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Search for lepton flavor violating τ^- decays into $\ell^- K_S^0$ and $\ell^- K_S^0 K_S^0$

Belle Collaboration

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ABSTRACT

We have searched for the lepton-flavor-violating decays $\tau^- \to \ell^- K_S^0$ and $\ell^- K_S^0 K_S^0$ ($\ell = e$ or μ), using a data sample of 671 fb^{-1} collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. No evidence for a signal was found in any of the decay modes, and we set the following upper limits for the branching fractions: $\mathcal{B}(\tau^- \to e^- K_S^0) < 2.6 \times 10^{-8}$, $\mathcal{B}(\tau^- \to \mu^- K_S^0) < 2.3 \times 10^{-8}$, $\mathcal{B}(\tau^- \to e^- K_S^0 K_S^0) < 7.1 \times 10^{-8}$ and $\mathcal{B}(\tau^- \to \mu^- K_S^0 K_S^0) < 8.0 \times 10^{-8}$ at the 90% confidence level.

1. Introduction

Lepton flavor violation (LFV) in charged lepton decays is forbidden in the Standard Model (SM) or highly suppressed if neutrino mixing is included. However, LFV appears in various extensions of the SM. In particular, the lepton-flavor-violating decays $\tau^- \to \ell^- K_S^0$ and $\tau^- \to \ell^- K_S^0 K_S^0$ (where $\ell = e$ or μ) are enhanced in supersymmetric and many other models [1–6]. Some of these models predict branching fractions which, for certain combinations of model parameters, can be as high as 10^{-7}; this level is already accessible in high-statistics *B*-factory experiments. Previously, we obtained 90% confidence level (C.L.) upper limits for the $\tau^- \to \ell^- K_S^0$ branching fractions ($\mathcal{B}$) using 281 fb^{-1} of data; the results were $\mathcal{B}(\tau^- \to e^- K_S^0) < 5.6 \times 10^{-8}$ and $\mathcal{B}(\tau^- \to \mu^- K_S^0) < 4.9 \times 10^{-8}$ [7]. The BaBar Collaboration has recently obtained 90% C.L. upper limits of $\mathcal{B}(\tau^- \to e^- K_S^0) < 3.3 \times 10^{-8}$ and $\mathcal{B}(\tau^- \to \mu^- K_S^0) < 4.0 \times 10^{-8}$ using a data sample of 469 fb^{-1} [8]. The most restrictive existing upper limits $\mathcal{B}(\tau^- \to e^- K_S^0 K_S^0) < 2.2 \times 10^{-6}$ and $\mathcal{B}(\tau^- \to \mu^- K_S^0 K_S^0) < 3.4 \times 10^{-6}$ at the 90% C.L. were set by the CLEO experiment using 13.9 fb^{-1} of data [9]. In this Letter, we present a search for the lepton-flavor-violating decays $\tau^- \to \ell^- K_S^0$ and $\ell^- K_S^0 K_S^0$ ($\ell = e$ or μ)[1] using 671 fb^{-1} of data collected at the $\Upsilon(4S)$ resonance and 60 MeV below with the Belle detector at the KEKB asymmetric-energy e^+e^- collider [10].

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL), all located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). The detector is described in detail elsewhere [11].

Leptons are identified using likelihood ratios calculated from the responses of various detector subsystems. For electron identification, the likelihood ratio is defined as $\mathcal{P}(e) = \mathcal{L}_e/(\mathcal{L}_e + \mathcal{L}_x)$, where $\mathcal{L}_e$ and $\mathcal{L}_x$ are the likelihoods for electron and non-electron hypotheses, respectively, determined using the ratio of the energy deposit in the ECL to the momentum measured in the SVD and CDC, the shower shape in the ECL, the matching between the position of the charged track trajectory and the cluster position in the ECL, the hit information from the ACC, and the dE/dx information in the CDC [12]. For muon identification, the likelihood ratio is defined as $\mathcal{P}(\mu) = \mathcal{L}_\mu/(\mathcal{L}_\mu + \mathcal{L}_\pi + \mathcal{L}_K)$, where $\mathcal{L}_\mu$, $\mathcal{L}_\pi$ and $\mathcal{L}_K$ are the likelihoods for the muon, pion and kaon hypotheses, respectively, based on the matching quality and penetration depth of associated hits in the KLM [13]. For this measurement, we use hadron identification likelihood variables based on the hit information from the ACC, the dE/dx information in the CDC, and the particle time-of-flight from the TOF. To distinguish hadron species, we use likelihood ratios, $\mathcal{P}(i/j) = \mathcal{L}_i/(\mathcal{L}_i + \mathcal{L}_j)$, where $\mathcal{L}_i$ ($\mathcal{L}_j$) is the likelihood for the detector response to a track with flavor hypothesis i (j).

