Measurement of the branching fractions and mass spectra for $\tau$ lepton decays including $K_S^0$ at Belle

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We report a study of $\tau$ lepton decays involving $K_S^0$ with a 669 fb$^{-1}$ data sample accumulated with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider. The branching fractions have been measured for the $\tau^- \rightarrow \pi^- K_S^0\bar{\nu}_\tau$, $K^- K_S^0\bar{\nu}_\tau$, $\pi^- K_S^0\pi^0\nu_\tau$, $K^- K_S^0\pi^0\nu_\tau$, $\pi^- K_S^0 K_S^0\bar{\nu}_\tau$, and $\pi^- K_S^0 K_S^0\pi^0\nu_\tau$ decays. We also provide the unfolded mass spectra for $\tau^- \rightarrow \pi^- K_S^0\pi^0\nu_\tau$ and $\tau^- \rightarrow K^- K_S^0\pi^0\nu_\tau$.

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INTRODUCTION

$\tau$ lepton is the only known lepton massive enough to decay into hadrons. Its hadronic decays are ideally suited to investigate the hadronic weak currents. Former studies for semileptonic $\tau$ decays done at LEP and CLEO [1] provide accurate results for measurements of branching fractions as well as spectral functions for one- or three-prong decay modes with any number of neutral mesons that do not suffer from Cabibbo and/or phase space suppression. However, because of limited statistics, their studies for Cabibbo-suppressed or multi-prong $\tau$ decay modes do not provide sufficient information for investigating the hadronic structure or for testing important standard model parameters, e.g., $|V_{us}|$.

In this analysis we use a data sample of 669 fb$^{-1}$ corresponding to $616 \times 10^6 \tau^+\tau^-$ pair events, which is two orders of magnitude larger than those that were available prior to the $B$-factory experiments. The $\tau^+\tau^-$ pair events, accumulated with the Belle detector [2], are produced at the KEKB asymmetric-energy $e^+e^-$ collider [3] running in the energy range of the $\Upsilon(4S)$ with a cross section comparable to that of $BB$ [4]. It is also worth noting that the $\tau^+\tau^-$ produced at the $\Upsilon(4S)$ are in a very clean experimental environment with low background.

The leptonic decay modes are used here for tagging $\tau$ events for a precise measurement of the four decay modes: $\tau^- \rightarrow \pi^- K_S^0\bar{\nu}_\tau$, $\tau^- \rightarrow K^- K_S^0\bar{\nu}_\tau$, $\tau^- \rightarrow \pi^- K_S^0\pi^0\nu_\tau$, and $\tau^- \rightarrow K^- K_S^0\pi^0\nu_\tau$. The other two decay modes, $\tau^- \rightarrow \pi^- K_S^0 K_S^0\bar{\nu}_\tau$ and $\tau^- \rightarrow \pi^- K_S^0 K_S^0\pi^0\nu_\tau$, however, are selected using one-prong decays for tagging to increase the signal.

EVENT SELECTION

The selection of $\tau^+\tau^-$ events is performed in two stages. At the first stage, loose conditions are applied for the primary $\tau^+\tau^-$ selection. A $\tau^+\tau^-$ event produced back-to-back in the $e^+e^-$ center-of-mass (CM) frame is divided into two hemispheres according to the plane perpendicular to the thrust axis. Each event is required to have only one track on one side of the hemisphere (tag side) and any number of tracks on the other side (signal side).

As a second step, we classified the events into two types, leptonic and hadronic events, using the combination of the number of charged tracks and their flavors on each side. The events on both sides containing a single track are classified as candidates of leptonic events, while the events where the tag side contains a single track with three or more tracks on the signal side are classified as hadronic events.

Particle identification (PID) is used to determine the flavor of charged tracks on both sides by defining and using the likelihood variables to identify the electron and muon track on the tag side and the charged pion or kaon on the signal side except the $K_S^0$ daughter tracks.

