Search for CP Violation in the Decay $\tau^- \rightarrow \pi^- K_S^0 (\geq 0\pi^0)$


(The BABAR Collaboration)

1 Laboratoire d’Annecy-le-Vieux de Physique des Particules (LAPP), Université de Savoie, CNRS/IN2P3, F-74941 Annecy-Le-Vieux, France
2 Universität de Barcelona, Facultat de Fisica, Departament ECM, E-08028 Barcelona, Spain
3 INFN Sezione di Bari, Dipartimento di Fisica, Università di Bari, I-70126 Bari, Italy
4 University of Bergen, Institute of Physics, N-5007 Bergen, Norway
5 Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA
6 Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany
7 University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1
8 Brunel University, Uxbridge, Middlesex UB8 3PH, United Kingdom
9 Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia
10 University of California at Irvine, Irvine, California 92697, USA
11 University of California at Riverside, Riverside, California 92521, USA
12 University of California at Santa Barbara, Santa Barbara, California 93106, USA
13 University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA
14 California Institute of Technology, Pasadena, California 91125, USA
15 University of Cincinnati, Cincinnati, Ohio 45221, USA
16 University of Colorado, Boulder, Colorado 80309, USA
17 Colorado State University, Fort Collins, Colorado 80523, USA
18 Technische Universität Dortmund, Institut für Kern- und Teilchenphysik, D-44221 Dortmund, Germany
19 Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany
20 Laboratoire Leprince-Ringuet, École Polytechnique, CNRS/IN2P3, F-91128 Palaiseau, France
21 University of Edinburgh, Edinburgh EH9 3JJ, United Kingdom
22 INFN Sezione di Ferrara, Dipartimento di Fisica, Università di Ferrara, I-44100 Ferrara, Italy
23 INFN Laboratori Nazionali di Frascati, I-00044 Frascati, Italy
24 INFN Sezione di Genova, Dipartimento di Fisica, Università di Genova, I-16146 Genova, Italy
25 Indian Institute of Technology Guwahati, Guwahati, Assam, 781 039, India
26 Harvard University, Cambridge, Massachusetts 02138, USA
27 Harvey Mudd College, Claremont, California 91711
28 Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany
29 Humboldt-Universität zu Berlin, Institut für Physik, Newtonstr. 15, D-12489 Berlin, Germany
30 Imperial College London, London, SW7 2AZ, United Kingdom
31 University of Iowa, Iowa City, Iowa 52242, USA
32 Iowa State University, Ames, Iowa 50011-3160, USA
33 Johns Hopkins University, Baltimore, Maryland 21218, USA
34 Laboratoire de l’Accélérateur Linéaire, IN2P3/CNRS et Université Paris-Sud 11, Centre Scientifique d’Orsay, B. P. 34, F-91898 Orsay Cedex, France
35 Lawrence Livermore National Laboratory, Livermore, California 94550, USA
36 University of Liverpool, Liverpool L69 7ZE, United Kingdom
37 Queen Mary, University of London, London, E1 4NS, United Kingdom
38 University of London, Royal Holloway and Bedford New College, Egham, Surrey TW20 0EX, United Kingdom
39 University of Louisville, Louisville, Kentucky 40292, USA
40 Johannes Gutenberg-Universität Mainz, Institut für Kernphysik, D-55099 Mainz, Germany
41 University of Manchester, Manchester M13 9PL, United Kingdom
42 University of Maryland, College Park, Maryland 20742, USA
43 University of Massachusetts, Amherst, Massachusetts 01003, USA
44 Massachusetts Institute of Technology, Laboratory for Nuclear Science, Cambridge, Massachusetts 02139, USA
45 McGill University, Montréal, Québec, Canada H3A 2T8
46 INFN Sezione di Milano, Dipartimento di Fisica, Università di Milano, I-20133 Milano, Italy
47 University of Mississippi, University, Mississippi 38677, USA
48 Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7
Abstract

We report a search for CP violation in the decay $\tau^- \rightarrow \pi^0 K_s^0 (\geq 0 \pi^0) \nu_\tau$ using a dataset of 437 million $\tau$ 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 $(0.45 \pm 0.24 \pm 0.11)\%$, approximately three standard deviations from the Standard Model prediction of $(0.33 \pm 0.01)\%$.

