Branching fraction of $K_s^0 K_s^0(0)$ decays

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We present a study of $\tau^{-} \rightarrow \pi^{-}K_{S}^{0}K_{L}^{0}(\pi^{0})\nu_{\tau}$ and $\tau^{-} \rightarrow K^{-}K_{S}^{0}\bar{K}_{L}^{0}(\pi^{0})\nu_{\tau}$ decays using a data set of 430 million $\tau$ lepton pairs, corresponding to an integrated luminosity of 468 fb$^{-1}$, collected with the BABAR detector at the PEP-II asymmetric energy $e^{+}e^{-}$ storage rings. We measure branching fractions of $(2.31 \pm 0.04 \pm 0.08) \times 10^{-4}$ and $(1.60 \pm 0.20 \pm 0.22) \times 10^{-5}$ for the $\tau^{-} \rightarrow \pi^{-}K_{S}^{0}\bar{K}_{L}^{0}\nu_{\tau}$ and $\tau^{-} \rightarrow \pi^{-}K_{S}^{0}\bar{K}_{L}^{0}\nu_{\tau}$ decays, respectively. We find no evidence for $\tau^{-} \rightarrow K^{-}K_{S}^{0}K_{S}^{0}\nu_{\tau}$ and $\tau^{-} \rightarrow K^{-}K_{S}^{0}\bar{K}_{L}^{0}\nu_{\tau}$ decays and place upper limits on the branching fractions of $6.3 \times 10^{-7}$ and $4.0 \times 10^{-7}$ at the 90% confidence level.

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The $\tau$ lepton can be used as a high-precision probe of the Standard Model and models of new physics. A recent BABAR paper, for example, presented a search for CP violation by measuring the decay-rate asymmetry of $\tau^{-} \rightarrow \pi^{-}K_{S}^{0}\nu_{\tau}$ decays [1]. One of the backgrounds in that analysis is $\tau^{-} \rightarrow \pi^{-}K_{S}^{0}\nu_{\tau}$, which has a large uncertainty in the branching fraction [2]. The uncertainty in the background from $\tau^{-} \rightarrow \pi^{-}K_{S}^{0}\nu_{\tau}$ decays was not a limitation of the decay-rate asymmetry measurement, but an improved measurement of the branching fraction and an understanding of the decay dynamics will be required for a future measurement at a high-luminosity B-factory.

This paper presents measurements of the branching fractions of $\tau^{-} \rightarrow \pi^{-}K_{S}^{0}\nu_{\tau}$ decays and the first search for $\tau^{-} \rightarrow K^{-}K_{S}^{0}\bar{K}_{L}^{0}(\pi^{0})\nu_{\tau}$ decays. In this work we use the $K_{S}^{0} \rightarrow \pi^{+}\pi^{-}$ decay mode. Here and throughout the paper, charge conjugation is implied.

Previously, ALEPH and CLEO measured the $\tau^{-} \rightarrow \pi^{-}K_{S}^{0}\nu_{\tau}$ branching fraction to be $(2.6 \pm 1.0 \pm 0.5) \times 10^{-4}$ [3] and $(2.3 \pm 0.5 \pm 0.3) \times 10^{-4}$ [4], respectively.
ALEPH set an upper limit on the $\tau^+ \rightarrow \pi^- K_S^0 K_S^0 \pi^0 \nu_\tau$ branching fraction of $2 \times 10^{-4}$ at the 95% confidence level [3].

The present analysis uses data recorded by the BABAR detector at the PEP-II asymmetric-energy $e^+e^-$ collider, operated at center-of-mass (CM) energies of 10.58 and 10.54 GeV at the SLAC National Accelerator Laboratory. The BABAR detector is described in detail in Ref. [5]. In particular, charged particle momenta are measured with a five-layer double-sided silicon vertex tracker and a 40-layer drift chamber, both within a 1.5 T superconducting solenoidal magnet. Charged kaons and pions are separated by ionization $(dE/dx)$ measurements in the silicon vertex detector and the drift chamber in combination with an internally reflecting Cherenkov detector. An electromagnetic calorimeter made of thallium-doped cesium iodide crystals provides energy measurements for electrons and photons, and an instrumented flux return detector identifies muons. Based on an integrated luminosity of 468 fb$^{-1}$, the data sample contains approximately 430 million $\tau$-pair events.

