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Search for neutrinoless τ decays involving π^0 or η mesons

CLEO Collaboration

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Abstract

We have searched for lepton flavor violating decays of the τ lepton using final states with an electron or a muon and one or two π^0 or η mesons but no neutrinos. The data used in the search were collected with the CLEO II detector at the Cornell Electron Storage Ring (CESR) and correspond to an integrated luminosity of 4.68 fb^{-1}. No evidence for signals was found, resulting in much improved limits on the branching fractions for the one-meson modes and the first upper limits for the two-meson modes.

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In physics all fundamental conservation laws have associated symmetries. Lepton flavor conservation is an experimentally observed phenomenon with no associated symmetry in the Standard Model. Lepton flavor violation is expected in many extensions of the Standard Model such as lepto-quark, supersymmetry, superstring, and left-right symmetric models, and models that include heavy neutral leptons. Gonzalez-Garcia and Valle have calculated [1], in a model with Dirac heavy neutral leptons, the branching fractions for τ decay into one lepton plus a photon or a π^0 or η meson. The branching fractions depend on the heavy neutral lepton masses and mixings. Given the constraints from other measurements, the branching fraction for $\tau^- \to \ell^- \pi^0$ [2] may still be as large as 10^{-6} for neutral lepton masses above a few TeV/c^2 and is higher than that for the radiative decay $\tau^- \to \ell^- \gamma$. Using a Grand Unified Theory (GUT) and superstring inspired model with heavy neutral leptons, Ilakovoc and collaborators [3] have calculated the branching fractions for τ decay into one lepton plus one or two mesons. The branching fractions depend on the masses of the Majorana neutrinos and the mixings between the heavy and light neutrinos. The decay $\tau^- \to \ell^- \pi^0$ may have a branching fraction as large as 10^{-6}. The previous upper limits [4] on the branching fractions for the decays into one lepton and a π^0 or η meson are of the order of $10^{-4} - 10^{-5}$ and for the decays into one lepton and two charged π mesons are of the order of 10^{-6}. There are no published results for the decays into one lepton and two neutral mesons ($\pi^0\pi^0$, $\eta\eta$ or $\pi^0\eta$). The CLEO II experiment with its large sample of τ events may have the sensitivity to observe the lepton flavor violating decays. In this Letter, we present the result of a search for the decays into one lepton and one or two π^0 or η mesons.

The data used in this analysis were collected with the CLEO II detector from e^+e^- collisions at the Cornell Electron Storage Ring (CESR) at a center-of-mass energy $\sqrt{s} \sim 10.6$ GeV. The total integrated luminosity of the data sample is 4.68 fb^{-1}, corresponding to the production of $N_{\tau\tau} = 4.26 \times 10^6$ $\tau^+\tau^-$ events. CLEO II is a general purpose spectrometer [5] with excellent charged particle and shower energy detection. The momenta and specific ionization (dE/dx) of charged particles are measured with three cylindrical drift chambers between 5 and 90 cm from the e^+e^- interaction point, with a total of 67 layers. These are surrounded by a scintillation time-of-flight system and a CsI(Tl) calorimeter with 7800 crystals. These detector systems are installed inside a superconducting solenoidal magnet (1.5 T), surrounded by an iron return yoke instrumented with proportional tube chambers for muon identification.

The $\tau^+\tau^-$ candidate events must contain exactly two oppositely charged tracks. 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 and 5 cm along the beam direction. We divide each event into two hemispheres (signal and tag), each containing one charged track, by the plane perpendicular to the thrust axis, which is calculated using both charged tracks and photons. The total invariant mass of the tag hemisphere must be less than the τ mass ($M_\tau = 1.777$ GeV/c^2) [4]. Because there is no neutrino in the signal hemisphere while there is at least one neutrino undetected in the tag hemisphere, the missing momentum of the event must point toward the tag hemisphere. To suppress the background from radiative Bhabhas and μ pairs, the direction of the missing momentum is further required to satisfy $|cos\theta_{missing}| < 0.90$, where θ is the polar angle with respect to the beam. To reject the background from two-photon interactions, we require the magnitude of the net transverse momentum vector of each event to be greater than 300 MeV/c.

The signal hemisphere must contain an electron or a muon. The electron candidate must have a shower energy to momentum ratio in the range, $0.8 < E/p < 1.1$, and have specific ionization loss within three standard deviations of that expected for an electron. The muon candidate must penetrate more than three absorption lengths of material.

