PHYSICAL REVIEW D **66**, 071101(R) (2002)

Search for neutrinoless τ decays involving the K_S^0 meson

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(Received 6 August 2002; published 2 October 2002)

We have searched for lepton flavor violating decays of the τ lepton with one or two K_S^0 mesons in the final state. The data used in the search were collected with the CLEO II and II.V detectors at the Cornell Electron Storage Ring (CESR) and correspond to an integrated luminosity of 13.9 fb^{-1} at the $\Upsilon(4S)$ resonance. No evidence for signals were found; therefore, we have set 90% confidence level (C.L.) upper limits on the branching fractions $\mathcal{B}(\tau^-\to e^-K_S^0)<9.1\times10^{-7}$, $\mathcal{B}(\tau^-\to\mu^-K_S^0)<9.5\times10^{-7}$, $\mathcal{B}(\tau^-\to e^-K_S^0K_S^0)<2.2\times10^{-6}$, and $\mathcal{B}(\tau^-\to\mu^-K_S^0K_S^0)<3.4\times10^{-6}$. These represent significantly improved upper limits on the two-body decays and first upper limits on the three-body decays.

DOI: 10.1103/PhysRevD.66.071101 PACS number(s): 13.35.Dx, 11.30.Hv, 14.40.Aq, 14.60.Fg

In physics, all fundamental conservation laws are expected to have associated symmetries. Lepton flavor conservation, however, is an experimentally observed phenomena with no associated symmetry in the standard model. Lepton flavor violation (LFV) is expected in many extensions of the standard model such as leptoquark, supersymmetry, superstring, left-right symmetric models, and models that include heavy neutral leptons [1]. Experimentally, both Super Kamiokande [2] and SNO [3] observe neutrino oscillation, which may imply LFV in the neutrino sector; therefore LFV is expected to occur in charged lepton decay at some branching fraction, albeit very small. The τ lepton provides a clean laboratory for such searches. Ilakovac [4] has calculated upper limits on branching fractions for many neutrinoless LFV modes within a model involving heavy Dirac neutrinos. The branching fractions depend on the heavy neutrino masses and mixings. For the decays $\tau^- \to \ell^- K_S^0$ [5], the branching fractions are of $\mathcal{O}(10^{-16})$, where ℓ can be e or μ. For the decays $\tau^- \to \ell^- K_S^0 K_S^0$ or $\tau^- \to \ell^- K^+ K^-$, the branching fractions are of $\mathcal{O}(10^{-7})$. The decays with two kaons in the final state are therefore of particular experimental interest. Previous published upper limits on the branching fractions for the decays $\tau^- \to \ell^- K_S^0$ are of $\mathcal{O}(10^{-4})$ [6]. There are no previous results for the decays $\tau^- \to \ell^- K_S^0 K_S^0$. In this paper, we present the results of a search for the decays into one lepton and one or two K_S^0 mesons, with the K_S^0 decaying into two charged pions.

The data used in this analysis were collected using the CLEO detector [7] 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 13.9 fb^{-1} corresponding to the production of $N_{\tau\tau} = 1.27 \times 10^7$ $\tau^+\tau^-$ events. The CLEO detector is a general purpose spectrometer with excellent charged particle and shower energy detection. The momenta of charged particles are measured with three drift chambers between 5 and 90 cm from the e^+e^- interaction point (IP), with a total of 67 layers. For $\sim$63% of the data collected, the innermost tracking chamber was replaced by a three-layer silicon vertex detector [8]. The specific ionization (dE/dx) of charged particles is also measured in the main drift chamber. The tracking system is surrounded by a scintillation time-of-flight system and a CsI(T1) 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 four or six charged tracks with zero net charge. The polar angle θ of each track with respect to the beam must satisfy $|\cos\theta| < 0.90$. To reject beam-gas events, the distance of closest approach of each non-K_S^0 track to the IP must be within 0.5 cm transverse to the beam and 5 cm along the beam direction. Photons are defined as energy clusters in the calorimeter with at least 60 MeV in the barrel ($|\cos\theta| < 0.80$) or 100 MeV in the end cap ($0.80 < |\cos\theta| < 0.95$). We further require every photon to be separated from the projection of any charged track by at least 30 cm unless its energy is greater than 300 MeV. In order to diminish QED background such as radiative Bhabha and μ-pair events with photon conversion, we require each event to have total energy less than 95% of the center-of-mass energy. This requirement rejects most of the QED background, while incurring a small loss in detection efficiency.

