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Search for neutrinoless τ decays: $\tau \to e\gamma$ and $\tau \to \mu\gamma$

CLEO Collaboration

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Abstract

A search for the lepton family number violating decays $\tau \to e\gamma$ and $\tau \to \mu\gamma$ has been performed using CLEO-II data. No evidence of a signal has been found and the corresponding upper limits are $B(\tau \to e\gamma) < 2.7 \cdot 10^{-6}$ and $B(\tau \to \mu\gamma) < 3.0 \cdot 10^{-6}$ at 90% CL.

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Non-conservation of the leptonic quantum number is expected in many extensions of the Standard Model and searches for lepton number violating decays provide strong constraints on possible new physics processes. The most stringent limits so far have been obtained in the studies of μ decays: $B(\mu \to e\gamma) < 4.9 \cdot 10^{-11}$ and $B(\mu \to eee) < 1.0 \cdot 10^{-12}$ [1]. Even though we cannot reach a similar level of sensitivity for τ's, the search for lepton number violating τ decays becomes competitive with the μ results in theoretical models with mass-dependent couplings. There have been several recent theoretical calculations based on specific supersymmetric, GUT and superstring models [2-4]. For example, a superstring model [4] gives an enhancement of τ decays over the corresponding μ decays of $B(\tau \to \mu\gamma) = 2 \times 10^5 B(\mu \to e\gamma)$.

Lepton number violating neutrinoless τ decays have been studied extensively. Upper limits have been set by CLEO [5] on branching fractions for 22 channels with 3 charged particles in the final state at the level of few times 10^{-6}, and the limit [6] $B(\tau \to \mu\gamma) < 4.2 \times 10^{-6}$ has also been published. This paper describes CLEO's first search for the neutrinoless decay $\tau \to e\gamma$. The upper limit of $B(\tau \to e\gamma) < 1.2 \times 10^{-4}$ at 90% CL was previously obtained by ARGUS [7]. A new analysis searching for the $\mu\gamma$ final state is also presented.

In this analysis we use data from the reaction $e^+e^- \to \tau^+\tau^-$ collected at CESR at or near the energy of $\Upsilon(4S)$. The data correspond to a total integrated luminosity of 4.68 fb^{-1} and contain about 4.24×10^6 $\tau^+\tau^-$ pairs. We search for events with a 1-vs-1 topology, where the signal candidate τ decays into $e\gamma$ or $\mu\gamma$ and the tag side includes all standard τ decays into one charged particle, any number of photons and at least one neutrino. The selection criteria are based on the studies of two Monte Carlo samples of 10,000 τ pair events each. The Monte Carlo uses the KORALB [8] generator with two-body phase space for the $e\gamma$ and $\mu\gamma$ decay modes and a detector simulation based on the GEANT package [9].

We select $\tau^+\tau^-$ pair events with exactly two good charged tracks, with total charge equal to zero, and with the angle between the charged tracks greater than 90°. Since radiative Bhabha scattering and μ-pair production provide high background rates, we allow only one identified electron or one identified muon per event. Thus in the $e\gamma$ search one of the tracks has to be positively identified as an electron while the other should be inconsistent with the electron hypothesis and in the $\mu\gamma$ search one of the tracks has to be identified as a muon while the other has to be inconsistent with the muon hypothesis. About 19.3% of $e\gamma$ Monte Carlo events and 36.2% of $\mu\gamma$ Monte Carlo events survive these criteria.

In addition, each candidate event must have exactly one photon separated by more than 20° from the closest charged track in the lepton hemisphere. This photon must lie in a good section of the calorimeter barrel (i.e., $|\cos\theta| < 0.71$, where θ is an angle between the photon and beam directions) and have energy deposition in the calorimeter greater than 300 MeV. This minimum energy cut is dictated by the kinematics of 2-body τ decay. The angle between the direction of the photon and the momentum of the electron or the muon track must satisfy $0.4 < \cos\theta_{l\gamma} < 0.8$, where the upper limit is again dictated by kinematics, and the lower limit by selection efficiency. The Monte Carlo expectation of the $\cos\theta_{e\gamma}$ distribution for the $\tau \to e\gamma$ channel is compared in Fig. 1 with the data. The corresponding distributions for $\tau \to \mu\gamma$ are similar. About 14.6% of the $e\gamma$ and 20.9% of the $\mu\gamma$ original Monte Carlo sample survive these initial selection criteria.

