Search for CP violation in the decay $\tau^- \rightarrow \pi^- K_{S0}(\geq 0)\pi^0\nu_{\tau}$

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Search for $CP$ violation in the decay $\tau^- \to \pi^- K^0(S\equiv\pi^0)\nu_\tau$
We report a search for CP violation in the decay $\tau^+ \rightarrow \pi^0 K^0_S$ ($\equiv 0\pi^0\nu_\tau$) using a data set of $437 \times 10^6 \tau$-lepton pairs, corresponding to an integrated luminosity of 476 fb$^{-1}$, collected with the BABAR detector at the PEP-II asymmetric-energy $e^+e^-$ storage rings. The CP-violating decay-rate asymmetry is determined to be $(0.36 \pm 0.23 \pm 0.11)\%$ approximately 2.8 standard deviations from the standard model prediction of $(0.36 \pm 0.01)\%$. 

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CP violation has been observed only in the $K$ and $B$ meson systems. However, Bigi and Sanda [1] predict that, in the standard model (SM), the decay of the $\tau$ lepton to final states containing a $K^0_S$ meson will also have a nonzero decay-rate asymmetry due to CP violation in the kaon sector. The decay-rate asymmetry

$$A_\theta = \frac{\Gamma(\tau^+ \rightarrow \pi^0 K^0_S\nu_\tau) - \Gamma(\tau^- \rightarrow \pi^- K^0_S\nu_\tau)}{\Gamma(\tau^+ \rightarrow \pi^0 K^0_S\nu_\tau) + \Gamma(\tau^- \rightarrow \pi^- K^0_S\nu_\tau)}$$

is predicted to be $(0.33 \pm 0.01)\%$ for decay times comparable to the lifetime $\tau_{K^0_S}$ of the $K^0_S$ meson. In a recent paper, Grossman and Nir [2] point out that Sanda and Bigi did not
include the interference between the amplitudes of intermediate $K_S^0$ and $K_L^0$, which is as important as the pure $K_S^0$ amplitude. Therefore, the decay-rate asymmetry depends on the reconstruction efficiency as a function of the $K_S^0 \rightarrow \pi^+\pi^-$ decay time. If the selection is sufficiently efficient for decay times that are long compared with the $K_S^0$ lifetime, then the predicted decay-rate asymmetry is almost unchanged relative to the prediction of Bigi and Sanda [1], due to a sign error [2].

If the measured decay-rate asymmetry shows a significant deviation from the SM value then this could be evidence for new physics. No evidence for CP violation has been found in related studies by BABAR and Belle in $D^+ \rightarrow K_S^0\pi^+$ decays [3,4], by the Belle collaboration in a study of the angular distribution of the decay products in $\tau^+ \rightarrow \pi^- K_S^0\nu_\tau$ decays [5], or by the CLEO collaboration [6].

This paper presents a measurement of $A_0$, using $\tau^- \rightarrow \pi^- K_S^0(\equiv 0\pi^0)\nu_\tau$ and charge conjugate decays. The SM asymmetry is identical for decays with any number of $\pi^0$ mesons. If there is an asymmetry due to new-physics dynamics, then the impact of including modes with one or more $\pi^0$ mesons may be different.

The 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 GeV and 10.54 GeV at the SLAC National Accelerator Laboratory. The BABAR detector is described in detail in Ref. [7]. In particular, charged kaons and pions are differentiated by ionization ($dE/dx$) measurements in the silicon vertex detector and the drift chamber in combination with an internally reflecting Cherenkov detector, with identification efficiency greater than 90% for pions and kaons with momenta above 1.5 GeV/c in the laboratory frame [8]. The probability of identifying a pion as a charged kaon is less than 2%. An electromagnetic calorimeter made of cesium iodide crystals provides energy measurements for electrons and photons, and an instrumented flux return detector identifies muons [9]. For momenta above 1 GeV/c in the laboratory frame, electrons and muons are identified with efficiencies of approximately 92% and 70%, respectively. Based on an integrated luminosity of 476 fb$^{-1}$, the data sample contains approximately $875 \times 10^6\tau$ leptons.

Simulated event samples are used to estimate the purity of the data sample. The production of $\tau$ pairs is simulated with the KK2F Monte Carlo (MC) event generator [10]. 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 [11], JETSET [12], and PHOTOS [13], respectively. Passage of the particles through the detector is simulated by Geant4 [14].