In order to optimize the event selection and estimate the signal efficiency, we use Monte Carlo (MC) samples. The signal

[1] Unless otherwise stated, charge-conjugate decays are included throughout this Letter.

and background events from generic $\tau^+\tau^-$ decays are generated by KKMC/TAUOLA [14]. The signal MC samples are generated by KKMC assuming a phase space model for the τ decay. Other backgrounds, including $B\bar{B}$ and continuum $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) events, Bhabha events, and two-photon processes, are generated by EvtGen [15], BHLUMI [16], and AAFH [17], respectively. The Belle detector response is simulated by a GEANT 3 [18] based program. The event selection is optimized mode-by-mode since the backgrounds are mode dependent. All kinematic variables are calculated in the laboratory frame unless otherwise specified. In particular, variables calculated in the e^+e^- center-of-mass (CM) system are indicated by the superscript "CM".

2. Data analysis

We search for $\tau^+\tau^-$ events, in which one τ (signal side) decays into ℓK_S^0 or $\ell K_S^0 K_S^0$, while the other τ (tag side) decays into a final state with one charged track, any number of additional photons and neutrinos. We reconstruct each K_S^0 meson candidate from a $\pi^+\pi^-$ pair. By selecting decays into one charged track on the tag side, we reduce background from $B\bar{B}$ and $q\bar{q}$ events. All charged tracks and photons are required to be reconstructed within a fiducial volume, defined by $-0.866 < \cos\theta < 0.956$, where θ is the polar angle with respect to the direction opposite to the e^+ beam. We select charged tracks with momenta transverse to the e^+ beam $p_t > 0.1$ GeV/c and photons with energies $E_\gamma > 0.1$ GeV.

Candidate τ-pair events are required to have four or six charged tracks with zero net charge for the ℓK_S^0 and $\ell K_S^0 K_S^0$ modes, respectively. Events are separated into two hemispheres corresponding to the signal (three-prong and five-prong for the ℓK_S^0 and $\ell K_S^0 K_S^0$ modes, respectively) and tag (one-prong) sides by the plane perpendicular to the thrust axis [19].

We require one or two K_S^0 candidates for the ℓK_S^0 and $\ell K_S^0 K_S^0$ modes, respectively. The K_S^0 is reconstructed from two oppositely charged tracks on the signal side that have an invariant mass 0.482 GeV/c^2 $< M_{\pi^+\pi^-} <$ 0.514 GeV/c^2, assuming the pion mass for both tracks. The $\pi^+\pi^-$ vertex is required to be displaced from the interaction point (IP) in the direction of the pion pair momentum [20]. In order to avoid fake K_S^0 candidates from photon conversions (i.e., $\gamma \to e^+e^-$), the invariant mass reconstructed by assigning the electron mass to the tracks, is required to be greater than 0.2 GeV/c^2. The electron and muon identification criteria are $\mathcal{P}(e) > 0.9$ with momentum $p > 0.3$ GeV/c and $\mathcal{P}(\mu) > 0.9$ with $p > 0.6$ GeV/c, respectively. In order to take into account the emission of bremsstrahlung photons from the electron, the momentum of each electron track is reconstructed by adding the momentum of every photon within 0.05 radians of the track direction. The electron (muon) identification efficiency for the ℓK_S^0 modes is 92% (87%) and that for the $\ell K_S^0 K_S^0$ modes is 79% (81%). The difference of efficiencies between ℓK_S^0 and $\ell K_S^0 K_S^0$ is due to the different signal momentum distributions. The probability to misidentify a pion as an electron and a muon is below 0.5% and 3%, respectively.

In order to suppress background from $q\bar{q}$ events, the following requirements on the number of the photon candidates on the signal and tag side (n_γ^{SIG} and n_γ^{TAG}) are imposed: $n_\gamma^{\mathrm{SIG}} \leqslant 1$ and $n_\gamma^{\mathrm{TAG}} \leqslant 3$. For the ℓK_S^0 modes only, we also require $n_\gamma^{\mathrm{TAG}} \leqslant 1$ if the track of the tag side is a lepton to reduce the background, in particular from $D^+ \to \ell^+\nu K_S^0(\to \pi^0\pi^0)$.