For electron identification we use both drift chamber dE/dx and calorimeter information. In the $e\gamma$ analysis we require that the electron candidate's specific ionization be within 3

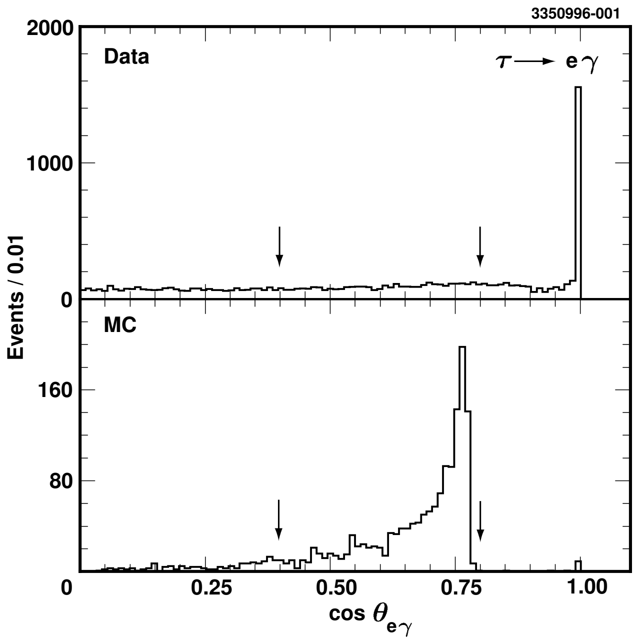

FIG. 1. The $\cos\theta_{e\gamma}$ distribution in data and signal Monte Carlo.

standard deviations of the expected value, and the energy, E, deposited in the calorimeter match the track momentum, p, measured in the drift chamber: $0.8 < E/|p| < 1.1$. After these cuts are applied, a large fraction of low momentum electrons, mostly from two photon processes, still survive on the tag side. Therefore, unless the tagging track is identified as a muon, we impose additional requirements: the tagging track's transverse momentum must be greater than 300 MeV/c, its momentum must point to the good portion of the calorimeter barrel ($|\cos\theta| < 0.71$), and the $E/|p|$ ratio must be less than 0.6.

In the $\mu\gamma$ analysis a particle is identified as a muon if it traverses at least three absorption lengths of the material, has correlated drift and muon chamber hits, and has a calorimeter response consistent with that of a minimum ionizing particle.

The main sources of background in the selected samples are due to Bhabha scattering, μ-pair production, radiative $\tau \to e\gamma\nu\nu$ and $\tau \to \mu\gamma\nu\nu$ decays, and two photon processes.

A large fraction of these backgrounds can be rejected by imposing a cut on the angle between the momentum of the tagging particle and the missing momentum of the event. We calculate the missing momentum as a negative of the sum of momenta of the two charged tracks and all showers detected in the calorimeter with energies above 30 MeV. Since there must be at least one undetected neutrino on the tag side, the missing momentum in a τ event is expected to fall into the tagging track hemisphere, while for all radiative processes the missing momentum should be uncorrelated with the charged track on the tag side (see Fig. 2). To reduce this background, we require that the cosine of the angle between the total missing momentum of the event and the momentum of the tagging particle be greater than 0.4.

The neutrino emission on the tag side should also result in a large total transverse momentum with respect to the beam direction. The data, however, show a pronounced peak near zero transverse momentum that comes mostly from copious 2-photon and radiative

QED processes. This background is eliminated by requiring the total transverse momentum of the event to be greater than 300 MeV/c (see Fig. 3). About 13.2% of $e\gamma$ and 17.9% of $\mu\gamma$ Monte Carlo events survive all the previous requirements.