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—the “signal” hemisphere and the “tag” hemisphere—using the event thrust axis [15]. 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 a $K_S^0 \rightarrow \pi^+\pi^-$ candidate reconstructed in the signal hemisphere, and exactly one oppositely charged prompt track in the tag hemisphere. 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. Furthermore, if a pair of tracks is consistent with coming from a $K_S^0$ or $\Lambda$ decay, or from a $\gamma$ conversion after a mass cut and a displaced vertex cut, neither track can be a prompt track. The components of momentum transverse to the $e^-$ beam axis for each of these two prompt tracks must be greater than 0.1 GeV/c in the laboratory frame. The event is rejected if the prompt track in the signal hemisphere is identified to be coming from a charged kaon. A $K_S^0$ candidate is defined as a pair of oppositely charged pion candidates with invariant mass between 0.488 and 0.508 GeV/c$^2$; furthermore, the distance between the beam spot and the $\pi^+\pi^-$ vertex must be at least 3 times its uncertainty (the $\pi^+\pi^-$ will be referred to as the “$K_S^0$ candidate daughters”). To reduce backgrounds from non-$\tau$-pair events, we require that the momentum of the charged particle in the tag hemisphere be less than 4 GeV/c in the CM frame and be identified as an electron ($e$ tag) or a muon ($\mu$ tag). To reduce backgrounds from Bhabha, $\mu^+\mu^-$, and $q\bar{q}$ events, we require the magnitude of the event thrust to be between 0.92 and 0.99.

Backgrounds from $q\bar{q}$ events are further reduced by rejecting events in which the invariant mass $M_{\text{rec}}$ of the charged particle (assumed to be a pion) is less than 1.15 GeV/c$^2$ and less than 1.50 GeV/c$^2$. The number of $\tau$ candidates is constructed from two clusters of energy deposits in the electromagnetic calorimeter that have no associated tracks (“neutral clusters”). 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 GeV/c$^2$ and 0.150 GeV/c$^2$. The number of entries in the $\tau^- \rightarrow \pi^- K_S^0\pi^0\nu_\tau$ mode is small and the corresponding invariant-mass plot is not included in Fig. 1.

The imperfect agreement between the $M_{\text{rec}}$ distributions in the data and MC simulation, seen in Fig. 1, is attributed to strange resonances that are not included in the simulation. The impact of the modeling of the $\tau$ decay modes in the MC simulation on the decay-rate asymmetry is
and tracks in the event), the number of neutral clusters in the tag hemisphere, the number of neutral clusters in the signal hemisphere, the magnitude of the thrust, and the component of the total momentum of the event transverse to the $e^-$ beam axis (calculated from all tracks and neutral clusters in both hemispheres). The variables used to construct $y(K^0_S)$ are the distance from the beam spot to the decay vertex of the $K^0_S$ candidate in the plane transverse to the $e^-$ beam axis, the invariant mass of the $K^0_S$ candidate daughters, the magnitude of the $K^0_S$ momentum, and the cosine of the polar angle of the $K^0_S$ candidate. The polar angle is the angle between the $K^0_S$ trajectory and the $e^-$ beam axis. The cosine of the polar angle discriminates low-angle photon conversions from genuine $K^0_S$ candidates. All kinematic quantities used in the construction of the two likelihood ratios, except for thrust, are determined in the laboratory frame. Events are selected if $y(\tau) > 0.2$ and $y(K^0_S) > 0.4$ (see Fig. 2), in order to minimize the contamination from background events while maintaining a high selection efficiency.

After all selection criteria are applied, a total of 199 064 (140 602) candidates are obtained in the $e$-tag ($\mu$-tag) sample, of which there are 99 842 (70 369) in the $\tau$ sample and 99 222 (70 233) in the $\tau^-$ sample.

The sample contains events from two $\tau$ decay modes, $\tau^- \rightarrow K^- K^0_S(\geq 0\pi^0) \nu_\tau$ and $\tau^- \rightarrow \pi^- K^0\bar{K}^0 \nu_\tau$, that also

found to be small and is included in the systematic uncertainties.