Photon candidates are defined as energy clusters in the calorimeter of at least 60 MeV in the barrel region ($|cos\theta| < 0.80$) or 100 MeV in the endcap region ($0.80 < |cos\theta| < 0.95$). We reconstruct π^0 and η mesons using the $\gamma\gamma$ decay channel. For the decays involving one meson, both photons must be in the barrel, whereas in the decays involving two mesons, at least one photon from each meson is required to be in the barrel. Photons with energies less than 300 MeV must be separated by at least 30 cm from the projection of any charged track on the surface of the calorimeter. There is no explicit cut on the maximum number of photons in the signal hemisphere in order to maintain a high detection efficiency while minimizing the dependence on the Monte Carlo simulation of electromagnetic showers. The signal hemisphere may contain photons not used in the π^0/η reconstruction. However, photon candidates with energy greater than 300 MeV or with a lateral shower profile consistent with that expected for a real photon must be used in the reconstruction. For the one-meson (two-meson) mode, events with more than two (four) such photons in the signal hemisphere are rejected.

To search for neutrinoless τ decays, we select τ candidates with invariant mass M and total energy E within the ranges,

$$
\begin{aligned}
-250 < \Delta E \equiv E - \sqrt{s}/2 < 150 \text{ MeV}, \\
-80 < \Delta M \equiv M - M_\tau < 60 \text{ MeV/c}^2.
\end{aligned}
$$

These requirements correspond approximately to three standard deviation limits, according to the Monte Carlo simulations (see below). We then look for π^0 and η candidates using the $\gamma\gamma$ invariant mass spectrum. The mass spectrum is expressed in standard deviations from the nominal π^0 or η mass [4],

$$
S_{\gamma\gamma} = (M_{\gamma\gamma} - M_{\pi^0,\eta})/\sigma_{\gamma\gamma},
$$

where $\sigma_{\gamma\gamma}$ is the mass resolution calculated from the energy and angular resolution of each photon. The $S_{\gamma\gamma}$ distributions may have multiple entries due to different combinations of photons in the π^0/η reconstruction. The signal region is defined as $-3 < S_{\gamma\gamma} < 2$ while the sideband regions are defined as $-10 < S_{\gamma\gamma} < -5$ and $4 < S_{\gamma\gamma} < 9$. No signal events satisfy these selection criteria for the one-meson modes and two signal events satisfy these selection criteria for the two-meson modes (see Table I). The ΔE vs. ΔM and $S_{\gamma\gamma}$ distributions of these events are shown in Fig. 1.

The detection efficiencies (ϵ) are estimated using a Monte Carlo simulation. In the Monte Carlo, one τ lepton decays according to a two-body (three-body) phase space distribution for the one-meson (two-meson) mode of interest and the other τ lepton decays generically according to the KORALB τ event generator [6]. The detector response is simulated using the GEANT program [7]. The background from generic τ decays is estimated using the KORALB Monte Carlo and the background from hadronic events is estimated using the Lund Monte Carlo [8]. The integrated luminosity of the generic τ and continuum Monte Carlo samples are 4.2 and 2.5 times that of the data. The detection efficiencies and background estimates

TABLE I. Summary of detection efficiencies, signal, backgrounds, 90% C.L. upper limits on the signal (see text) and branching fractions. All blank entries correspond to zero events.

Mode	$\epsilon(\%)$	N_{ob}	N_{bg}	$N_{bg}^{\tau MC}$	$N_{bg}^{q\bar{q}\ MC}$	λ_0	λ_G	λ_P	λ	$\mathcal{B}(10^{-6})$
$e^-\pi^0$	8.71					2.30	2.32	2.30	2.32	3.7
$\mu^-\pi^0$	8.08		0.5			2.30	2.32	2.30	2.32	4.0
$e^-\eta$	9.97					2.30	2.32	2.30	2.32	8.2
$\mu^-\eta$	8.49					2.30	2.32	2.30	2.32	9.6
$e^-\pi^0\pi^0$	5.12				0.4	2.30	2.34	2.30	2.34	6.5
$\mu^-\pi^0\pi^0$	3.71	1		0.5		3.89	3.97	3.61	3.68	14
$e^-\eta\eta$	6.09					2.30	2.34	2.30	2.34	35
$\mu^-\eta\eta$	3.48					2.30	2.34	2.30	2.34	60
$e^-\pi^0\eta$	5.52	1				3.89	3.96	3.61	3.68	24
$\mu^-\pi^0\eta$	3.73			0.2	0.4	2.30	2.34	2.30	2.34	22