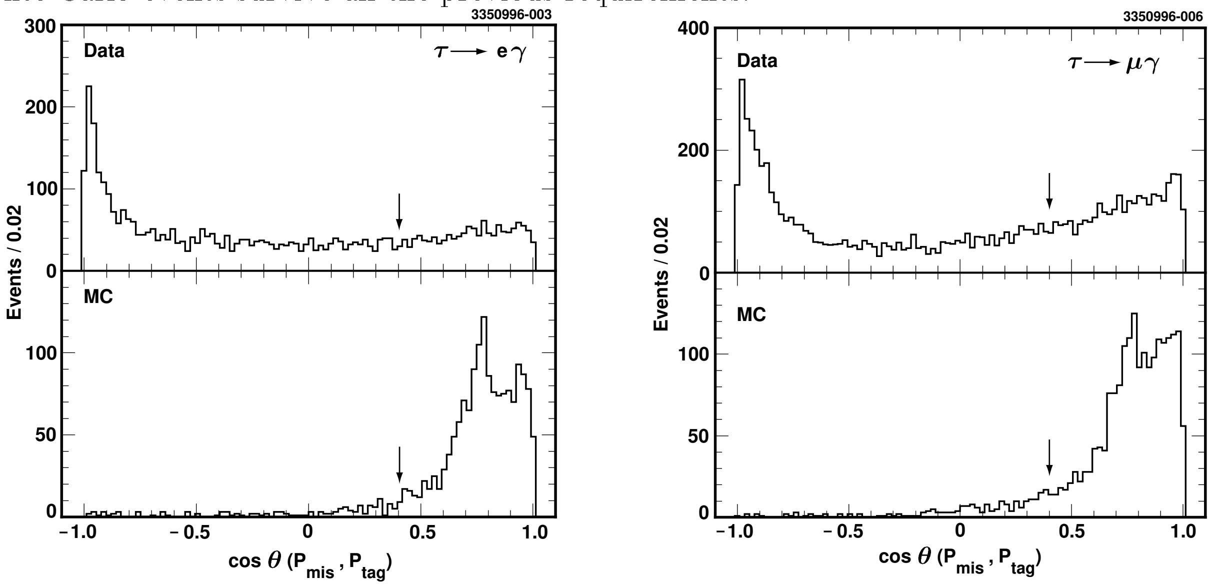

FIG. 2. The cosine of the angle between the missing momentum and the momentum of the tagging track in data and signal Monte Carlo for $\tau \to e\gamma$ and $\tau \to \mu\gamma$. Region $\cos\theta(\vec{p}_{mis}, \vec{p}_{tag}) < 0.4$ is rejected.