A likelihood ratio $y(\tau)$ is used to distinguish $\tau$-pair events from $q\bar{q}$ events, and a second likelihood ratio $y(K^0_S)$ is used to reduce the background in the sample of $K^0_S \rightarrow \pi^+ \pi^-$ candidates. The likelihood ratio $y_i(\hat{x}_i)$, where $i$ refers to $\tau$ or $K^0_S$, is defined as $y_i(\hat{x}_i) = L^1_i(\hat{x}_i)/(L^1_i(\hat{x}_i) + wL^0_i(\hat{x}_i))$ where $w$ is the background-to-signal ratio estimated from the MC simulation, $L^0_i$ ($L^1_i$) is the likelihood function for signal (background) events, and $\hat{x}_i$ is the set of variables used for likelihood $i$. Each likelihood function is a product of one-dimensional probability distribution functions of the variables $\hat{x}_i$ obtained from the MC simulation. For $y(\tau)$, the variables $\hat{x}_i$ are the visible energy (sum of the energies associated with all neutral calorimeter clusters

FIG. 1 (color online). Invariant-mass distributions for the combined $e$-tag and $\mu$-tag samples. The label in each plot indicates the reconstructed decay mode (including the charge conjugate mode). Points with error bars represent data whereas the histograms represent the simulated sample. The histogram labeled as “Signal” includes the $\tau^- \rightarrow \pi^- K^0_S(\geq 0\pi^0) \nu_\tau$, residual $\tau^- \rightarrow K^- K^0_S(\geq 0\pi^0) \nu_\tau$, and $\tau^- \rightarrow \pi^- K^0\bar{K}^0 \nu_\tau$ modes. All selection criteria (including the likelihood ratio requirement), except the invariant-mass ($M_{rec}$) criterion, have been applied. The vertical lines and arrows indicate the $M_{rec} < 1.8$ GeV/$c^2$ selection criterion.

FIG. 2 (color online). The likelihood ratio $y(\tau)$ used to distinguish $\tau$ events from $q\bar{q}$ events (top plot) and the likelihood ratio $y(K^0_S)$ used to select $\tau$ decays with a $K^0_S \rightarrow \pi^+ \pi^-$ (bottom plot). All selection cuts, except the plotted likelihood ratio requirement, have been applied. Points with error bars represent data while histograms correspond to simulated events. The histogram labeled as “Signal” includes the $\tau^- \rightarrow \pi^- K^0_S(\geq 0\pi^0) \nu_\tau$, residual $\tau^- \rightarrow K^- K^0_S(\geq 0\pi^0) \nu_\tau$, and $\tau^- \rightarrow \pi^- K^0\bar{K}^0 \nu_\tau$ modes. The vertical lines indicate the selection criteria.
have $K_S^0$ mesons in the final state. The decay $\tau^- \to \pi^- K_S^0 \nu_\tau$ satisfies the selection criteria if one of the neutral kaons decays into $\pi^+ \pi^-$ and the other neutral kaon decays into $2\pi^0$ or appears as a $K_S^0$ meson.

The selected candidate sample also contains a small background component from $\tau$ decays not containing a $K_S^0$ in the final state, as well as continuum $q\bar{q}(u, d, s$ and $c$-quark) events. There is no background from $BB$ events.

The numbers of background events of each type are estimated from the MC simulation. The accuracy of the background estimation is evaluated by measuring the ratios estimated from the MC simulation in this region. The correction factors are determined to be $(C25/C6)/(C25/C28)$ for the non-$K_S^0 \tau$ background in the $e$-tag ($\mu$-tag) samples, respectively. The total numbers of background events are then estimated from the MC simulation in this region. The correction factors are determined to be $0.81 \pm 0.03 (0.49 \pm 0.03)$ for the $q\bar{q}$ background and $0.9 \pm 0.4 (1.0 \pm 0.4)$ for the non-$K_S^0 \tau$ background in the $e$-tag ($\mu$-tag) samples, respectively.

The asymmetry will be modified due to the different nuclear-nucleon cross sections and including a nuclear screening factor of $A^{0.76}$, where $A$ is the atomic weight [17]. The correction, which is subtracted from the measured asymmetry, is found to be $(0.07 \pm 0.01)$% for both the $e$-tag and the $\mu$-tag samples. The error includes the statistical uncertainty in the MC simulation, the uncertainties in the kaon-nucleon cross sections [16], and an uncertainty due to the assumption of isospin invariance. The latter effect is taken to be 5% by observing that isospin symmetry in pion-nucleon cross sections holds to within a few percent. The error on the exponent of the atomic weight of the nuclear screening factor is 0.003 [17] and its contribution to the uncertainty in the asymmetry correction is negligible.

The measured decay-rate asymmetries (after correcting for the difference in neutral kaon nuclear interactions) are $(-0.39 \pm 0.23 \pm 0.13)$% for the $e$-tag sample and $(-0.12 \pm 0.27 \pm 0.10)$% for the $\mu$-tag sample, where the errors include the statistical uncertainties on the signal asymmetry (see Table II).

