

Search for lepton flavor violating τ^- decays with a K_S^0 meson

Belle Collaboration

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Received 9 May 2006; accepted 24 May 2006

Available online 19 June 2006

Editor: M. Doser

Abstract

We have searched for the lepton flavor violating decays $\tau^- \rightarrow \ell^- K_S^0$ ($\ell = e$ or μ), using a data sample of 281 fb^{-1} collected with the Belle detector at the KEKB e^+e^- asymmetric-energy collider. No evidence for a signal was found in either of the decay modes, and we set the following upper limits for the branching fractions: $\mathcal{B}(\tau^- \rightarrow e^- K_S^0) < 5.6 \times 10^{-8}$ and $\mathcal{B}(\tau^- \rightarrow \mu^- K_S^0) < 4.9 \times 10^{-8}$ at the 90% confidence level. These results improve the previously published limits set by the CLEO Collaboration by factors of 16 and 19, respectively.

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PACS: 11.30.Fs; 13.35.Dx; 14.60.Fg

1. Introduction

Lepton flavor violation (LFV) is allowed in many extensions of the Standard Model (SM), such as Supersymmetry (SUSY) and leptoquark models. In particular, lepton flavor violating decays with K_S^0 mesons are discussed in models with heavy singlet Dirac neutrinos [1], R -parity violation in SUSY [2,3], dimension-six effective fermionic operators that induce τ - μ mixing [4]. Experiments at the B -factories allow searches for lepton flavor violating decays with a very high sensitivity. The best upper limits of $\mathcal{B}(\tau^- \rightarrow e^- K_S^0) < 9.1 \times 10^{-7}$ and $\mathcal{B}(\tau^- \rightarrow \mu^- K_S^0) < 9.5 \times 10^{-7}$ at the 90% confidence level were set by the CLEO experiment using 13.9 fb^{-1} of data [5].

In this Letter, we report a search for the lepton flavor violating decays $\tau^- \rightarrow \ell^- K_S^0$ ($\ell = e$ or μ)¹ using 281 fb^{-1} of data collected at the $\Upsilon(4S)$ resonance and 60 MeV below it with the Belle detector at the KEKB e^+e^- asymmetric-energy collider [6].

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 Čerenkov 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 [7].

Particle identification is very important in this measurement. We use particle identification likelihood variables based on the ratio of the energy deposited in the ECL to the momentum measured in the SVD and CDC, the shower shape in the ECL, the particle range in the KLM, the hit information from the ACC, the measured dE/dX in the CDC and the particle's time-of-flight from the TOF. For lepton identification, we form a likelihood ratio based on the electron probability $\mathcal{P}(e)$ [8] and the muon probability $\mathcal{P}(\mu)$ [9] determined by the responses of the appropriate subdetectors.

For Monte Carlo (MC) simulation studies, the following programs have been used to generate background events: KORALB/TAUOLA [10] for $\tau^+\tau^-$, QQ [11] for $B\bar{B}$ and continuum, BHLUMI [12] for Bhabha events, KKMC [13] for

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¹ Unless otherwise stated, charge conjugate decays are included throughout this paper.

$e^+e^- \rightarrow \mu^+\mu^-$ and AAFH [14] for two-photon processes. Since the QQ generator does not include some rare processes that potentially contribute to final states with a K_S^0 meson, we generated special samples of $e^+e^- \rightarrow D^{*+}D^{*-}$, a process that was recently observed by the Belle Collaboration [15]. Signal MC is generated by KORALB/TAUOLA. Signal τ decays are two-body and assumed to have a uniform angular distribution in the τ lepton’s rest frame. The Belle detector response is simulated by a GEANT 3 [16] based program. All kinematic variables are calculated in the laboratory frame unless otherwise specified. In particular, variables calculated in the e^+e^- center-of-mass (CM) frame 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 ($K_S^0 \rightarrow \pi^+\pi^-$), while the other τ (tag side) decays into one charged track (with a sign opposite to that of the signal-side lepton) and any number of additional photons and neutrinos. Thus, the experimental signature is:

$$\{\tau^- \rightarrow \ell^- (= e^- \text{ or } \mu^-) + K_S^0 (\rightarrow \pi^+\pi^-)\} \\ + \{\tau^+ \rightarrow (\text{a track})^+ + (n^{\text{TAG}}\gamma \geq 0) + X(\text{missing})\}.$$