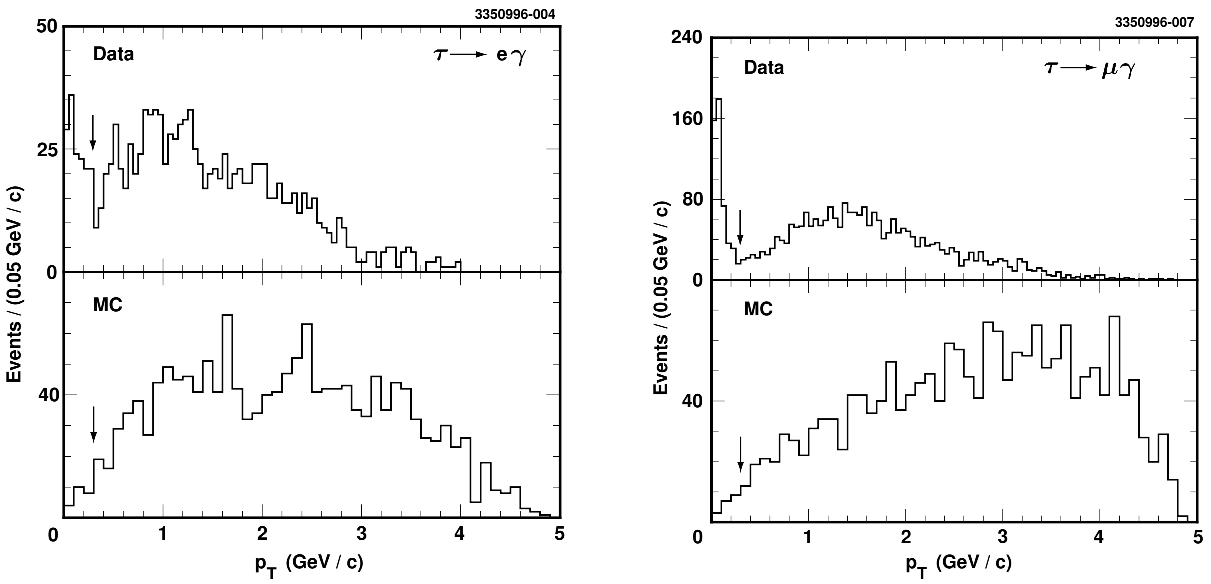

FIG. 3. Total transverse momentum of the event in data and signal Monte Carlo for $\tau \to e\gamma$ and $\tau \to \mu\gamma$. Region $p_T < 0.3$ GeV/c is rejected.

The final signal selection criteria are based on kinematic constraints since a neutrinoless τ decay should have a total energy and an effective mass of the $e\gamma$ or $\mu\gamma$ consistent with the beam energy and τ mass respectively. To define a signal region in the mass vs energy plane we study the corresponding Monte Carlo distributions. We fit each distribution to a gaussian function plus a polynomial. The order of the polynomial was increased until a fit with a confidence level above 20% was obtained. The signal region was then defined to be within ± 3 standard deviations of the fitted gaussian component of the distribution. In Table 1 we show mean values of the τ mass and beam energy and their corresponding resolutions obtained with this fitting technique. The $\pm 3\sigma$ energy cut was imposed on the difference $\Delta E = E_{l\gamma} - E_{run}$ between the total energy of lepton and photon and the beam energy of a particular run. The input τ mass and beam energy in the Monte Carlo samples were 1.777 GeV/c^2 and 5.29 GeV respectively. After these cuts were applied, no $e\gamma$ and three $\mu\gamma$ events remained in the signal region.

TABLE 1. Mean values of effective mass, energy and corresponding resolutions obtained from the fits to Monte Carlo data.

channel	m_τ, GeV/c^2	σ_m, GeV/c^2	$E_{l\gamma} - E_{run}$, GeV	σ_E, GeV	MC efficiency, %
$\tau \to e\gamma$	1.772	0.024	-0.013	0.060	10.1
$\tau \to \mu\gamma$	1.774	0.025	-0.010	0.053	14.4

We estimate the amount of the expected background in each signal region directly from the data by extrapolating it from a sideband region. We assume that the background distributions are linear in the vicinity of m_τ and $\Delta E = 0$ and define the sideband regions between 5 and 8 standard deviations as shown in Fig. 4. The region $|m_{l\gamma} - m_\tau| > 5\sigma_m$, $|\Delta E| > 5\sigma_E$, where $m_{l\gamma}$ is an effective mass of lepton and photon, captures only 4.3% of the $e\gamma$ and 1.8% of the $\mu\gamma$ Monte Carlo samples, so we can neglect the small bias introduced by this extrapolation back into the signal region. The extrapolation from the sidebands allows us to estimate the expected background as 2.0 events for the $e\gamma$ sample and 5.5 events for the $\mu\gamma$ analysis. To check that the background value is stable with respect to the sideband region geometry, we varied the sideband definition. The background estimates were the same within ± 0.5 events for the $e\gamma$ and ± 1.0 event for the $\mu\gamma$ channel. Finally, we estimate the background values as 2.0 ± 0.5 in the $e\gamma$ and 5.5 ± 1.0 in the $\mu\gamma$ analysis. The background rate is higher for the $\mu\gamma$ analysis because the selection criteria for the tagging track are loose, and a large fraction of soft muons that failed the standard identification procedure, mostly from $\mu\mu\gamma$ processes, survive on the tag side.