We divide each event into two hemispheres (signal and tag), one containing one charged track and the other containing three or five charged tracks, using the plane perpendicular to the thrust axis [9]. The thrust axis is calculated from both charged tracks and photons. The invariant mass of the tag hemisphere must be less than the τ mass, $M_\tau = 1.777$ GeV/c^2 [10]. The signal hemisphere must contain an electron or a muon and one or two K_S^0 mesons. The electron candidate must have shower energy to momentum ratio in the range, $0.85 < E/p < 1.10$, and when available, the specific ionization lost must be consistent with that expected for an electron. The muon candidate must penetrate at least three absorption lengths of iron. The K_S^0 candidate is reconstructed in the $\pi^+\pi^-$ final state with a detached vertex, and the invariant mass must be within approximately three standard deviations of the nominal mass, $485 < m_{\pi\pi} < 510$ MeV/c^2, as determined from a signal Monte Carlo simulation (see below). In order to diminish radiative Bhabha and μ-pair events further, neither pion should be consistent with identification as an electron. Since 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, $0 < \cos\theta_{tag\ missing} < 1.0$. In order to suppress the background from radiative Bhabha and μ-pair events, the direction of the missing momentum of the event is required to satisfy $|\cos\theta_{missing}| < 0.90$. For the decay $\tau^- \to e^- K_S^0$, $\cos\theta_{tag\ missing}$ is further restricted to be less than 0.99 to reduce the radiative backgrounds. This corresponds to the minimum ratio of background to detection efficiency. The background is estimated from the sidebands in the invariant mass vs total energy distribution of the decay candidates.

To search for decay candidates, we select τ candidates with invariant mass and total energy consistent with the expectations. The following kinematic variables are used to select the candidate events:

$$\Delta E = E - E_{beam}$$

$$\Delta M = M - M_\tau,$$

where E_{beam} is the beam energy, and E and M are the reconstructed τ energy and mass. The ΔE vs ΔM distributions of the decay candidates in the data and signal Monte Carlo samples are shown in Figs. 1 and 2. The center of the signal region is slightly shifted from zero in the ΔE vs ΔM plane to account for initial state radiation and shower leakage. The signal region is defined as the area within three standard deviations (σ) of the expectation for both kinematic variables, as determined from a signal Monte Carlo simulation. In the Monte Carlo simulation, one τ lepton decays according to two- or three-body phase space for the mode of interest, and the other τ lepton decays generically according to the KORALB-TAUOLA τ event generator [11]. The phase space

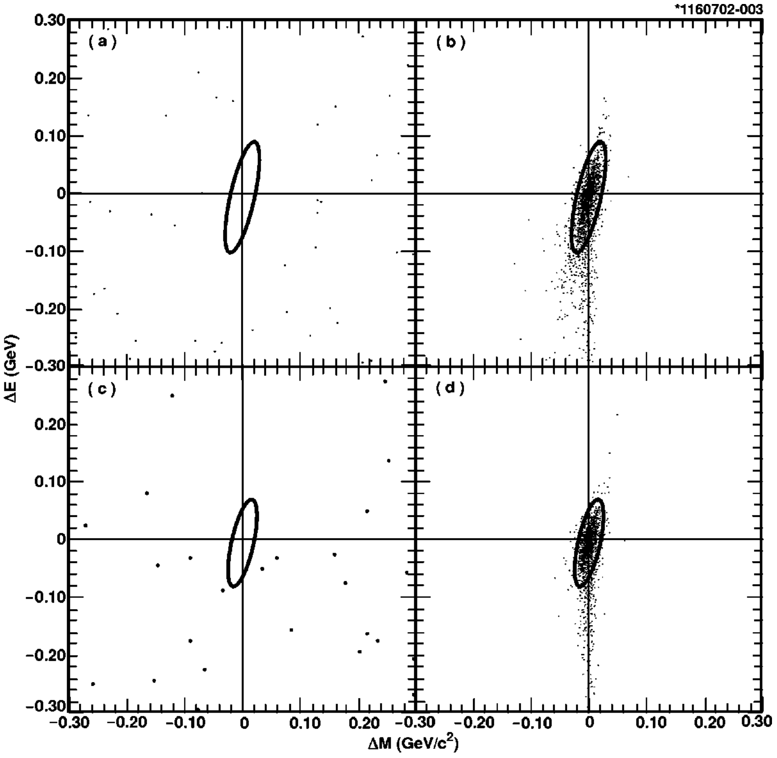

FIG. 1. ΔE vs ΔM distribution of the (a) data and (b) signal Monte Carlo sample for the decay $\tau^- \to e^- K_S^0$; (c) and (d) show the corresponding distributions for $\tau^- \to \mu^- K_S^0$. The normalization of the signal Monte Carlo sample is arbitrary. The ellipses indicate the signal region (see text).

model is appropriate for an unpolarized tau. If the Lorentz structure of the neutrinoless decay is $V-A$, as in the standard model, correlations between the spins of the two τ's in the event will lead to slightly higher detection efficiency than phase space, while $V+A$ decays will lead to lower detection efficiency. The detector response is simulated using the GEANT program [12]. The estimated detection efficiencies (ϵ) [13] are summarized in Table I.