PACS numbers: 13.35.Dx, 11.30.Er

1 CP violation has been observed only in the $K$ and $B$ meson systems. However, Bigi and Sanda predict that, in the Standard Model (SM), the decay of the $\tau$ lepton to final states containing a $K^0$ meson will also have a non-zero decay-rate asymmetry due to CP violation in the kaon sector. The decay-rate asymmetry $A_Q = \frac{\Gamma (\tau^+ \rightarrow \pi^+ K_s^0 \nu_\tau) - \Gamma (\tau^- \rightarrow \pi^0 K_s^0 \nu_\tau)}{\Gamma (\tau^+ \rightarrow \pi^+ K_s^0 \nu_\tau) + \Gamma (\tau^- \rightarrow \pi^0 K_s^0 \nu_\tau)}$ is predicted to be $(0.33 \pm 0.01)\%$ [1]. Significant deviation from the SM value could be evidence for new physics.

2 No evidence for CP violation has been found in related studies by BABAR in $D^+ \rightarrow K_s^0 \pi^+$ decays [2], 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 [3], or by the CLEO collaboration [4].

3 This paper presents a measurement of $A_Q$ using $\tau^- \rightarrow K^0_s (\geq 0 \pi^0) \nu_\tau$ and charge conjugate decays. The analysis uses data recorded by the BABAR detector at the PEP-II asymmetric-energy $e^+e^-$ storage rings 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. [5]. In particular, charged kaons and pions are differentiated by ionization $(dE/dx)$ measurements in 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 [6]. The probability of identify-
ing 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, whereas an instrumented flux return detector identifies muons [5]. 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 million $\tau$ 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 [8]. 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 [9], JETSET [10], and PHOTOS [11], respectively. Passage of the particles through the detector is simulated by GEANT [12].

The $\tau$ pairs are 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 [13]. The event thrust axis is calculated using two charged particles, the $K_S^0$ candidate and all photon candidates in the entire event. We select events with one charged particle and a $K_S^0 \rightarrow \pi^+\pi^-$ candidate reconstructed in the signal hemisphere, and exactly one oppositely charged particle in the tag hemisphere. The tracks, excluding those from the $K_S^0$, must originate from the beam spot. The components of momentum transverse to the $e^-$ beam axis for each of these latter two charged particles must be greater than 0.1 GeV/c in the laboratory frame. The event is rejected if the charged particle in the signal hemisphere is identified as a charged kaon. $K_S^0$ candidates are 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 three times its uncertainty. 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 $M_{ee}$ of the charged particle (assumed to be a pion), the $K_S^0$ candidate, and up to three $\pi^0$ candidates, all in the signal hemisphere, is greater than 1.8 GeV/c$^2$ (see Fig. 1). If more than three $\pi^0$ candidates are reconstructed in the signal hemisphere, the three with invariant mass closest to the world-average $\pi^0$ mass [14] are included in the calculation of $M_{ee}$ and the rest are ignored. The $\pi^0$ candidates are constructed 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 GeV/c$^2$ and 0.150 GeV/c$^2$. The number of events in the $\tau^- \rightarrow \pi^- K_S^0 (\geq 0\pi^0) \nu_\tau$, residual $\tau^- \rightarrow K^- K_S^0 (\geq 0\pi^0) \nu_\tau$, and $\tau^- \rightarrow \pi^- K_S^0 \bar{\nu}_\tau$ modes. All selection criteria (including the likelihood ratio requirement), except the invariant mass ($M_{ee}$) criterion, have been applied. The vertical lines and arrows indicate the $M_{ee} < 1.8$ GeV/c$^2$ selection criterion.