Simulated event samples are used to estimate the selection efficiency and purity of the data sample. The production of $\tau$ pairs is simulated with the KK2F Monte Carlo (MC) event generator [6]. Subsequent decays of the $\tau$ lepton, continuum $q\bar{q}$ events (where $q = u, d, s, c$), and final-state radiative effects are modeled with Tauola [7] and EvtGen [8], JETSET [9], and PHOTOS [10], respectively. Passage of the particles through the detector is simulated by Geant4 [11].

The $\tau^- \rightarrow \pi^- K_S^0 K_S^0 \nu_\tau$ decay is simulated with Tauola using $\tau^- \rightarrow K^- K^0 \nu_\tau$. The $\tau^- \rightarrow \pi^- K_S^0 K_S^0 \pi^0 \nu_\tau$ decay is simulated with EvtGen using $\tau^- \rightarrow K^- K^0 \pi^0 \nu_\tau$ and $\tau^- \rightarrow K^0 K^0 \pi^- \nu_\tau$. As we later show, the $\tau^- \rightarrow K^- K^0 \nu_\tau$ and $\tau^- \rightarrow K^- K^0 \pi^0 \nu_\tau$ have a $K^*$ (892) meson that is observed in the $\pi^- K_S^0$ channel, and the $\tau^- \rightarrow K^0 K^0 \pi^- \nu_\tau$ has a $K^*$ (892) meson that is observed in the $\pi^0 K_S^0$ channel.

The $\tau$ pair is produced back-to-back in the $e^+e^-$ CM frame. As a result, the decay products of the two $\tau$ leptons can be separated from each other by dividing the event into two hemispheres—referred to later as the “signal” hemisphere and the “tag” hemisphere—using the plane perpendicular to the event thrust axis [12]. The event thrust axis is calculated using all charged particles and all photon candidates in the entire event.

We select events with one prompt track and two $K_S^0 \rightarrow \pi^+ \pi^- \pi^0$ candidates reconstructed in the signal hemisphere, and exactly one oppositely charged prompt track in the tag hemisphere. All tracks are required to have the components of momentum transverse to the $e^-$ beam axis be greater than 0.1 GeV/c in the laboratory frame. A prompt track is defined to be a track with its point of closest approach to the beam spot being less than 1.5 cm in the plane transverse to the $e^-$ beam axis and less than 2.5 cm in the direction of the $e^-$ beam axis. A $K_S^0$ candidate is defined as a pair of oppositely charged tracks where neither track is identified as a prompt track. The invariant mass of the $K_S^0$ candidate is required to be between 0.475 and 0.515 GeV/c$^2$ (see Fig. 1). Furthermore, the distance between the beam spot and the $\pi^+ \pi^-$ vertex must be at least three times its uncertainty (the di-pion pair will be referred to as the “$K_S^0$ candidate daughters”).

The charged hadron must be identified as a charged pion or a charged kaon. The efficiency for selecting charged pions and kaons is approximately 95 and 90%, respectively. The probability of misidentifying a charged pion (kaon) as a charged kaon (pion) is estimated to be 1% (5%).

The charged pion and kaon samples are divided into samples with zero and one $\pi^0$ mesons. Events with two or more $\pi^0$ mesons are rejected. The $\pi^0$ candidate is reconstructed from two clusters of energy deposits in the electromagnetic calorimeter that have no associated tracks. The energy of each cluster is required to be greater than 30 MeV in the laboratory frame, and the invariant mass of the two clusters must be between 0.115 and 0.15 GeV/c$^2$.
The branching fraction of the (π⁻K_S^0)^2 system, and the (π⁻K_S^0K_S^0), (π⁻K_S^0) and (K_S^0K_S^0) invariant mass distributions for events that pass the \( \tau^- \rightarrow \pi^- K_S^0 K_S^0 \nu_\tau \) selection criteria. The invariant mass requirement is not required for the plot of the (π⁻K_S^0K_S^0) invariant mass. There are two entries per event in the Dalitz plot and in the (π⁻K_S^0) mass plot. The points are data and the histograms are the prediction of the Monte Carlo simulation. The signal decays are represented by the white histogram (\( \tau^- \rightarrow K^- K^0 \nu_\tau \)), The beige (light shaded) histogram shows the \( \tau^- \rightarrow K^- K^0_\pi^0 \nu_\tau \) and \( \tau^- \rightarrow K^{*0} K^0 \nu_\tau \) (\( \tau^- \rightarrow \pi^- K_S^0 K_S^0 \pi^0 \nu_\tau \)) decays. The red (dark shaded) histogram is the q\overline{q} background. The mass plots use \( \tau^- \rightarrow \pi^- K_S^0 K_S^0 \nu_\tau \) events that have been weighted based on the Dalitz plot distributions in the top left plot.