To ensure that the missing particles are neutrinos rather than photons or charged particles that fall outside the detector acceptance, we impose additional requirements on the missing momentum vector, $\vec{p}_{\mathrm{miss}}$, calculated by subtracting the vector sum of the momenta of all tracks and photons from the sum of the e^+ and e^- beam momenta. We require that the magnitude of $\vec{p}_{\mathrm{miss}}$ be greater

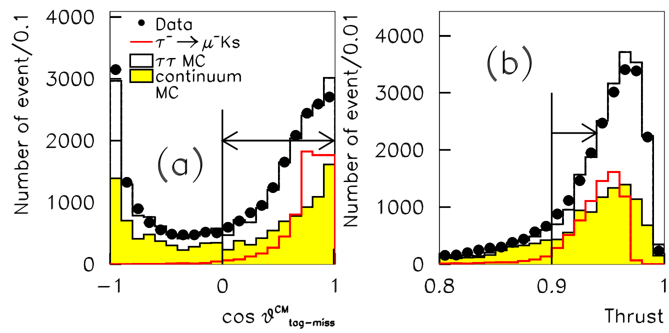

Fig. 1. Kinematic distributions used in the event selection of the $\tau^- \to \mu^- K_S^0$ mode: (a) the cosine of the opening angle between a charged track on the tag side and the missing momentum in the CM system ($\cos\theta^{\mathrm{CM}}_{\mathrm{tag-miss}}$); and (b) the magnitude of the thrust. The signal MC ($\tau^- \to \mu^- K_S^0$) distributions with arbitrary normalization are shown for comparison; the background MC distributions are normalized to the data luminosity. Selected regions are indicated by the arrows from the marked cut boundaries.

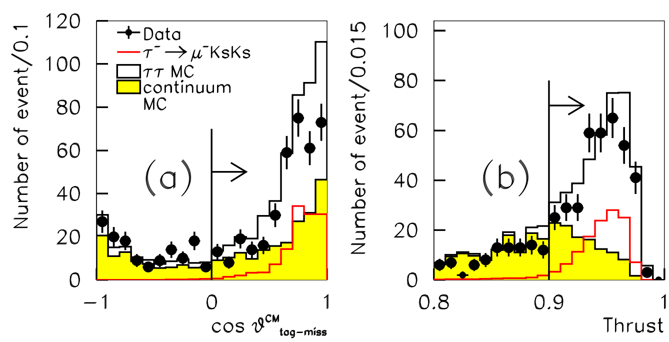

Fig. 2. Kinematic distributions used in the event selection of the $\tau^- \to \mu^- K_S^0 K_S^0$ mode: (a) the cosine of the opening angle between a charged track on the tag side and the missing momentum in the CM system ($\cos\theta^{\mathrm{CM}}_{\mathrm{tag-miss}}$); and (b) the magnitude of the thrust. The signal MC ($\tau^- \to \mu^- K_S^0 K_S^0$) distributions with arbitrary normalization are shown for comparison; the background MC distributions are normalized to the data luminosity. Selected regions are indicated by the arrows from the marked cut boundaries.

than 0.4 GeV/c and that its direction point into the fiducial volume of the detector. Since neutrinos are emitted only on the tag side, the direction of $\vec{p}_{\mathrm{miss}}$ should lie within the tag side of the event. The cosine of the opening angle between $\vec{p}_{\mathrm{miss}}$ and the tag-side track in the CM system, $\cos\theta^{\mathrm{CM}}_{\mathrm{tag-miss}}$, should be $0.0 < \cos\theta^{\mathrm{CM}}_{\mathrm{tag-miss}}$ for both modes (see Figs. 1(a) and 2(a)). For the ℓK_S^0 modes, we also require that $\cos\theta^{\mathrm{CM}}_{\mathrm{tag-miss}} < 0.99$ to reduce background from Bhabha, $\mu^+\mu^-$ and two-photon events, as radiated photons from the tag-side track result in missing momentum if they overlap with the ECL clusters associated with the tag-side track.