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 charged tracks with a zero net charge. Events are separated into two hemispheres corresponding to the signal (three-prong) and tag (one-prong) sides by the plane perpendicular to the thrust axis [17]. The magnitude of the thrust is required to be larger than 0.9 to suppress the $q\bar{q}$ continuum background. The K_S^0 is reconstructed from two oppositely-charged tracks in the signal side that have an invariant mass $0.482 \text{ GeV}/c^2 < M_{\pi^+\pi^-} < 0.514 \text{ GeV}/c^2$, assuming a 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 [18]. In order to avoid fake K_S^0 candidates from photon conversions (i.e. $\gamma \rightarrow e^+e^-$), the invariant mass reconstructed by assigning the electron mass to the tracks, is required to be greater than $0.2 \text{ GeV}/c^2$. The signal side track not used in the K_S^0 reconstruction is required to satisfy the lepton identification selection. The electron and muon identification criteria are $\mathcal{P}(e) > 0.9$ with $p > 0.3 \text{ GeV}/c$ and $\mathcal{P}(\mu) > 0.9$ with $p > 0.6 \text{ GeV}/c$, respectively. After the event selection described above, most of the remaining background comes from generic $\tau^+\tau^-$ and continuum events that contain a real K_S^0 meson.

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}_{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}_{miss} be greater than $0.4 \text{ GeV}/c$ and that its direction point into the fiducial volume of the detector, as shown for the $\tau^- \rightarrow \mu^- K_S^0$ mode in Fig. 1(a) and (b). The total visible energy in the CM frame, $E_{\text{vis}}^{\text{CM}}$, is defined as the sum of the energies of the K_S^0 candidate, the lepton, the tag-side track (with a pion mass hypothesis) and all photon candidates. We require $E_{\text{vis}}^{\text{CM}}$ to satisfy the condition: $5.29 \text{ GeV} < E_{\text{vis}}^{\text{CM}} < 10.0 \text{ GeV}$ (see Fig. 1(c)). Since neutrinos are emitted only on the tag side, the direction of \vec{p}_{miss} should lie within the tag side of the event. The cosine of the opening angle between \vec{p}_{miss} and the tag-side track in the CM system, $\cos\theta_{\text{tag-miss}}^{\text{CM}}$, is therefore required to be greater than 0 (see Fig. 1(d)). For all kinematic distributions shown in Fig. 1, reasonable agreement between the data and background MC is observed. In order to suppress background from $q\bar{q}$ ($q = u, d, s, c$) continuum events, the following requirements on the number of the photon candidates on the signal and tag side are imposed: $n^{\text{SIG}} \leq 1$ and $n^{\text{TAG}} \leq 2$, respectively.

Finally, the correlation between the reconstructed momentum of the ℓK_S^0 system, $p_{\ell K_S}$, and the cosine of the opening angle between the lepton and K_S^0 , $\cos\theta_{\ell K_S}$ is employed to further suppress background from generic $\tau^+\tau^-$ and continuum events via the requirements: $\cos\theta_{\ell K_S} < 0.14 \times \log(p_{\ell K_S} - 2.7) + 0.7$, where $p_{\ell K_S}$ is in GeV/ c (see Fig. 2). While this condition retains 99% of the signal, 99% of the generic $\tau^+\tau^-$ and 84% of the uds continuum background are removed. Following all the selection criteria, the signal detection efficiencies for the $\tau^- \rightarrow e^- K_S^0$ and $\tau^- \rightarrow \mu^- K_S^0$ modes are 15.0% and 16.2%, respectively.