The leptonic events in which the $\tau$ lepton on one side decays to $e^-\bar{\nu}_e\nu_\tau$ and the other side to $\mu^-\bar{\nu}_\mu\nu_\tau$ ($e\mu$ events), are selected for normalization. The branching fractions for $\tau^- \rightarrow e^-\bar{\nu}_e\nu_\tau$ and $\tau^- \rightarrow \mu^-\bar{\nu}_\mu\nu_\tau$ are measured with good precision and can be used as a normalization for the branching fraction measurement. The detection efficiency and its statistical error for $e\mu$ events is $(19.31 \pm 0.03)\%$.

Hadronic events are selected by different tagging with at least one $K_S^0 \rightarrow \pi^+\pi^-$, which is reconstructed with a vertex fit using the momentum of two oppositely charged tracks on the signal side. The lepton-tagged events are defined as those with one $\tau$ decaying to leptons, while the other decays to hadrons. Lepton tagging is used for $\tau^- \rightarrow K_S^0 K_S^0$, $K^- K_S^0$, $\pi^- K_S^0\pi^0$, and $K^- K_S^0\pi^0$ events. Since the signal yield for events involving more than one $K_S^0$ is

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smaller than that involving a single $K_S^0$, we use both lepton and hadron tagging for $\pi^0 K_S^0 K_S^0$ and $\pi^- K_S^0 K_S^0 \pi^0$ events. The decay modes used for hadron tagging are $\tau^- \rightarrow h^- (\geq 0 \hbar^0) \nu_\tau$ where $h = \pi, K$.

The signal $\pi^0 \rightarrow \gamma \gamma$ is reconstructed from the invariant mass determined from the momenta of two photons detected on the signal side. The distribution of the difference between the invariant mass of the two photons and the nominal $\pi^0$ mass normalized to the resolution, $S_{\gamma\gamma} = (m_{\gamma\gamma} - m_{\pi^0})/\sigma_{\gamma\gamma}$, is used to determine the number of genuine $\pi^0$s and to estimate the level of background from mass sidebands.

**DETERMINATION OF BRANCHING FRACTIONS**

The branching fractions for decay modes containing a single $K_S^0$ are obtained using

$$B(\tau^- \rightarrow X^- \nu_\tau) = \frac{N^{\text{Sig}}_{\tau^-X^-}}{N_{e\mu} B_e + B_\mu},$$

where $X$ is the signal channel under study, $N^{\text{Sig}}_{X^-\,i\rightarrow \ell X^-\,i\rightarrow}$ is the number of events with an efficiency correction, where the $\tau$ lepton on one side decays into a signal mode and the $\tau$ lepton on the other decays into leptons, $N_{e\mu} \equiv N^{\text{data}}_{e\mu}/N_{e\mu}$ is the number of events with an efficiency correction for $e\mu$ events, $B_e$ and $B_\mu$ are the world-average branching fractions for $\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$ and $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$, respectively.

In order to increase the number of candidates, $\pi^- K_S^0 K_S^0$ and $\pi^- K_S^0 K_S^0 \pi^0$ events are selected by both lepton and hadron tagging. To determine the branching fraction for multiple $K_S^0$ modes, we used

$$B(\tau^- \rightarrow X^- \nu_\tau) = \frac{N^{\text{Sig}}_{X^-A}}{2 \times N_{\tau^-} \times B(\tau^- \rightarrow A^- \bar{\nu}_A)},$$

where $A$ indicates a one-prong combination of particles: e.g., $\tau^- \rightarrow l^- \bar{\nu}_l \nu_\tau$ and $\tau^- \rightarrow h^- (\geq 0 \hbar^0) \nu_\tau$.