The invariant mass distribution predicted by the MC for the hadronic final state particles and for their combinations does not perfectly describe the data. In particular, the peak of the (π⁻K_S^0K_S^0) invariant mass distribution in the MC is found to peak approximately 5% lower than the peak observed in the data. To improve the modeling of the data we have weighted the \( \tau^- \rightarrow \pi^- K_S^0 K_S^0 \nu_\tau \) in Tauola using the Dalitz plot distribution for the \( \pi^- K_S^0 \) invariant mass (shown for the data sample in Fig. 2). The weighting function is from a two-dimensional (9 \times 9) matrix using \( M^2(\pi^- K_S^0) \) with both \( \pi^- K_S^0 \) combinations (the matrix is constructed to be symmetric). The weighted events are used in all the mass plots and we observe an improvement in the modeling of the data.

The branching fractions of the two charged pion modes are determined simultaneously to take into account the cross feed of each decay mode into the other sample. The branching fraction is

\[
B_j = \sum_i e^{-1}(N_{i\text{data}} - N_{i\text{bkgd}})/(2N_{\tau\tau})
\]

where \( j \) represents the \( \tau^- \rightarrow \pi^- K_S^0 K_S^0 \nu_\tau \) and \( \tau^- \rightarrow \pi^- K_S^0 K_S^0 \pi^0 \nu_\tau \) decay modes; \( i \) represents the \( (\pi^- K_S^0 K_S^0) \) or \( (\pi^- K_S^0 K_S^0) \) reconstruction modes; \( N_{i\text{data}} \) and \( N_{i\text{bkgd}} \) are
FIG. 3 (color online). The ($\pi^- K_S^0 K_S^0$), ($\pi^- K_S^0 K_S^0 \pi^0$), ($\pi^- K_S^0$), and ($\pi^0 K_S^0$) invariant mass distributions that pass the $\tau^- \rightarrow \pi^- K_S^0 K_S^0 \pi^0 \nu_\tau$ selection criteria [except for the plot of the ($\pi^- K_S^0 K_S^0$) invariant mass where the selection requirement on the mass is not included]. There are two entries per event in the ($\pi^- K_S^0$) and ($\pi^0 K_S^0$) mass plots. The points are data and the histograms are the predictions of the Monte Carlo simulation. The two signal channels are shown in the white ($\tau^- \rightarrow K^- K^0 \pi^0 \nu_\tau$) and beige (light shaded) ($\tau^- \rightarrow K^0 K^0 \pi^0 \nu_\tau$) histograms. The dark blue (medium shaded) histogram is $\tau^- \rightarrow K^- K^0 \pi^- \nu_\tau$, ($\tau^- \rightarrow K^- K^0 \nu_\tau$) decays. The red (dark shaded) histogram is the $q\bar{q}$ background. The mass plots use $\tau^- \rightarrow \pi^- K_S^0 K_S^0 \nu_\tau$ events that have been weighted based on the Dalitz plot distributions shown in Fig. 2.

The columns in Table I give the number of data and background events for each reconstruction mode. Table I also gives the selection efficiency matrix, where the horizontal row gives the efficiency for selecting the true decay for each reconstructed mode. For example, the efficiency for selecting a true $\tau^- \rightarrow \pi^- K_S^0 K_S^0 \nu_\tau$ decay is

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TABLE I. Results for the charged pion decays. The background events are primarily $q\bar{q}$ events.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$\tau^- \rightarrow \pi^- K_S^0 K_S^0 \nu_\tau$</th>
<th>$\tau^- \rightarrow \pi^- K_S^0 K_S^0 \pi^0 \nu_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Branching fraction</td>
<td>$(2.31 \pm 0.04 \pm 0.08) \times 10^{-4}$</td>
<td>$(1.60 \pm 0.20 \pm 0.22) \times 10^{-5}$</td>
</tr>
<tr>
<td>Events</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>4985</td>
<td>409</td>
</tr>
<tr>
<td>Estimated background</td>
<td>98 $\pm$ 17</td>
<td>35 $\pm$ 7</td>
</tr>
<tr>
<td>Selection efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau^- \rightarrow \pi^- K_S^0 K_S^0 \nu_\tau$</td>
<td>$(4.93 \pm 0.02)$%</td>
<td>$(0.21 \pm 0.01)$%</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \pi^- K_S^0 K_S^0 \pi^0 \nu_\tau$</td>
<td>$(3.04 \pm 0.10)$%</td>
<td>$(2.65 \pm 0.09)$%</td>
</tr>
<tr>
<td>Fractional systematic errors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Selection efficiency</td>
<td>0.008</td>
<td>0.12</td>
</tr>
<tr>
<td>Background</td>
<td>0.004</td>
<td>0.04</td>
</tr>
<tr>
<td>Common systematics</td>
<td>0.034</td>
<td>0.03</td>
</tr>
<tr>
<td>Total</td>
<td>0.035</td>
<td>0.13</td>
</tr>
</tbody>
</table>