3. Results

Signal candidates are examined in the two-dimensional plots of the $\ell^- K_S^0$ invariant mass, $M_{\ell K_S^0}$, and the difference of their energy from the beam energy in the CM system, ΔE . A signal event should have $M_{\ell K_S^0}$ close to the τ -lepton mass and ΔE close to 0. For both modes, the $M_{\ell K_S^0}$ and ΔE resolutions are parameterized from the MC distributions around the peak with bifurcated Gaussian shapes to account for initial state radiation. These Gaussian have widths $\sigma_{M_{\ell K_S^0}}^{\text{high/low}} = 6.2/7.4 \text{ MeV}/c^2$

and $\sigma_{\Delta E}^{\text{high/low}} = 20/26 \text{ MeV}$ for the $\tau^- \rightarrow e^- K_S^0$ mode, and $\sigma_{M_{\mu K_S^0}}^{\text{high/low}} = 6.1/5.9 \text{ MeV}/c^2$ and $\sigma_{\Delta E}^{\text{high/low}} = 19/23 \text{ MeV}$ for the $\tau^- \rightarrow \mu^- K_S^0$ mode, where the “high/low” superscript indicates the higher/lower side of the peak.

We blind a region of $\pm 5\sigma_{M_{\ell K_S^0}}$ around the τ mass in $M_{\ell K_S^0}$ and a region of $-0.5 \text{ GeV} < \Delta E < 0.5 \text{ GeV}$ so as not to bias our choice of selection criteria. Fig. 3 shows scatter-plots for data and signal MC samples distributed over $\pm 15\sigma$ in the $M_{\ell K_S^0}$ - ΔE plane. Most of the surviving background events in both modes come from $D^\pm \rightarrow \pi^\pm K_S^0$ and $D^\pm \rightarrow \ell^\pm \nu K_S^0$

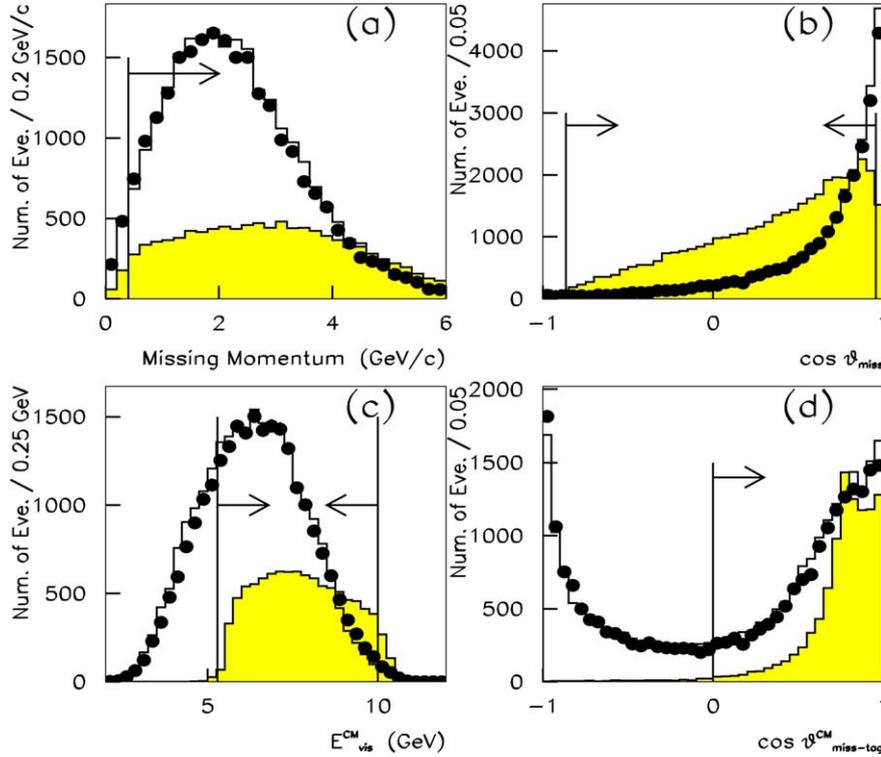


Fig. 1. Kinematic distributions used in the event selection after K_S^0 mass and muon identification requirements: (a) the momentum of the missing particle; (b) the polar angle of the missing particle; (c) the total visible energy in the CM frame; (d) the opening angle between the missing particle and tag-side track in the CM frame. The signal MC distributions are indicated by the filled histograms, the total background including $\tau^+\tau^-$ and $q\bar{q}$ is shown by the open histogram, and solid circles are data. While the signal MC ($\tau^- \rightarrow \mu^- K_S^0$) distribution is normalized arbitrarily, the data and background MC are normalized to the same luminosity. Selected regions are indicated by arrows from the marked cut boundaries.