To understand the origin of the events remaining in the signal region, we applied our selection criteria to about 27×10^6 continuum hadronic Monte Carlo events and 17×10^6 generic τ Monte Carlo events. No hadronic Monte Carlo events satisfied the selection requirements. There are 2 $e\gamma$ and 4 $\mu\gamma$ events from generic τ Monte Carlo that survived all the cuts. After normalization to the same luminosity as the data, these correspond to 0.5 and 1.0 event, respectively, and are in agreement with the numbers of events found in the signal regions.

Before discussing effects caused by systematic uncertainties, we estimate the upper limits on the branching fractions for the $\tau \to e\gamma$ and $\tau \to \mu\gamma$ channels using the statistics of a Poisson process with background [10]:

$$\frac{e^{-(\mu_B+\lambda)} \sum_{n=0}^{n_0} \frac{(\mu_B+\lambda)^n}{n!}}{e^{-\mu_B} \sum_{n=0}^{n_0} \frac{\mu_B^n}{n!}} = 0.1 \ , \qquad (1)$$

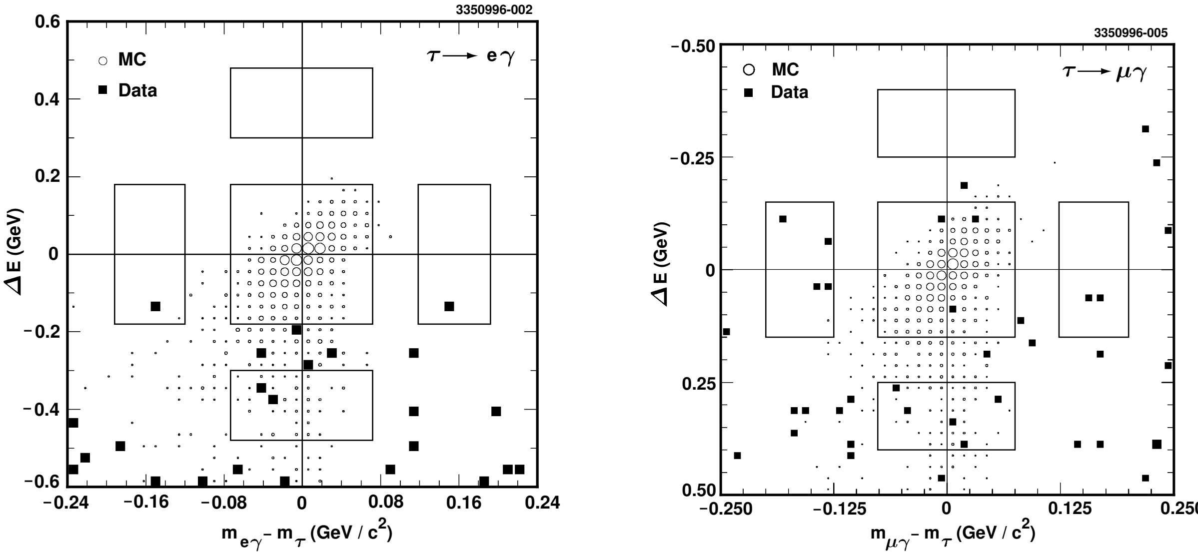

FIG. 4. ΔE vs $m_{l\gamma} - m_\tau$ distributions for $\tau \to e\gamma$ and $\tau \to \mu\gamma$. Solid squares represent the data, open circles represent the signal Monte Carlo distributions.

where λ is the number of events for the upper limit at 90% confidence level, μ_B is the expected background and n_0 is the number of observed events. The upper limit UL for a branching fraction is:

$$UL = \frac{\lambda}{2\epsilon N_{\tau\tau}} \ , \tag{2}$$

where ϵ is the event selection efficiency and $N_{\tau\tau}$ is the total number of τ-pairs produced.