---
The theoretical prediction for the branching fraction is in good agreement with the previous measurements of $(2.6 \pm 1.0 \pm 0.5) \times 10^{-4}$ [3] and $(2.3 \pm 0.5 \pm 0.3) \times 10^{-4}$ [4]. The theoretical prediction for the branching fraction is $4.8 \times 10^{-4}$ [16]. Decays involving a pion and two kaon mesons can have contributions from both axial and vector currents at the same time, and the vector contribution for branching fraction is estimated to be $1.4 \times 10^{-4}$ [16].

Assuming isospin symmetry [17] and using other measurements, we can estimate the branching fraction is equal if isospin is an exact symmetry (the branching fractions are also equal). Hence

\[ B(\tau^+ \to K^0_S K^+ \ell^- \nu_{\ell}) = B(\tau^- \to \pi^- K^+ K^- \ell^- \nu_{\ell}) - 2B(\tau^+ \to \pi^0 K^0_S K^0_S \ell^- \nu_{\ell}) \]

and we obtain

\[ B(\tau^+ \to K^0_S K^0_S \ell^- \nu_{\ell}) = (9.8 \pm 0.5) \times 10^{-4} \]
TABLE II. Results for the charged kaon decays. The background events are primarily $q\bar{q}$ events.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$\tau^- \rightarrow K^- K^0 \ell^+ \nu_\ell$</th>
<th>$\tau^- \rightarrow K^- K^0 \pi^0 \nu_\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Branching fraction</td>
<td>$(1.9 \pm 3.0 \pm 0.3) \times 10^{-7}$</td>
<td>$(1.5 \pm 1.8 \pm 0.1) \times 10^{-7}$</td>
</tr>
<tr>
<td>Limit (90% CL)</td>
<td>$6.3 \times 10^{-7}$</td>
<td>$4.0 \times 10^{-7}$</td>
</tr>
<tr>
<td>Events Data</td>
<td>23</td>
<td>1</td>
</tr>
<tr>
<td>Estimated background</td>
<td>$20.0 \pm 0.5$</td>
<td>$0.15 \pm 0.02$</td>
</tr>
<tr>
<td>Selection efficiency</td>
<td>$(3.85 \pm 0.04)%$</td>
<td>$(1.37 \pm 0.03)%$</td>
</tr>
</tbody>
</table>

where $B(\tau^- \rightarrow \pi^- K^+ K^- \nu_\tau) = (14.4 \pm 0.4) \times 10^{-4}$ [2] based on measurements from BABAR [18] and Belle [19]. The prediction is in good agreement with the branching fraction measured by ALEPH of $(10.1 \pm 2.3 \pm 1.3) \times 10^{-4}$ [3].

The $(\pi^- K^0_S)$ invariant mass distribution for events that pass the $\tau^- \rightarrow K^- K^0 K^0_S \ell^+ \nu_\ell$ selection show evidence for $K^+K^-$ peak (see Fig. 3). The $(\pi^0 K^0_S)$ invariant mass has an excess near 0.9 GeV/c$^2$ in data with respect to the MC simulation suggesting that $K^0$ mesons may also contribute to this decay. We model the $\tau^- \rightarrow \pi^- K^- K^0 S \ell^+ \nu_\ell$ decay using $\tau^- \rightarrow K^+ K^- \ell^+ \nu_\ell$ and $\tau^- \rightarrow K^+ K^- \ell^+ \nu_\ell$, because a model based on a phase space distribution of the final state particles does not describe the $(\pi^- K^0_S)$ invariant mass distribution. The relative contribution of $\tau^- \rightarrow K^+ K^- \pi^0 \ell^+ \nu_\ell$ to $\tau^- \rightarrow K^+ K^- \ell^+ \nu_\ell$ is determined to be $(0.17 \pm 0.03)$ by simultaneously fitting the $(\pi^- K^0_S)$ and $(\pi^0 K^0_S)$ invariant mass distributions (see Fig. 3). The predicted Monte Carlo distributions are fit to the data spectra after the subtraction of the $\tau^- \rightarrow \pi^- K^0 K^0_S \ell^+ \nu_\ell$ and background events. The normalizations of the two modes are varied with the constraint that the values be positive numbers. If we do not include the $\tau^- \rightarrow K^+ K^- \ell^+ \nu_\ell$, then we observe a disagreement between the data and MC samples in the lower-mass and higher-mass regions of the $M(\pi^- K^0_S)$ and $M(\pi^0 K^0_S)$ distributions in Fig. 3.