In both cases, the number of signal events $N^{\text{Sig}}_i$ is given as

$$N^{\text{Sig}}_i = \sum_j (E^{-1})_{ij} (N^{\text{Data}}_{ij} - N^{\text{BG}}_{ij}),$$

where $i$ is the true decay channel of interest and $j$ is the decay channel reconstructed in the analysis, $N^{\text{Data}}_{ij}$ is the number of selected events and $N^{\text{BG}}_{ij}$ is the estimated background coming from decay modes other than six under consideration, and non-$\tau$ processes. $E_{ij}$ is the efficiency matrix. The diagonal components are the efficiency for the $i$-th channel and the other components are the probability of migration from the $i$-th to $j$-th decay modes.

For the branching fraction measurement, the number of the background events coming from $\tau$ decays other than the six modes studied should be determined. To determine the background, generic MC samples of $\tau$ lepton decays generated using branching fractions provided by the Particle Data Group (PDG) are used. The non-$\tau$ decay contributions are relatively small, at a level of 1%, and dominated by $q\bar{q}$ continuum events.

**EFFICIENCY AND CORRECTIONS**

In order to determine the signal efficiency and cross-feed rates for the decay modes of interest, a 17.2 million $\tau^+\tau^-$ MC sample is used. Since a difference between MC and data is inevitable, we evaluate corrections associated with a difference between MC and data for PID and the reconstruction of the neutral particles, $K_S^0$ and $\pi^0$. The corrections of the PID efficiency for electron and muon are derived from two-photon events and those for charged pions and kaons are derived from $D^-\pi^+$ and $D^0 K^-\pi^+$ control samples. The correction for the $K_S^0$ reconstruction efficiency obtained is $0.979 \pm 0.007$ using $D^-\rightarrow D^0 \pi^-$, $D^0 \rightarrow K_S^0 \pi^+\pi^-$ control samples. The MC-data correction for the $\pi^0$ efficiency is determined to be $0.957 \pm 0.015$.

For the $\pi^- K_S^0 \pi^0$ and $K^- K_S^0 \pi^0$ modes, the number of cross-feed events from $\pi^- K_S^0$ and $K^- K_S^0$ with spurious $\pi^0$ is estimated and subtracted by using sidebands of $S_{\gamma\gamma}$. By this subtraction, the cross-feed contributions from $\tau^- \rightarrow h^- (\geq 0 \hbar^0) \nu_\tau$ and/or $\tau^- \rightarrow h^- (\geq 0 \hbar^0) \nu_\tau$ are removed successfully.

By taking into account the corrections and the efficiency losses by subtraction, the efficiency migration matrix $E_{ij}$ is obtained and summarized in Table I. The diagonal elements represent the signal efficiency; otherwise - the cross-feed rates among the decay modes of interest.

**SYSTEMATIC UNCERTAINTY**

The sources of systematic uncertainties are categorized into the uncertainty of detection/reconstruction efficiency (EFF), hadron decay models (HDM), background estimation (BGE), normalization (NORM) and rejection...
of energetic photons ($\gamma$ veto). The uncertainty of efficiency consists of several items: track finding, PID, $K_S^0$ and $\pi^0$ reconstruction and the $\pi^0$ sideband subtraction for $\pi^- K_S^0 \pi^0$ and $K^- K_S^0 \pi^0$. These uncertainties are integrated into the efficiency migration matrix [2]. The uncertainties from the decay model implemented into the MC sample are estimated by using weighting sets of MC samples generated with different hadron decay models. The background uncertainty mostly contributed by other $\tau$ lepton decays is estimated by varying the fractions according to their uncertainties in PDG. By adding these uncertainties in quadrature, the total systematic uncertainties for $\pi^- K_S^0$, $K^- K_S^0$, $\pi^- K_S^0 \pi^0$, $K^- K_S^0 \pi^0$, $\pi^- K_S^0 K^0_S$ and $\pi^- K_S^0 K^0_S \pi^0$ are 2.8%, 3.9%, 4.0%, 5.0%, 4.2% and 6.9%, respectively. The summary of systematic uncertainties is shown in Table III.