FIG. 1: 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 $\tau^- \rightarrow \pi^- K_S^0 (\geq 0\pi^0) \nu_\tau$, residual $\tau^- \rightarrow K^- K_S^0 (\geq 0\pi^0) \nu_\tau$, and $\tau^- \rightarrow \pi^- K_S^0 \bar{\nu}_\tau$ modes in the MC simulation on the decay-rate asymmetry. The imperfect agreement between the histograms and the data is attributed to $K^*$ 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 found to be small and is included in the systematic uncertainties.
The likelihood ratio $y(\tau)$ is used to distinguish $\tau$-pair events from $q\bar{q}$ events (top plot) and the likelihood ratio $y(K^0_s)$ is used to select $\tau$ decays with a $K^0_s \to \pi^+\pi^-$ (bottom plot). All selection cuts, except the 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 $\tau^- \to \pi^- K^0_s (0\pi^0) \nu_\tau$, residual $\tau^- \to K^- K^0_s (0\pi^0) \nu_\tau$, and $\tau^- \to \pi^- K^0 \nu_\tau$ modes. The vertical lines indicate the selection criteria.

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 $K^0_s \to \pi^+\pi^-$ candidates. The likelihood ratio $y_i(\vec{x}_i)$, where $i$ refers to $\tau$ or $K^0_s$, is defined as $y_i(\vec{x}_i) \equiv \frac{L^i(\vec{x}_i)}{L^i(\vec{x}_i) + wL^0(\vec{x}_i)}$ where $w$ is the background-to-signal ratio estimated from the MC simulation, $L^i(\vec{x}_i)$ is the likelihood function for signal (background) events, and $\vec{x}_i$ is the set of variables used for likelihood $i$. Each likelihood function is a product of one-dimensional prob-ability distribution functions of the variables $\vec{x}_i$ obtained from the MC simulation. For $y(\tau)$, the variables $\vec{x}_i$ are the visible energy (sum of the energies associated with all neutral calorimeter clusters 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 pion 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 $\pi^+\pi^-$ daughters of the $K^0_s$ candidate, 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 is used to discriminate 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 199064 (140602) candidates are obtained in the $e$-tag ($\mu$-tag) sample, of which there are 99842 (70369) in the $\tau^-$ sample and 99222 (70233) in the $\tau^+$ sample.

The sample contains backgrounds from two $\tau$ decay modes, $\tau^- \to K^- K^0_s (0\pi^0) \nu_\tau$ and $\tau^- \to \pi^- K^0 \nu_\tau$, that have known background asymmetries. The SM asymmetry from the $\tau^- \to K^- K^0_s (0\pi^0) \nu_\tau$ mode is equal and opposite to that of the $\tau^- \to \pi^- K^0 \nu_\tau$ mode whereas the asymmetry for $\tau^- \to \pi^- K^0 \nu_\tau$ is zero. The additional $\pi^0$ mesons in the decay modes are not expected to change the asymmetry. The MC simulation is used to predict the composition of the sample (see Table I) and to evaluate the correction to be applied to the measured asymmetry. The decay $\tau^- \to \pi^- K^0 \nu_\tau$ 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 $K^0_s$ meson.

The selected candidates contain a small background component from $\tau$ decays not containing a $K^0_s$ in the final state and continuum $q\bar{q}$ events. In a simulated sample, less than 10 $B\bar{B}$ background events are observed to pass the selection criteria. The numbers of background events are estimated from the Monte Carlo simulation. The accuracy of the background estimation is evaluated by measuring the ratios of data to simulated event yields in the region $y(\tau) < 0.1$ and $y(K^0_s) < 0.1$. A correction factor is then applied to the background such that the number of simulated events in the region matches with data. The numbers of background events are estimated to be 1393±79 (1120±65) for $\tau^-$ decays and 1401±74 (1055±74) for $\tau^+$ decays in the $e$-tag ($\mu$-tag) samples, where the uncertainties include the statistical uncertainties from the sizes of the Monte Carlo samples and the uncertainties of the correction factors.

After the subtraction of background composed of $q\bar{q}$ and non-$K^0_s$ $\tau$ decays, the decay-rate asymmetry is measured to be $(-0.32 \pm 0.23)%$ for the $e$-tag sample and $(-0.05 \pm 0.27)%$ for the $\mu$-tag sample, where the errors are statistical. However, the asymmetry measured at this stage still includes other $\tau$ decays with $K^0_s$ in the final state.

