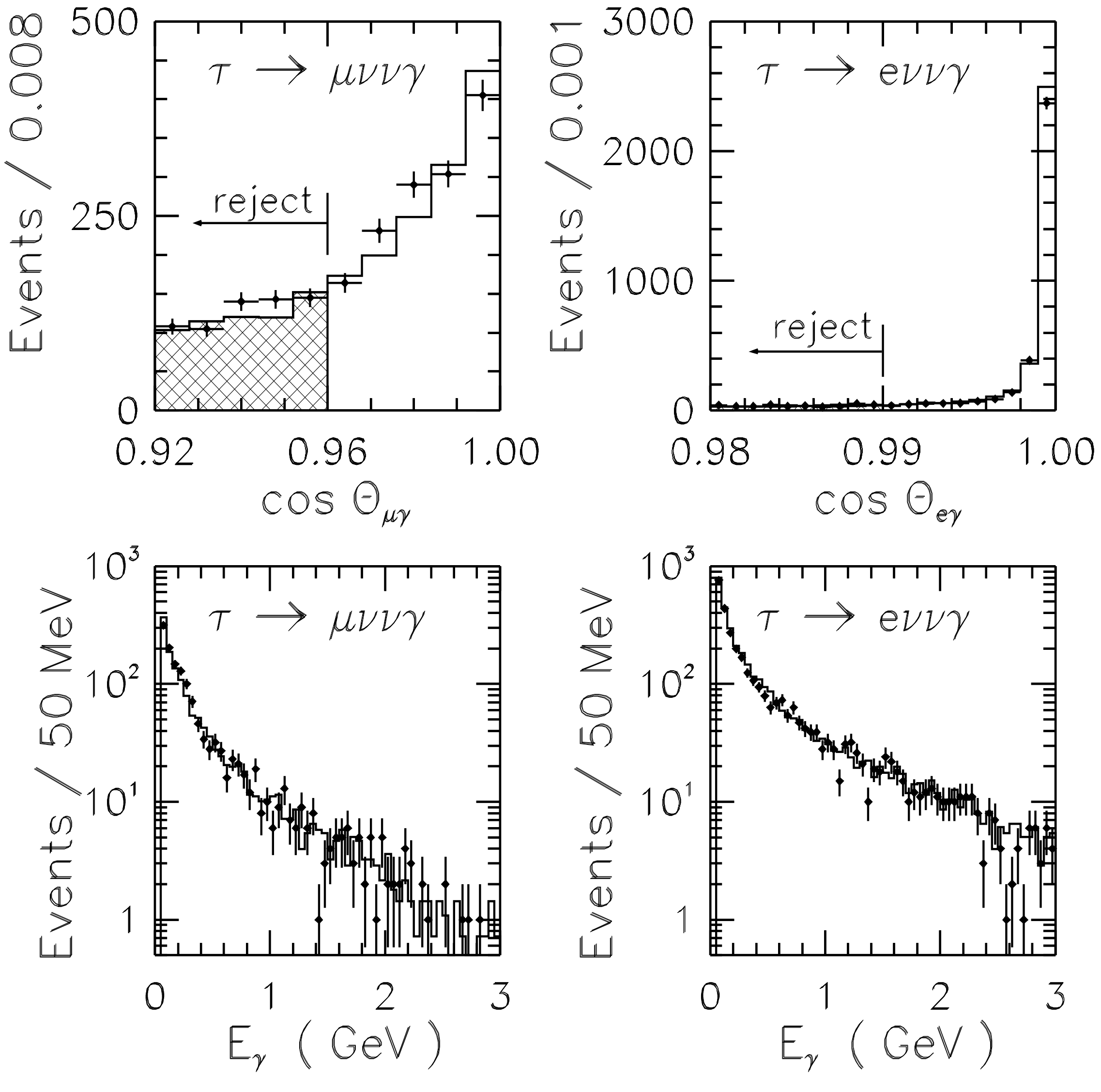

FIG. 1. Distributions in $\cos\theta_{\ell\gamma}$ and E_γ for data (solid circles) and Monte Carlo (histogram) for both muonic and electronic radiative decays of the τ. Each distribution shown here is the sum over all tag modes. Only events satisfying the $\cos\theta_{\ell\gamma}$ requirement are used in the E_γ distributions.

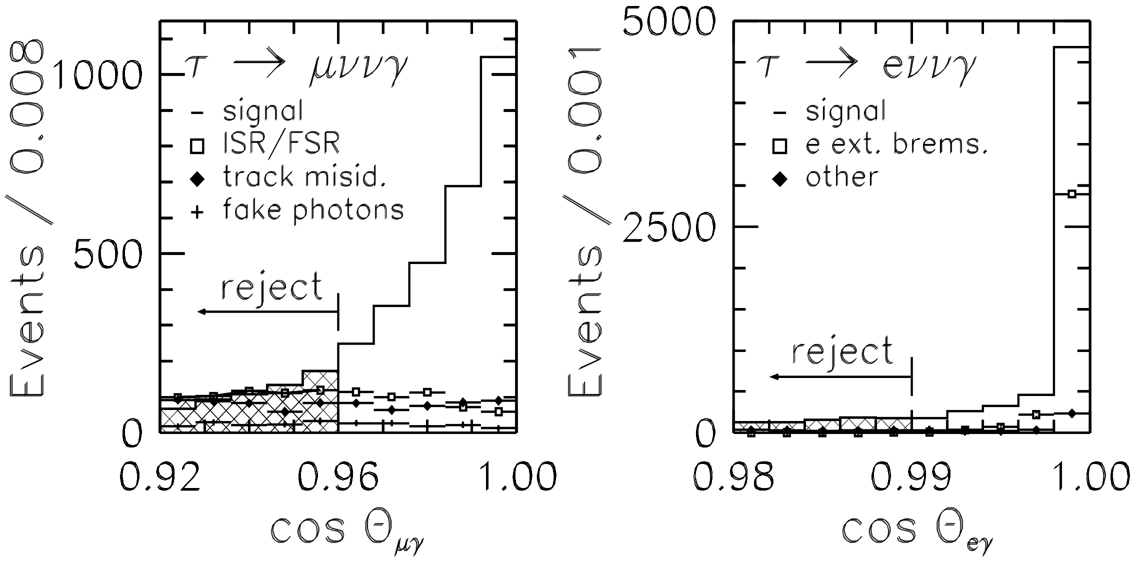

FIG. 2. Distributions in $\cos\theta_{\ell\gamma}$ for signals and different tau source backgrounds, from Monte Carlo simulations.