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

$$\mathcal{B}=\frac{\lambda}{2\epsilon N_{\tau\tau}\mathcal{B}_1(\mathcal{B}_{K_S^0\to\pi^+\pi^-})^n},$$

where $\mathcal{B}_1=(84.71\pm0.13)\%$ is the inclusive 1-prong branch-

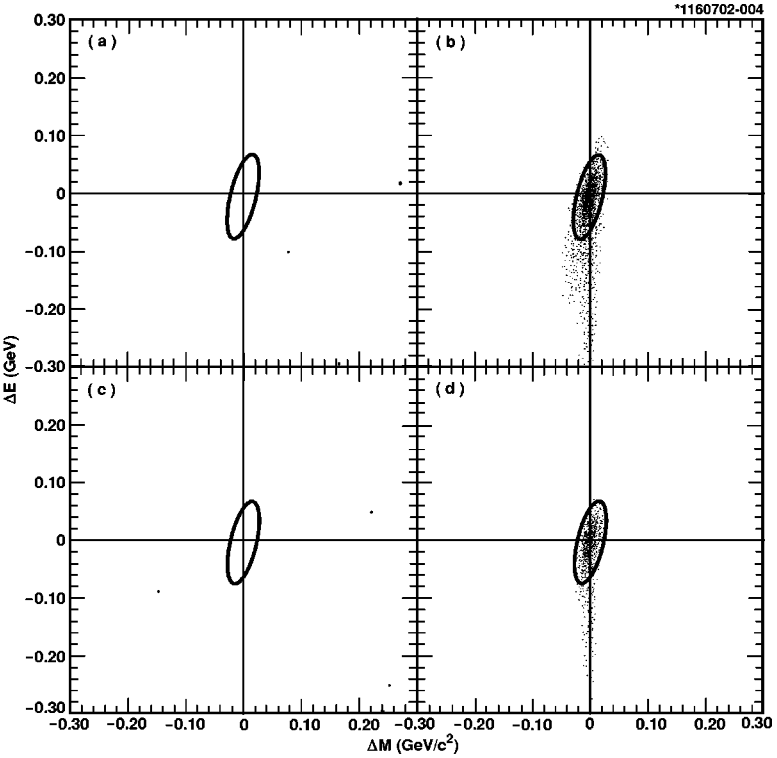

FIG. 2. ΔE vs ΔM distribution of the (a) data and (b) signal Monte Carlo sample for the decay $\tau^- \to e^- K_S^0 K_S^0$; (c) and (d) show the corresponding distributions for $\tau^- \to \mu^- K_S^0 K_S^0$. The normalization of the signal Monte Carlo sample is arbitrary. The ellipses indicate the signal region (see text).

TABLE I. Summary of detection efficiency (with statistical uncertainty), 90% C.L. upper limits on the branching fraction with and without including systematic uncertainty.

Mode	ϵ (%)	$\mathcal{B}(10^{-7})$ (stat)	$\mathcal{B}(10^{-7})$
$e^- K_S^0$	19.4 ± 0.4	8.5	9.1
$\mu^- K_S^0$	19.0 ± 0.4	8.7	9.5
$e^- K_S^0 K_S^0$	12.1 ± 0.1	20	22
$\mu^- K_S^0 K_S^0$	8.0 ± 0.1	30	34

ing fraction [10], $\mathcal{B}_{K_S^0 \to \pi^+ \pi^-} = (68.61 \pm 0.28)\%$ is the branching fraction for K_S^0 to decay to two charged pions, and n is the number of K_S^0 mesons in the final state. No candidate decays are observed, so we take λ as 2.44 events in each mode at 90% confidence level, according to the frequentist method [14]. The upper limits on the branching fractions with and without systematic uncertainties are shown in Table I. The systematic uncertainties include the $\tau^+ \tau^-$ cross section (1%), luminosity (1%), track reconstruction efficiency (1% per charged track), K_S^0 detection efficiency (2% per K_S^0), lepton identification (1.5% for electron and 4% for muon), and the statistical uncertainties in the detection efficiencies due to limited Monte Carlo samples (1–2 %).

Black *et al.* [15] have analyzed the constraints on the new physics scale for dimension-six fermionic effective operators involving τ-μ mixing, motivated by the observed ν_μ-ν_τ oscillation. The most stringent lower limits from exotic heavy quarks and τ decays on the physics scale of the operators involving quarks are ~10 TeV. The new upper limit on $\mathcal{B}(\tau^- \to \mu^- K_S^0)$ presented in this paper yields a lower limit of 17.3 and 18.2 TeV for the axial vector and pseudoscalar operators, respectively.

In conclusion, we have searched for τ decays involving K_S^0 mesons that violate lepton flavor, but find no evidence for a signal. This results in improved upper limits for the decays $\tau^- \to \ell^- K_S^0$ and first upper-limits for the decays $\tau^- \to \ell^- K_S^0 K_S^0$. The upper limits for the $\tau^- \to \ell^- K_S^0 K_S^0$ final states are more stringent than those found previously for $\ell^- K^+ K^-$ [16].

We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. M. Selen thanks the PFF program of the NSF and the Research Corporation, and A.H. Mahmood thanks the Texas Advanced Research Program. This work was supported by the National Science Foundation, and the U.S. Department of Energy.

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