are summarized in Table I. Also listed are background estimates based on the numbers of events in the sideband (N_{sb}) and corner-band (N_{cb}), if appropriate, regions in the $S_{\gamma\gamma}$ distribution, $N_{bg} = \frac{1}{2}N_{sb} - \frac{1}{4}N_{cb}$, assuming a linear background distribution. In the data, N_{sb} and N_{cb} are measured to be zero except for $\tau^- \to \mu^-\pi^0$ which has $N_{sb} = 1$, indicating that the analysis is almost background free. Because of the paucity of events, rather than comparing the number of events observed to the expected background in each individual mode, we will sum over all the modes for comparison. The two events observed is somewhat higher than the 0.5 events expected from the sideband technique but consistent with the 1.5 events estimated by the Monte Carlo simulations. There is therefore no significant evidence for a signal. The background estimated from the data using the sideband technique is used to compute the upper limit on the signal.

The upper limit on the branching fraction is related to the upper limit λ on the signal by

$$\mathcal{B} = \frac{\lambda}{2\epsilon N_{\tau\tau}\mathcal{B}_1\mathcal{B}_{\pi^0}^m\mathcal{B}_\eta^n}$$

where $\mathcal{B}_1$ is the inclusive 1-prong branching fraction [4], $\mathcal{B}_{\pi^0}$ ($\mathcal{B}_\eta$) is the branching fraction [4] for $\pi^0 \to \gamma\gamma$ ($\eta \to \gamma\gamma$), and m (n) is the number of π^0 (η) mesons in the final state. The 90% confidence level upper limits on the signal are summarized in Table I. We calculate the upper limit λ using a Monte Carlo technique, which incorporates both the Poisson statistics of the signal and the systematic errors. The systematic errors include the statistical uncertainty in the background estimate due to limited statistics in the sideband (and corner-band if appropriate) regions. This statistical uncertainty is incorporated using Poisson statistics [9]. All other sources of systematic errors are incorporated using Gaussian statistics. These include the uncertainties in the $\tau^+\tau^-$ cross section (1.0%), luminosity (1.0%), track reconstruction (3.0%), lepton identification (1.5% for e and 4.0% for μ), π^0 or η meson reconstruction (5.0% per meson), branching fraction of $\eta \to \gamma\gamma$ (0.8%) [4], and the statistical uncertainties in the detection efficiencies due to limited Monte Carlo samples (2-3% for the one-meson modes and 3-4% for the two-meson modes). These uncertainties are added in quadrature in computing λ. For comparison, we also list the upper limits λ_0, λ_G and λ_P. λ_0 is calculated using only Poisson statistics for the signal, λ_G includes all the systematic errors except the statistical uncertainty in the background estimate, and λ_P includes only the statistical error in the background estimate. λ_G is larger than λ_0 as expected. However, λ_P is smaller than λ_0 when the observed number of events is non-zero and the estimated background is zero [9]. This is not unexpected because in the calculation of λ_P we allow for the estimated zero background to fluctuate up, in contrast to λ_0 in which the background is estimated to be zero with no uncertainty.

The upper limits on the branching fractions for the modes involving one neutral meson are significantly more stringent than the published results [4]. There are no previous limits for the modes involving two neutral mesons. The limits for the $\pi^0\pi^0$ modes are comparable with the limits for the $\pi^+\pi^-$ modes [4]. In the model of Gonzalez-Garcia and Valle [1], the limit on $\tau^- \to e^-\pi^0$ extends the heavy lepton mass vs. mixing region previously excluded from other measurements: neutral leptons with mass greater than 6-10 TeV/c^2 for mixing with the third generation in the range 0.05-0.02 are now excluded [10].