For the $e\gamma$ analysis, $n_0 = 0$ gives us $\lambda = 2.3$ events, and the corresponding upper limit is $B(\tau \to e\gamma) < 2.7 \times 10^{-6}$ at 90% CL. For the $\mu\gamma$ analysis, $n_0 = 3$ and $\mu_B = 5.5$ give us the value of $\lambda = 3.6$ events, and the corresponding upper limit of $B(\tau \to \mu\gamma) < 2.9 \times 10^{-6}$ at 90% CL.

The systematic uncertainty in detector sensitivity $S = 2\epsilon N_{\tau\tau}$ is estimated as 9% for both $e\gamma$ and $\mu\gamma$ channels. This uncertainty is obtained by adding in quadrature uncertainties in track reconstruction efficiency (3%), photon reconstruction efficiency (5%), cut selection (5%), luminosity (1.4%), lepton identification (1.5% for e and 4% for μ) and Monte Carlo statistics (3% for $e\gamma$ and 2.5% for $\mu\gamma$). The upper limit for the $\mu\gamma$ channel is also affected by uncertainty in background estimate. To incorporate systematic uncertainties into the upper limits, we assume that the errors related to $\epsilon N_{\tau\tau}$ and to the background estimates have gaussian distributions and apply a technique described in Ref. [11]. This technique reweights the Poisson probability (1) of observing $\lambda = R \cdot S$ or a larger number of events by a gaussian probability density of the detector sensitivity S and a gaussian probability density of the number of background events μ_B. It gives a new value of the upper limit at 90% CL:

$$\int_0^\infty \int_0^\infty e^{-RS} \frac{\sum_{n=0}^{n_0} \frac{(\mu_B + RS)^n}{n!}}{\sum_{n=0}^{n_0} \frac{\mu_B^n}{n!}} \frac{1}{\sqrt{2\pi}\sigma_S} e^{-(S-S_0)^2/2\sigma_S^2} \frac{1}{\sqrt{2\pi}\sigma_B} e^{-(\mu_B - \mu_{B0})^2/2\sigma_B^2} dS d\mu_B = 0.1 \ , \tag{3}$$

where R is a new upper limit, S_0 is an unbiased estimate of S, μ_{B0} is an estimated value of background, and σ_S/S_0 and σ_B/μ_{B0} are relative uncertainties in detector sensitivity and background estimate respectively. The efficiencies, numbers of events, expected background values and the recalculated upper limits for the decay branching ratios incorporating systematic errors are summarized in Table 2.

TABLE 2. Summary of the results.

channel	MC efficiency, %	n_0	μ_B	λ	Upper limit at 90% CL
$\tau \to e\gamma$	10.1	0	2.0	2.3	2.7×10^{-6}
$\tau \to \mu\gamma$	14.4	3	5.5	3.7	3.0×10^{-6}

These results are limited by the total integrated luminosity and represent a significant improvement over previous analyses.

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REFERENCES

[1] K. Hikasa *et al.*, Physical Review **D45**, S1 (1992).
[2] R. Barbieri and L.J. Hall, Physics Letters **B338**, 212 (1994).
[3] J. Hisano et al., Physics Letters **B357**, 579 (1995).
[4] R. Arnowitt and P. Nath, Physical Review Letters **66**, 2708 (1991).
[5] J. Bartelt *et al.*, Physical Review Letters **73**, 1890 (1994).
[6] A. Bean *et al.*, Physical Review Letters **70**, 138 (1993).
[7] H. Albrecht *et al.*, Zeitschrift für Physik **C55**, 179 (1992).
[8] S. Jadach and Z. Was, Comput. Phys. Commun. **64**, 267 (1991); S. Jadach *et al.*, Comput. Phys. Commun. **76**, 361 (1993).
[9] R. Brun *et al.*, GEANT version 3.15, CERN dd/ee/84-1.
[10] L. Montanet *et al.*, Physical Review **D50**, 1173 (1994).
[11] R. Cousins and V. Highland, Nucl. Instr. and Meth. **A320**, 331 (1992).