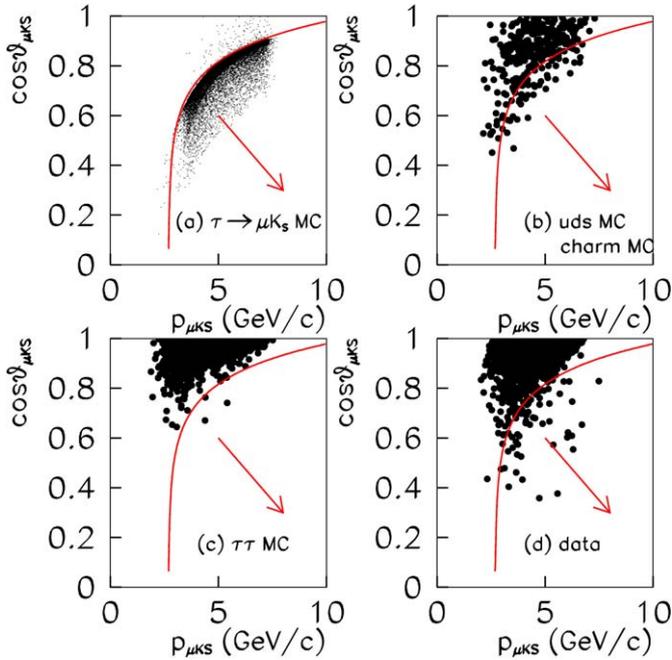


Fig. 2. Scatter-plots of (a) signal MC ($\tau^- \rightarrow \mu^- K_S^0$), (b) continuum MC, (c) generic $\tau^+\tau^-$ MC events and (d) data on the $p_{\mu K_S}$ vs $\cos\theta_{\mu K_S}$ plane. Selected regions are indicated by curves with arrows.

decays. The remaining continuum backgrounds in the $\tau^- \rightarrow \mu^- K_S^0$ mode are combinations of a true K_S^0 meson and a fake lepton.

To optimize our search sensitivity, we select an elliptically shaped signal region of minimum area with the same signal acceptance as that of a rectangular box corresponding to $\pm 5\sigma$ in the MC resolution for the $M_{\ell K_S^0} - \Delta E$ plane. The signal efficiencies after all requirements are 11.8% for the $\tau^- \rightarrow e^- K_S^0$ and 13.5% for the $\tau^- \rightarrow \mu^- K_S^0$, respectively.

As there are few remaining MC background events in the signal ellipse, we estimate the background contribution using the $M_{\ell K_S^0}$ sideband regions defined by rectangular areas beside the signal ellipse shown in Fig. 3(a) and (b). Extrapolation to the signal region assumes that the background distribution is flat in $M_{\ell K_S^0}$. We find the expected background in the ellipse to be 0.2 ± 0.2 events for both modes. Finally, we uncover the blinded region and find no data events in the signal region of the $\tau^- \rightarrow e^- K_S^0$ and $\tau^- \rightarrow \mu^- K_S^0$ modes (see Fig. 3(a) and (b)). Since no statistically significant excess of data over the expected background in the signal region is observed, we apply a frequentist approach to calculate upper limits on the signal yields [19]. The resulting limits for the signal yields at 90% confidence level, s_{90} , are 2.23 events in both modes. The upper limits on the branching fraction before the inclusion of systematic uncertainties are then calculated as

$$\mathcal{B}(\tau^- \rightarrow \ell^- K_S^0) < \frac{s_{90}}{2\epsilon \mathcal{B}(K_S^0 \rightarrow \pi^+\pi^-) N_{\tau\tau}}, \quad (1)$$