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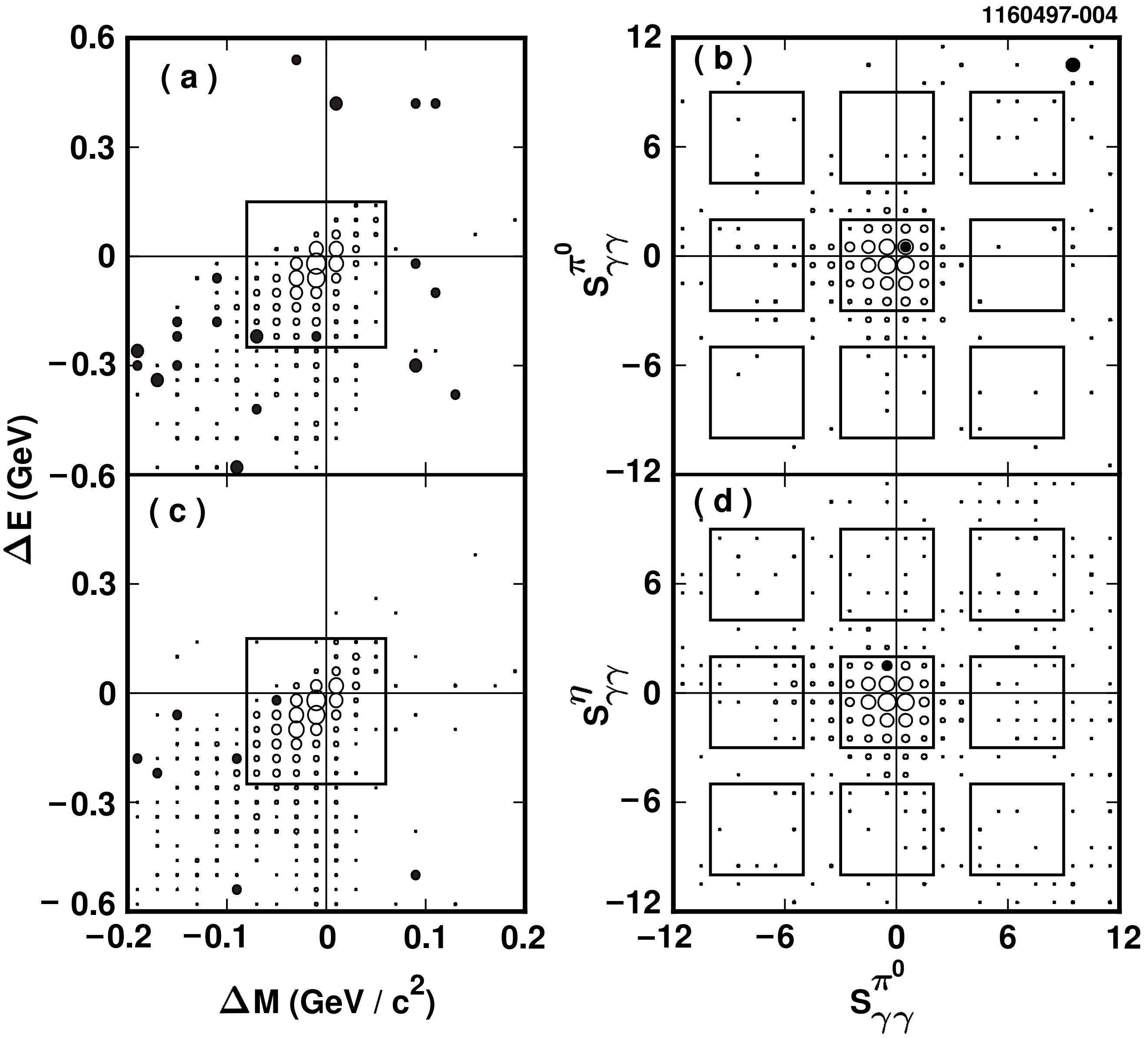

FIG. 1. (a) ΔE vs. ΔM distribution of $\tau^- \to \mu^- \pi^0 \pi^0$ candidates with $-12 < S_{\gamma\gamma} < 12$ in the data and signal Monte Carlo (open circles) samples. (b) $S_{\gamma\gamma}$ vs. $\mathrm{S}_{\gamma\gamma}$ distribution for the center box in the ΔE vs. ΔM plane. (c) and (d) are the corresponding distributions for $\tau^- \to e^- \pi^0 \eta$. The signal, sideband, and corner-band regions in the $S_{\gamma\gamma}$ vs. $\mathrm{S}_{\gamma\gamma}$ plane are indicated by the 9 boxes. The size of the circles is proportional to the number of entries. The scale for the signal Monte Carlo event distributions is arbitrary.