MC simulation shows that two main background sources are $q\bar{q}$ continuum and cross-feed from τ decays whereas the background from Bhabha, $\mu^+\mu^-$ and two-photon events is negligible. To further suppress the $q\bar{q}$ background, the magnitude of the thrust is required to be larger than 0.9. As shown in Figs. 1(b) and 2(b), the signal efficiency is nearly unchanged, while the large $q\bar{q}$ background is substantially reduced (by about 70% and 50% for the ℓK_S^0 and $\ell K_S^0 K_S^0$ modes, respectively). The invariant mass reconstructed from the charged track and any photon on the tag side is required to be less than 1.0 and 1.777 GeV/c^2 for the ℓK_S^0 and $\ell K_S^0 K_S^0$ modes, respectively. For the ℓK_S^0 modes, we impose a kaon veto $\mathcal{L}(K/\pi) < 0.6$ if the track on the tag side is a hadron, to suppress $e^+e^- \to q\bar{q}$ background; due to the conservation of strangeness by

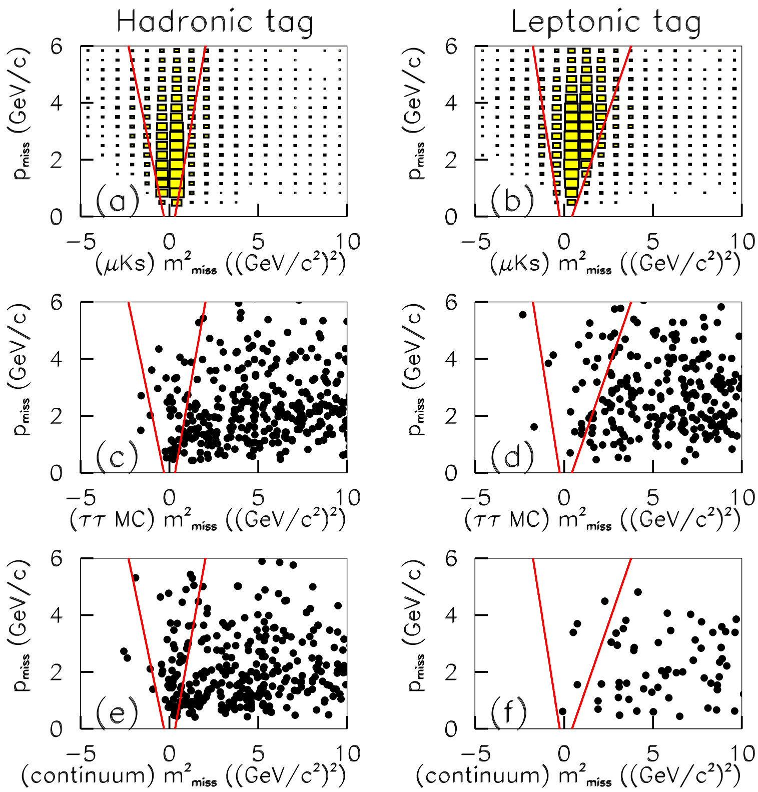

Fig. 3. Scatter-plots of p_{miss} vs. m^2_{miss}: (a), (c) and (e) show the signal MC ($\tau^- \to \mu^- K^0_S$), the generic $\tau^+\tau^-$ MC and $q\bar{q}$ distributions, respectively, for the hadronic tags while (b), (d) and (f) show the same distributions for the leptonic tags. Selected regions are indicated by lines.

the strong interaction, the K^0_S in such events is often accompanied by another kaon.

Both kinematic distributions for the ℓK^0_S modes shown in Fig. 1 are in reasonable agreement between data and background MC, while for the $\ell K^0_S K^0_S$ modes a clear difference is observed. This difference between the data and background MC in Fig. 2 originates from large uncertainties in the branching fractions $\mathcal{B}(\tau^- \to \pi^- K^0_S K^0_S \nu_\tau) = (2.4 \pm 0.5) \times 10^{-4}$ and $\mathcal{B}(\tau^- \to \pi^- K^0 \bar{K}^0 \pi^0 \nu_\tau) \times (\mathcal{B}(K^0 \to K^0_S))^2 = (3.1 \pm 2.3) \times 10^{-4} \times 1/4$ and the dynamics of these decays [21]. Since the final estimate of the background uses information from the data, this discrepancy does not directly affect our results.