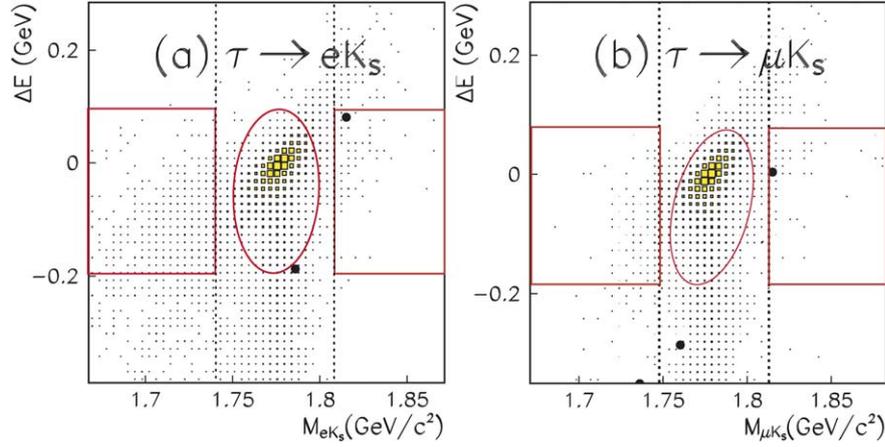


Fig. 3. Scatter-plots of data in the $M_{\ell K_S^0} - \Delta E$ plane: (a) and (b) correspond to the $\pm 15\sigma$ area for the $\tau^- \rightarrow e^- K_S^0$ and $\tau^- \rightarrow \mu^- K_S^0$ modes, respectively. The data are indicated by the solid circles. The filled boxes show the MC signal distribution with arbitrary normalization. The elliptical signal region shown by a solid curve is used for evaluating the signal yield. The vertical dashed lines denote the boundaries of the blind regions, while the rectangular areas beside the signal region are used to estimate the expected background in the elliptical region.

where $\mathcal{B}(K_S^0 \rightarrow \pi^+\pi^-) = 0.6895 \pm 0.0014$ [20] and $N_{\tau\tau} = 251 \times 10^6$ is the number of τ -pairs produced in 281 fb^{-1} of data. We obtain $N_{\tau\tau}$ using $\sigma_{\tau\tau} = 0.892 \pm 0.002 \text{ nb}$, the $e^+e^- \rightarrow \tau^+\tau^-$ cross section at the $\Upsilon(4S)$ resonance calculated by KKMC [13]. The resulting values are $\mathcal{B}(\tau^- \rightarrow e^- K_S^0) < 5.5 \times 10^{-8}$ and $\mathcal{B}(\tau^- \rightarrow \mu^- K_S^0) < 4.8 \times 10^{-8}$.

The dominant systematic uncertainties on the detection sensitivity: $2\epsilon N_{\tau\tau} \mathcal{B}(K_S^0 \rightarrow \pi^+\pi^-)$ come from K_S^0 reconstruction and tracking efficiencies. These are 4.5% and 4.0%, respectively, for both modes. Other sources of the systematic uncertainties are: the trigger efficiency (0.5%), lepton identification (2.0%), MC statistics (0.3%), branching fraction of $K_S^0 \rightarrow \pi^+\pi^-$ (0.2%) and luminosity (1.4%). Assuming no correlation between them, all these uncertainties are combined in quadrature to give a total of 6.5%.

While the angular distribution of $\tau^- \rightarrow \ell^- K_S^0$ decay is initially assumed to be uniform in this analysis, it is sensitive to the lepton flavor violating interaction structure [21]. The spin correlation between the τ lepton in the signal and that in the tag side must be considered. A possible nonuniformity was taken into account by comparing the uniform case with those assuming $V - A$ and $V + A$ interactions, which result in the maximum possible variations. No statistically significant difference in the $M_{\ell K_S^0} - \Delta E$ distribution or the efficiencies is found compared to the case of the uniform distribution. Therefore, systematic uncertainties due to these effects are neglected in the upper limit evaluation.