A control sample of $\tau^- \to h^- h^+ (\geq 0\pi^0) \nu_\tau$ (excluding $K^0_s \to \pi^+\pi^-$ decays) in both data and MC simulation, where $h^-$ ($h^+$) represents a negatively (positively) charged hadron, is used to confirm that no significant decay-rate asymmetry is induced by the Bhabha detector or the selection criteria. The control sample is selected
iso-spin symmetry to the $K^\pm$ nucleon cross-sections [14]. The correction, which is subtracted from the measured asymmetry, is found to be $(0.14 \pm 0.03)\%$ for $e$-tag and $(0.14 \pm 0.02)\%$ for $\mu$-tag samples. The error includes the statistical uncertainty in the MC simulation, the uncertainties in the kaon-nucleon cross-sections [14], and an uncertainty due to the assumption of iso-spin invariance.

The last effect is taken to be 5\% by observing that iso-spin symmetry in pion-nucleon cross-sections holds to within a few percent.

The measured decay-rate asymmetries (after correcting for the difference in neutral kaon nuclear interactions) are $(-0.46 \pm 0.23 \pm 0.13)\%$ for the $e$-tag sample and $(-0.19 \pm 0.27 \pm 0.10)\%$ for the $\mu$-tag sample, where the first error is statistical and the second is systematic. The systematic uncertainties of the $e$-tag and $\mu$-tag results are almost completely uncorrelated. The weighted average of the two decay-rate asymmetries is $(-0.34 \pm 0.18 \pm 0.08)\%$.

The decay-rate asymmetry is diluted due to $\tau^- \rightarrow K^- K^0_S \nu_\tau$ and $\tau^- \rightarrow \pi^- K^0 \nu_\tau$ decays. The measured asymmetry $A$ is related to the signal asymmetry $A_1$ and the remaining background asymmetries $A_2$ and $A_3$ by:

$$A = \frac{f_1 A_1 + f_2 A_2 + f_3 A_3}{f_1 + f_2 + f_3} A_{SM}$$

where $f_1$, $f_2$, and $f_3$ are the fractions of $\tau^- \rightarrow \pi^- K^0_S (\geq 0\pi^0) \nu_\tau$, $\tau^- \rightarrow K^- K^0_S (\geq 0\pi^0) \nu_\tau$, and $\tau^- \rightarrow \pi^- K^0 \nu_\tau$ in the total selected sample as shown in Table II. Within the Standard Model, $A_1 = -A_2 = A_{SM} = (0.33 \pm 0.01)\%$ and $A_3 = 0$. We compare our result with the prediction of Bigi and Sanda by dividing the measured decay-rate asymmetry of $(-0.34 \pm 0.18 \pm 0.08)\%$ by $(f_1 - f_2)/(f_1 + f_2 + f_3) = 0.75 \pm 0.04$ (the correction is identical for the $e$-tag and $\mu$-tag samples). The uncertainty on the correction includes the statistical uncertainty and uncertainties in the branching fractions. Finally, the decay-rate asymmetry for the $\tau^- \rightarrow \pi^- K^0_S (\geq 0\pi^0) \nu_\tau$ decay mode is measured, for the first time, to be $(-0.45 \pm 0.24 \pm 0.11)\%$. 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, to be $(-0.45 \pm 0.24 \pm 0.11)\%$. The measurement is approximately three standard deviations from the SM prediction of $(0.33 \pm 0.01)\%$.

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support BaBar. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), IN2P3 (France), CEA (France), INFN (Italy), PHYSHEP4 (USA), RFBR (Russia), and Würzburg (Germany).
FOM (The Netherlands), NFR (Norway), MES (Russia), MICIN (Spain), STFC (United Kingdom). Individuals have received support from the Marie Curie EIF (European Union), the A. P. Sloan Foundation (USA) and the Binational Science Foundation (USA-Israel).

∗ Now at Temple University, Philadelphia, Pennsylvania 19122, USA
† Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy
‡ Now at the University of Huddersfield, Huddersfield HD 13DH, UK
§ Now at University of South Alabama, Mobile, Alabama 36688, USA
¶ Also with Università di Sassari, Sassari, Italy