Finally, to suppress backgrounds from generic $\tau^+\tau^-$ and $q\bar{q}$ events, we apply a selection based on the magnitude of the missing momentum p_{miss} and the missing mass squared m^2_{miss}. The latter is defined as $E^2_{miss} - p^2_{miss}$, where $E_{miss} = E_{total} - E_{vis}$, E_{total} is the sum of the beam energies and E_{vis} is the total visible energy. We apply different selection criteria depending on the type of the one-prong tag: the number of emitted neutrinos is two if the tagging track is an electron or muon (leptonic tag) while it is one if the tagging track is a hadron (hadronic tag). The requirements are listed in Table 1 (see also Fig. 3). While this condition retains 83% (71%) of the ℓK^0_S ($\ell K^0_S K^0_S$) signal events, 84% (95%) of the generic $\tau^+\tau^-$ and 80% (86%) of the continuum background are removed.

3. Results

Signal candidates are examined in two-dimensional plots of the ℓK^0_S and $\ell K^0_S K^0_S$ invariant mass, M_{sig} ($= M_{\ell K^0_S}$, $M_{\ell K^0_S K^0_S}$), and the difference of their energy from the beam energy in the CM system, ΔE. A signal event should have M_{sig} close to the τ-lepton mass and ΔE close to zero. For both modes, the M_{sig} and ΔE resolutions are parameterized from the MC distributions around the peak region using asymmetric Gaussian shapes to take into account initial state radiation. The widths of these Gaussians are shown in Table 2.

Table 1
The selection criteria for the missing momentum (p_{miss}) and missing mass squared (m^2_{miss}) correlations, where p_{miss} is in GeV/c and m^2_{miss} is in (GeV/c^2)^2.

Modes	Hadronic tag	Leptonic tag
ℓK^0_S	$p_{miss} > -3.0 \times m^2_{miss} - 0.9$	$p_{miss} > -4 \times m^2_{miss} - 1.0$
	$p_{miss} > 3.5 \times m^2_{miss} - 1.1$	$p_{miss} > 1.8 \times m^2_{miss} - 0.8$
$\ell K^0_S K^0_S$	$p_{miss} > -2 \times m^2_{miss} - 1.0$	$p_{miss} > -2 \times m^2_{miss} - 1.0$
	$p_{miss} > 2 \times m^2_{miss} - 1.0$	$p_{miss} > 1.3 \times m^2_{miss} - 0.8$

Table 2
Summary of M_{sig} and ΔE resolutions ($\sigma^{high/low}_{M_{sig}}$ (MeV/c^2) and $\sigma^{high/low}_{\Delta E}$ (MeV)). Here σ^{high} (σ^{low}) means the standard deviation on the higher (lower) side of the peak.

Mode	$\sigma^{high}_{M_{sig}}$	$\sigma^{low}_{M_{sig}}$	$\sigma^{high}_{\Delta E}$	$\sigma^{low}_{\Delta E}$
$\tau^- \to e^- K^0_S$	7.3	7.5	19.4	30.0
$\tau^- \to \mu^- K^0_S$	6.2	6.8	19.1	26.4
$\tau^- \to e^- K^0_S K^0_S$	5.6	6.4	12.6	21.9
$\tau^- \to \mu^- K^0_S K^0_S$	5.2	6.0	11.2	17.2

To evaluate the branching fractions, we use an elliptical signal region that contains 90% of the signal MC events satisfying all selection criteria. The shape of the signal region is chosen to minimize its area and therefore obtain the highest sensitivity. We blind the data in the signal region until all selection criteria are finalized so as not to bias our choice of selection criteria. Fig. 4 shows scatter-plots for data events and signal MC samples distributed