Upper limits on the branching fractions at the 90% confidence level including these systematic uncertainties are calculated with the POLE program without conditioning [22]. The resulting upper limits on the branching fractions at the 90% confidence level are

$$\mathcal{B}(\tau^- \rightarrow e^- K_S^0) < 5.6 \times 10^{-8},$$

$$\mathcal{B}(\tau^- \rightarrow \mu^- K_S^0) < 4.9 \times 10^{-8}.$$

4. Discussion

In the R -parity violating SUSY scenario, there are three kinds of terms (λ , λ' and λ'') with a total of 45 couplings. In this model, τ^- could decay into $\ell^- K_S^0$ via tree-level scalar neutrino exchange by the $\lambda\lambda'$ couplings. Using our results, the limits on the products $\lambda\lambda'$ as a function of the scalar neutrino mass ($M_{\tilde{\nu}}$) are given as [2],

$$\begin{aligned} & |\lambda_{i31}\lambda'_{i12}| \ (i = 1, 2), \quad |\lambda_{i31}\lambda'_{i21}| \ (i = 2, 3) \\ & < 4.5 \times 10^{-4} \ (M_{\tilde{\nu}}/100 \text{ GeV}/c^2)^2 \quad \text{for } \tau^- \rightarrow e^- K_S^0, \\ & |\lambda_{i32}\lambda'_{i12}| \ (i = 1, 2), \quad |\lambda_{i23}\lambda'_{i21}| \ (i = 1, 3) \\ & < 4.1 \times 10^{-4} \ (M_{\tilde{\nu}}/100 \text{ GeV}/c^2)^2 \quad \text{for } \tau^- \rightarrow \mu^- K_S^0, \end{aligned}$$

where i is the generation number. These bounds are more stringent than the previous bounds obtained in R -parity violating models from τ^- decay including a pseudoscalar meson [2,3].

The improved sensitivity to rare τ lepton decays achieved in this work can be used to constrain the new physics scale for the dimension-six fermionic effective operators involving τ - μ flavor violation, motivated by neutrino oscillations [4]. From our upper limit for the branching fraction of the $\tau^- \rightarrow \mu^- K_S^0$ decay, lower bounds of 36.2 and 37.2 TeV can be obtained for the axial-vector and pseudoscalar operators, respectively.

5. Conclusion

In conclusion, we have searched for the lepton flavor violating decays $\tau^- \rightarrow \ell^- K_S^0$ ($\ell = e$ or μ) using data collected with the Belle detector at the KEKB e^+e^- asymmetric-energy collider. We found no signal in either mode. The following upper limits on the branching fractions at the 90% confidence level are obtained: $\mathcal{B}(\tau^- \rightarrow e^- K_S^0) < 5.6 \times 10^{-8}$ and $\mathcal{B}(\tau^- \rightarrow \mu^- K_S^0) < 4.9 \times 10^{-8}$. These results improve the search sensitivity by factors of 16 and 19, respectively, compared to the previous limits obtained by the CLEO experiment.

Acknowledgements

We thank the KEKB group for the excellent operation of the accelerator, the KEK cryogenics group for the efficient operation of the solenoid, and the KEK computer group and the National Institute of Informatics for valuable computing and Super-SINET network support. We acknowledge support from the Ministry of Education, Culture, Sports, Science, and Technology of Japan and the Japan Society for the Promotion of Science; the Australian Research Council and the Australian Department of Education, Science and Training; the National Science Foundation of China and the Knowledge Innovation Program of Chinese Academy of Sciences under contract No. 10575109 and IHEP-U-503; the Department of Science and Technology of India; the BK21 program of the Ministry of Education of Korea, and the CHEP SRC program and Basic Research program (grant No. R01-2005-000-10089-0) of the Korea Science and Engineering Foundation; the Polish State Committee for Scientific Research under contract No. 2P03B 01324; the Ministry of Science and Technology of the Russian Federation; the Slovenian Research Agency; the Swiss National Science Foundation; the National Science Council and the Ministry of Education of Taiwan; and the US Department of Energy.

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