| TABLE III: Coefficients of the covariance matrix for statistical ($\oplus$) systematic uncertainty covariance. |
|-----------------|----------------|----------------|----------------|----------------|----------------|
|                  | $\pi^- K_S^0$ | $K^- K_S^0$ | $\pi^- K_S^0 \pi^0$ | $K^- K_S^0 \pi^0$ | $\pi^- K_S^0 K^0_S$ | $\pi^- K_S^0 K^0_S \pi^0$ |
| $\pi^- K_S^0$   | 1              | 0.28          | -0.08          | 0.01           | -0.01          | 3.9e-3          |
| $K^- K_S^0$     | 1              | 0.03          | -0.14          | -0.9e-3        | 0.3e-3         |                   |
| $\pi^- K_S^0 \pi^0$ | 1              | -0.21         | -0.06          | 0.02           |                |                   |
| $K^- K_S^0 \pi^0$ | 1              | 2.9e-3        | -1.0e-3        |                |                |                   |
| $\pi^- K_S^0 K^0_S$ | 1              | -0.37         |                |                |                |                   |
| $\pi^- K_S^0 K^0_S \pi^0$ | 1 |                |                |                |                |                   |

The correlations of these uncertainties are also taken into account by the covariance matrix $\text{cov}(B_i, B_j)$ using the formula given in Ref. [2]. The results including both systematic and statistical uncertainties are shown as the coefficients of the covariance $\text{cov}(B_i, B_j)/\sqrt{\text{cov}(B_i, B_i) \text{cov}(B_j, B_j)}$ in Table III.

RESULTS

Using the formula given in Eq. (1), Eq. (2) and Eq. (3), the branching fractions for six decay modes are obtained simultaneously. The branching fraction for $\tau^- \rightarrow \pi^- K_S^0 \nu_\tau$ is found to be $(4.13 \pm 0.01 \pm 0.12) \times 10^{-3}$, which is consistent with our previous study [3]. The branching fractions for $\tau^- \rightarrow K^- K_S^0 \nu_\tau$, $\pi^- K_S^0 \pi^0 \nu_\tau$ and $K^- K_S^0 \pi^0 \nu_\tau$ are measured to be $(7.36 \pm 0.04 \pm 0.29) \times 10^{-4}$, $(1.92 \pm 0.02 \pm 0.08) \times 10^{-3}$, and $(7.44 \pm 0.11 \pm 0.37) \times 10^{-4}$, respectively, which are among the most precise results to date. The branching fractions for $\pi^- K_S^0 K^0_S$ and $\pi^- K_S^0 K^0_S \pi^0$ have been measured for the first time to be $(2.39 \pm 0.03 \pm 0.09) \times 10^{-4}$ and $(2.06 \pm 0.13 \pm 0.14) \times 10^{-5}$, respectively.

STUDY OF $\tau^- \rightarrow \pi^- K_S^0 K^0_S \pi^0 \nu_\tau$

Not only the branching fraction but also the hadron current can be studied in $\tau^- \rightarrow \pi^- K_S^0 K^0_S \pi^0 \nu_\tau$ using the invariant mass of $K_S^0 K^0_S \pi^0$, $M(K_S^0 K^0_S \pi^0)$. As can be seen in Fig. 1, the $M(K_S^0 K^0_S \pi^0)$ distribution shows a significant peak at around 1280 MeV/$c^2$, which can be understood as the $f_1(1285)$ resonance in $\tau$ decays. In order to determine the mass and width for the resonances, we used the probability distribution function (PDF) consisting of a Breit-Wigner function for the signal and a second-order polynomial for the background. So the signal is parameterized as