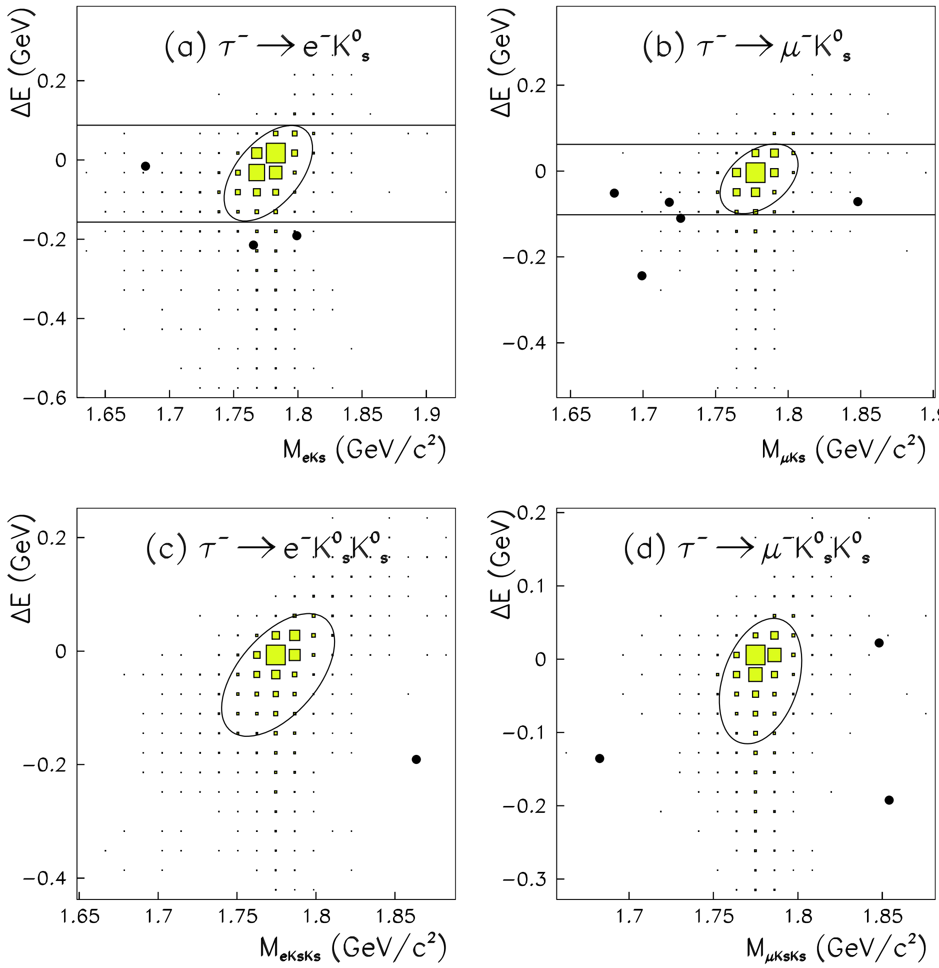

Fig. 4. Scatter-plots of data in the M_{sig}–ΔE plane: (a), (b), (c) and (d) correspond to the $\pm 20\sigma$ area for the $\tau^- \to e^- K^0_S$, $\tau^- \to \mu^- K^0_S$, $\tau^- \to e^- K^0_S K^0_S$ and $\tau^- \to \mu^- K^0_S K^0_S$ modes, respectively. Data is indicated by the solid circles. The filled boxes show the MC signal distribution with arbitrary normalization. The elliptical signal regions shown by the solid curves are used for evaluating the signal yield. In (a) and (b), the region between the horizontal solid lines excluding the signal region is used as a sideband.

Table 3
The signal efficiency (ε), the number of the expected background events (N_{BG}) estimated from the sideband data, the total systematic uncertainty (σ_{syst}), the number of observed events in the signal region (N_{obs}), 90% C.L. upper limit on the number of signal events including systematic uncertainties (s_{90}) and 90% C.L. upper limit on the branching fraction for each individual mode.

Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	s_{90}	$\mathcal{B}$ ($\times 10^{-8}$)
$\tau^- \to e^- K^0_S$	10.2	0.18 ± 0.18	6.6	0	2.25	< 2.6
$\tau^- \to \mu^- K^0_S$	10.7	0.35 ± 0.21	6.8	0	2.10	< 2.3
$\tau^- \to e^- K^0_S K^0_S$	5.82	0.07 ± 0.07	11.2	0	2.44	< 7.1
$\tau^- \to \mu^- K^0_S K^0_S$	5.08	0.12 ± 0.08	11.3	0	2.40	< 8.0

over $\pm 20\sigma$ in the $M_{\text{sig}} - \Delta E$ plane. As MC simulation shows, the dominant background in the signal region comes from events with a fake lepton from a pion. Therefore, we estimate the number of expected background by multiplying the number of data events in the signal region with selected hadrons ($\mathcal{P}(\ell) \leqslant 0.9$) by the fake lepton ratio. The latter is calculated as the number of events in the data with $P(\ell) > 0.9$ divided by the number of events in the data with $P(\ell) \leqslant 0.9$ in the sideband region. For the ℓK^0_S modes we define the sideband region as the box inside the two horizontal lines (see Fig. 4(a) and (b)) with the signal region excluded since real leptons from $D^+ \to \ell^+ \nu K^0_S$ populate the region below the ΔE signal one. For the $\ell K^0_S K^0_S$ modes, events that lie within a $\pm 20\sigma$ region but outside the signal region are treated as sideband events (see Fig. 4(c) and (d)). The final signal efficiency and the number of expected background events in the signal region for each mode are summarized in Table 3.