Additional studies show no evidence for any charge-dependent biases in the selection criteria. We find no decay-rate asymmetry in the MC sample of $\tau^- \to \pi^- K_S^0 (\approx 0\pi^0) \nu_\tau$ decays (no CP violation is modeled in the simulation) where the error on the decay-rate asymmetry is 0.14% for the $e$-tag and 0.17% for the $\mu$-tag events. We vary the selection criteria around their nominal values, and no significant changes in the asymmetry are observed.

The decay-rate asymmetry of the background events was studied by examining the events rejected by the likelihood ratio criteria and was found to be consistent with zero for both data and MC simulation.

A recent paper [17] suggests that the decay-rate asymmetry will be modified due to the different nuclear-interaction cross sections of the $K^0$ and $\bar{K}^0$ mesons with the material in the detector. This effect is not included in the MC simulation. A correction to the asymmetry accounting for this effect is calculated on an event-by-event basis using the momentum and polar angle of the $K_S^0$ candidate together with the nuclear-interaction cross sections for neutral kaons, which are related by isospin symmetry to the $K^\pm$ nucleon cross sections [16]. The kaon-nucleus cross sections are determined by using the kaon-nucleus cross sections and including a nuclear screening factor of $A^{0.76}$, where $A$ is the atomic weight [17]. The correction, which is subtracted from the measured asymmetry, is found to be $(0.07 \pm 0.01)$% for both the $e$-tag and the $\mu$-tag samples. The error includes the statistical uncertainty in the MC simulation, the uncertainties in the kaon-nucleon cross sections [16], and an uncertainty due to the assumption of isospin invariance. The latter effect is taken to be 5% by observing that isospin symmetry in pion-nucleon cross sections holds to within a few percent. The error on the exponent of the atomic weight of the nuclear screening factor is 0.003 [17] and its contribution to the uncertainty in the asymmetry correction is negligible.

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<td>$\tau^- \to \pi^- K_S^0 (\approx 0\pi^0) \nu_\tau$</td>
<td>78.7 ± 4.0</td>
<td>78.4 ± 4.0</td>
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<tr>
<td>$\tau^- \to K^- K_S^0 (\approx 0\pi^0) \nu_\tau$</td>
<td>4.2 ± 0.3</td>
<td>4.1 ± 0.3</td>
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<tr>
<td>$\tau^- \to \pi^- K_S^0 \bar{\nu}_\tau$</td>
<td>15.7 ± 3.7</td>
<td>15.9 ± 3.7</td>
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<tr>
<td>Other background</td>
<td>1.40 ± 0.06</td>
<td>1.55 ± 0.07</td>
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<tr>
<th></th>
<th>$e$ tag</th>
<th>$\mu$ tag</th>
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<td>Detector and selection bias</td>
<td>0.12%</td>
<td>0.08%</td>
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<tr>
<td>Background subtraction</td>
<td>0.05%</td>
<td>0.06%</td>
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<tr>
<td>$K^0/\bar{K}^0$ interaction</td>
<td>0.01%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Total</td>
<td>0.13%</td>
<td>0.10%</td>
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TABLE I. Breakdown of the sample after all selection criteria have been applied. The errors of the decay modes with $K_S^0$ are dominated by the uncertainties in the branching fractions. The background from other $\tau$ decays and $e^-e^+ \to q\bar{q}$ background are estimated using the data and MC simulation samples.

TABLE II. Summary of systematic uncertainties in the decay-rate asymmetries.
Furthermore, due to the systematic uncertainties of the first error is statistical and the second is systematic. The region obtained from the Monte Carlo sample. The top plot shows the background asymmetries \( t/\tau_{K^0_S} \) in the region. The relative efficiency is normalized to be unity for the decay-rate asymmetry is diluted due to the decay-rate asymmetry, where the error is due to the uncertainty in the relative selection efficiency. After applying the correction factor, the SM decay-rate asymmetry is predicted to be \((0.36 \pm 0.01)\%\).

In conclusion, we have performed a search for \( CP \) violation using the \( \tau \rightarrow \pi^- K^0_S(\geq 0\pi^0)\nu_\tau \) decay mode. The decay-rate asymmetry is measured for the first time and is found to be \((-0.36 \pm 0.23 \pm 0.11)\%\). The measurement is 2.8 standard deviations from the SM prediction of \((0.36 \pm 0.01)\%\).

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