$$S(m) = \frac{m M_0}{(M^2 - m^2)^2 + (m \Gamma_0)^2}$$

where $M$ and $\Gamma_0$ are the nominal mass and width, $m$ is the mass of the $K_S^0 K^0_S \pi^0$ system. The total number of signal events is found to be $80 \pm 16$. The mass and width are $1278 \pm 4$ MeV/$c^2$ and $35 \pm 7$ MeV/$c^2$, consistent with the $f_1(1285)$ properties. From the total number of $\tau^- \rightarrow \pi^- K_S^0 K^0_S \pi^0 \nu_\tau$ and the number of $f_1(1285) \rightarrow K_S^0 K^0_S \pi^0$ among the $\tau^- \rightarrow \pi^- K_S^0 K^0_S \pi^0 \nu_\tau$ events, the branching fraction of $\tau^- \rightarrow f_1(1285) \pi^0 \nu_\tau$ to $\tau^- \rightarrow K_S^0 K^0_S \pi^0 \nu_\tau$ is found to be $(1.05 \pm 0.24) \times 10^{-5}$. In this fit, possible interference between $f_1$ and non-$f_1$ amplitude is ignored, which will cause considerable model uncertainties in the $f_1$ parameters and the branching fraction. Further studies are in progress.

FIG. 1: Invariant mass of $K^0_S K^0_S \pi^0$ in $\tau^- \rightarrow \pi^- K_S^0 K^0_S \pi^0 \nu_\tau$ events. A significant $f_1(1285)$ signal is seen. The solid line is a fit with a Breit-Wigner and a second-order polynomial function.
The mass spectra provide important information for hadronic weak currents: the $\pi^- K_S^0 \pi^0$ mode contributes to the Cabibbo-suppressed weak current, while the $K^- K_S^0 \pi^0$ mode has both vector and axial-vector components. The axial-vector component is interesting as the Wess-Zumino-Witten anomalous term [9]. The measured mass spectra are distorted due to the finite resolution, resolutions as well as the cross-feed backgrounds. The results are shown in Figs. 2. A clear resonance-like structure due to $K_1(1280)$ is seen in $\tau^- \rightarrow \pi^- K_S^0 \pi^0 \nu_\tau$. 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 SINET3 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 Natural Science Foundation of China under contract No. 10575109 and 10775142; the Department of Science and Technology of India; the BK21 program of the Ministry of Education of Korea, the CHEP SRC program and Basic Research program (grant No. R01-2005-000-10089-0) of the Korea Science and Engineering Foundation, and the Pure Basic Research Group program of the Korea Research Foundation; the Polish State Committee for Scientific Research; the Ministry of Education and Science of the Russian Federation and the Russian Federal Agency for Atomic Energy; the Slovenian Research Agency; the Swiss National Science Foundation; the National Science Council and the Ministry of Education of Taiwan; and the U.S. Department of Energy.

**CONCLUSION**

Using $616 \times 10^6 \, \tau^+\tau^-$ events collected with the Belle detector, we measured several branching fractions for hadronic $\tau$ decays involving $K_S^0$: $\pi^- K_S^0$, $K^- K_S^0$, $\pi^- K_S^0 \pi^0$, $K^- K_S^0 \pi^0$, $\pi^- K_S^0 K_S^0 \pi^0$, $K^- K_S^0 K_S^0 \pi^0$ and $\pi^- K_S^0 K_S^0 \pi^0$ and provided the covariance matrix, which includes both statistical and systematic uncertainties. We also provide the correlation of the systematic errors as the covariance matrix. The invariant mass of $K_S^0 K_S^0 \pi^0$ in the $\pi^- K_S^0 K_S^0 \pi^0$ mode shows a clear peak around the mass of 1280 MeV/c$^2$, which most probably comes from the $f_1(1285)$ current. In addition, we measured the unfolded mass spectra for $\tau^- \rightarrow \pi^- K_S^0 \pi^0 \nu_\tau$ and $\tau^- \rightarrow K^- K_S^0 \pi^0 \nu_\tau$ using the SVD unfolding technique.

**FIG. 2:** Unfolded invariant mass spectra for $\pi^- K_S^0 \pi^0$(left) in $\tau^- \rightarrow \pi^- K_S^0 \pi^0 \nu_\tau$ and $K^- K_S^0 \pi^0$(right) in $\tau^- \rightarrow K^- K_S^0 \pi^0 \nu_\tau$. The error bars show statistical error and are within the closed circles in many points.

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