The dominant systematic uncertainties on the detection sensitivity come from K^0_S reconstruction and tracking efficiencies. These are 4.5% per K^0_S candidate and 1.0% per track. Other sources of systematic uncertainties are: lepton identification (2.2–2.7)%, MC statistics (0.8–1.0)%, trigger efficiency (0.01–0.4)%, and integrated luminosity (1.4%). The uncertainty from $\mathcal{B}(K^0_S \to \pi^+\pi^-)$ is negligible. All these uncertainties are added in quadrature to provide total systematic uncertainties that range from 6.6% to 11.3%.

Finally, we examine the blinded region and find no data events in the signal region for any of the decay modes (see Fig. 4). Therefore, we set the following upper limits on the branching fractions based on the Feldman–Cousins method [22]. The 90% C.L. upper limit on the number of signal events (s_{90}) is obtained using the POLE program [23], based on the number of expected background events, observed data and the systematic uncertainty. The upper limit on the branching fraction is then given by

$$\mathcal{B}\big(\tau^- \to \ell^- K_S^0\big(K_S^0\big)\big) < \frac{s_{90}}{2\varepsilon\mathcal{B}(K_S^0 \to \pi^+\pi^-)^n N_{\tau\tau}}, \qquad (1)$$

where ε is the signal efficiency, $\mathcal{B}(K_S^0 \to \pi^+\pi^-) = (69.20 \pm 0.5)\%$ [21], and n is 1 and 2 for the ℓK_S^0 and $\ell K_S^0 K_S^0$ modes, respectively. The value $N_{\tau\tau} = 6.17 \times 10^8$ is obtained from the product of the integrated luminosity and the cross section of τ-pair production 0.919 ± 0.003 nb [24]. The resulting upper limits on the branching fractions at the 90% C.L. are

$$\mathcal{B}\big(\tau^- \to e^- K_S^0\big) < 2.6 \times 10^{-8},$$
$$\mathcal{B}\big(\tau^- \to \mu^- K_S^0\big) < 2.3 \times 10^{-8},$$
$$\mathcal{B}\big(\tau^- \to e^- K_S^0 K_S^0\big) < 7.1 \times 10^{-8},$$
$$\mathcal{B}\big(\tau^- \to \mu^- K_S^0 K_S^0\big) < 8.0 \times 10^{-8}.$$

For the ℓK_S^0 modes, these results improve the existing upper limits by about a factor of 2, compared to our previously published limits [7]. For the $\ell K_S^0 K_S^0$ modes, these results improve the upper limits by factors of 31 and 43 for the $eK_S^0 K_S^0$ and $\mu K_S^0 K_S^0$, respectively, compared to the previously published limits obtained by the CLEO experiment [9].

4. Summary

We have searched for the lepton-flavor-violating decays $\tau^- \to \ell^- K_S^0$ and $\ell^- K_S^0 K_S^0$ ($\ell = e$ or μ) using data collected with the Belle detector at the KEKB e^+e^- asymmetric-energy collider. We find no signal for any decay modes. The following upper limits on branching fractions at the 90% confidence level are obtained: $\mathcal{B}(\tau^- \to e^- K_S^0) < 2.6 \times 10^{-8}$, $\mathcal{B}(\tau^- \to \mu^- K_S^0) < 2.3 \times 10^{-8}$, $\mathcal{B}(\tau^- \to e^- K_S^0 K_S^0) < 7.1 \times 10^{-8}$ and $\mathcal{B}(\tau^- \to \mu^- K_S^0 K_S^0) < 8.0 \times 10^{-8}$. These results are currently the most stringent upper limits for the ℓK_S^0 and the $\ell K_S^0 K_S^0$ modes. These limits can be used to constrain new physics scenarios beyond the Standard Model.

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