The same criteria are used to select $\tau^- \rightarrow K^- K^0 \ell^+ \nu_\ell$ and $\tau^- \rightarrow K^- K^0 \ell^+ \nu_\ell$ decays except that the charged track is required to be a kaon. The numbers of events are given in Table II and found to be consistent with the estimated background prediction. The background is almost entirely due to cross feed of $\tau^- \rightarrow \pi^- K^0 S \ell^+ \nu_\ell$ and $\tau^- \rightarrow \pi^- K^0 \pi^0 \ell^+ \nu_\ell$, decays and very little background from $q\bar{q}$ events. The branching fractions are determined for each channel independently and used to place upper limits on the branching fractions of $B(\tau^- \rightarrow K^- K^0 \ell^+ \nu_\ell) < 6.3 \times 10^{-7}$, $B(\tau^- \rightarrow K^- K^0 \pi^0 \ell^+ \nu_\ell) < 4.0 \times 10^{-7}$, at the 90% confidence level.

The $\tau^- \rightarrow K^- K^0 \ell^+ \nu_\ell$, and $\tau^- \rightarrow K^- K^+ K^- \ell^+ \nu_\ell$, branching fractions are also predicted to be equal assuming isospin symmetry. The $\tau^- \rightarrow K^- K^+ K^- \ell^+ \nu_\ell$ branching fraction is $(2.1 \pm 0.8) \times 10^{-5}$ [2] based on measurements from BABAR [18] and Belle [19]. BABAR finds that a $\tau^- \rightarrow K^- \ell^+ \nu_\ell$ contribution can account for all of the $\tau^- \rightarrow K^- K^+ K^- \ell^+ \nu_\ell$ decays. This suggests that the $\tau^- \rightarrow K^- K^0 K^0_S \ell^+ \nu_\ell$ and, consequently, the $\tau^- \rightarrow K^- K^0 K^0_S \pi^0 \ell^+ \nu_\ell$ branching fractions should be small in the limit of isospin symmetry.

In summary, we have measured the branching fractions of the $\tau^- \rightarrow \pi^- K^0 K^0_S \ell^+ \nu_\ell$ and $\tau^- \rightarrow \pi^- K^0 K^0_S \pi^0 \ell^+ \nu_\ell$, to be $(2.31 \pm 0.04 \pm 0.08) \times 10^{-4}$ and $(1.60 \pm 0.20 \pm 0.22) \times 10^{-5}$, respectively. The $\tau^- \rightarrow \pi^- K^0 K^0_S \pi^0 \ell^+ \nu_\ell$, branching fraction is significant improvement on the previous measurements and the $\tau^- \rightarrow \pi^- K^0 K^0_S \ell^+ \nu_\ell$ branching fraction is the first measurement. In addition, we place the first upper limits on the branching fractions of $6.3 \times 10^{-7}$ and $4.0 \times 10^{-7}$ on the $\tau^- \rightarrow K^- K^0 K^0_S \ell^+ \nu_\ell$ and $\tau^- \rightarrow K^- K^0 K^0_S \pi^0 \ell^+ \nu_\ell$, decay modes at the 90% confidence level.

We are grateful for the extraordinary contributions of our PEP-II colleagues in achieving the excellent luminosity and machine conditions that have made this work possible. The success of this project also relies critically on the expertise and dedication of the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its support and the kind hospitality extended to them. This work is supported by the U.S. Department of Energy and National Science Foundation, the Natural Sciences and Engineering Research Council (Canada), the Commissariat à l’Energie Atomique and Institut National de Physique Nucléaire et de Physique des Particules (France), the Bundesministerium für Bildung und Forschung and Deutsche Forschungsgemeinschaft (Germany), the Istituto Nazionale di Fisica Nucleare (Italy), the Foundation for Fundamental Research on Matter (The Netherlands), the Research Council of Norway, the Ministry of Education and Science of the Russian Federation, Ministerio de Ciencia e Innovacion (Spain), and the Science and Technology Facilities Council (United Kingdom). Individuals have received support from the Marie-Curie IEF program (European Union) and the A.P. Sloan Foundation (USA).