Search for CP Violation in $\tau \to K\pi\nu_\tau$ Decays

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We search and find no evidence for CP violation in τ decays into the $K\pi\nu_\tau$ final state. We provide limits on the imaginary part of the coupling constant Λ describing a relative contribution of the CP violating processes with respect to the standard model to be $-0.172 < \mathrm{Im}(\Lambda) < 0.067$ at 90% C.L.

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The origin and source of CP violation in fundamental fermion interactions are topics of great interest. CP violation has been observed in the quark sector [1–4]. Increasing evidence for the existence of neutrino masses and their mixing opens the possibility of CP violation in the neutrino sector [5]. It would be odd if the mixing effects were limited to the quarks and neutrinos only and did not appear in the charged lepton sector. Such mixing could lead to CP violation. There are strict limits on the mixing among the charged leptons coming from the searches for lepton number violation [6]. Nevertheless, various extensions of the standard model allow for the existence of CP violation not only due to the mixing but also due to the interference between τ decays mediated by the W and a scalar boson [7,8]. We search for CP violation in τ decays and interpret the results within the context of a model with an exchange of a charged scalar with complex couplings. Previous searches for CP non-conservation in τ decays into $\pi\pi^0\nu_\tau$ [9] benefited from the large branching fraction yielding small statistical errors; however, possible CP violating effects are isospin suppressed in this case [10,11]. Here we study single τ decays into the $K\pi\nu_\tau$ final state. Although this decay mode has a smaller branching fraction, it is suppressed by the weaker $\mathrm{SU}(3)_f$ symmetry only and, therefore, has a greater discovery potential. A previous search using this decay was reported in Ref. [12].

The most general way to search for CP violation is to define a CP-odd observable and then to determine its average value. A value different from zero would indicate CP violation. Various CP-odd observables have different sensitivity to CP violation. However, there is "optimal" observable ξ that has the smallest associated statistical error [13,14]. For a decay described by CP-even P_{even} and CP-odd P_{odd} components of the amplitude, the optimal variable is defined as $\xi = P_{\mathrm{odd}}/P_{\mathrm{even}}$. In order to construct ξ we need to know the explicit forms of CP-even and -odd parts of the amplitude in terms of experimentally measured parameters of the decay. This is possible only within a specific model. Thus the choice of ξ is model dependent.

We search for CP violation in the decay $\tau \to K\pi\nu_\tau$ in the context of a model where the CP symmetry is broken by an interference between the standard model W exchange and an exchange of a scalar boson such as a charged Higgs [7,8] with a complex coupling Λ. We assume that CP symmetry is conserved at the τ pair production vertex. For this model, the matrix element for the τ^- decay into the $K\pi^-\nu_\tau$ final state is [10]

$$A(\tau^- \to K\pi^-\nu_\tau) \sim \bar{u}(\nu)\gamma_\mu(1-\gamma_5)u(\tau)f_V Q^\mu + \Lambda\bar{u}(\nu)(1+\gamma_5)u(\tau)f_S M\,, \quad (1)$$

where f_V and f_S are the vector and the scalar form factors, respectively, chosen to be Breit-Wigner shapes for $K^*(892)$ and $K_0^*(1430)$ resonances, $M = 1\ \mathrm{GeV}/c^2$ is a constant providing a normalization of the scalar term, and Q^μ is

$$Q^\mu = \left[(p_\pi - p_K)^\mu - \frac{m_\pi^2 - m_K^2}{(p_\pi + p_K)^2}(p_\pi + p_K)^\mu\right]. \quad (2)$$

Here, p_π, p_K, m_π, and m_K are the momenta and masses of the outgoing pion and kaon. The square of the matrix element is

$$|A|^2 \sim |f_V|^2[2(q\cdot Q)(Q\cdot k) - (q\cdot k)Q^2] + |\Lambda|^2|f_S|^2M^2(q\cdot k) + 2\,\mathrm{Re}(\Lambda)\,\mathrm{Re}(f_S f_V^*)Mm_\tau(Q\cdot k) - 2\,\mathrm{Im}(\Lambda)\,\mathrm{Im}(f_S f_V^*)Mm_\tau(Q\cdot k)\,, \quad (3)$$

where q and k are the four-vectors of the τ lepton and the neutrino, respectively, and m_τ is the τ lepton mass. The first three terms are CP even and the last term both violates SU(3) flavor symmetry and is CP odd.

To construct the optimal observable we need to express $(q\cdot Q)$, $(Q\cdot k)$, Q^2, and $(q\cdot k)$ in terms of experimentally measured decay parameters. From the energy and momentum conservation law we obtain

$$(q\cdot Q) = (Q\cdot k) = -2\left\{\left[\left(\frac{m_\tau^2 + m_H^2}{2m_H}\right)^2 - m_\tau^2\right]\left[\left(\frac{m_H^4 + (m_\pi^2 - m_K^2)^2}{4m_H^2}\right) - m_\pi^2\right]\right\}^{1/2}\cos\alpha\,, \quad (4)$$

$$Q^2 = 2m_\pi^2 + 2m_K^2 - [m_H^4 + (m_\pi^2 - m_K^2)^2]/m_H^2\,, \quad (5)$$

$$(q\cdot k) = (m_\tau^2 - m_H^2)/2\,, \quad (6)$$

where m_H is an invariant mass of the (πK) system. The angle between the pion and τ flight directions in the $(K\pi)$ rest frame is denoted as α. The angle α is not measured directly, but can be expressed on average by the combination of the measurable angles of the directions of the K and τ with respect to the z axis [10,11]. The optimal observable ξ is constructed from the above quantities.

The data used in this analysis were collected with the CLEO detector [15,16] at CESR operating on or near $\Upsilon(4S)$ resonance. The data correspond to a total integrated luminosity of 13.3 fb^{-1} and contain 12.2 million $\tau^+\tau^-$ pairs. We estimate backgrounds by analyzing samples of Monte Carlo (MC) events following the same procedures that are applied to the CLEO data. The generation of τ pair production and decay is modeled by the KORALB event generator [17], modified to include the charged scalar contribution to the $\tau \to K\pi\nu_\tau$ decay. The detector response is simulated with a GEANT-based [18] Monte Carlo.

Tau leptons are produced in pairs in e^+e^- collisions. Since the CLEO detector is more efficient for unambiguously detecting $K_S^0 \to \pi^+\pi^-$ decays than for charged kaons, we use the $\tau \rightarrow K_S^0\pi^\pm\nu_\tau$ decay. At CESR, the decay products of τ^+ and τ^- are well separated in the detector. We select the candidate events on the basis of the one- vs three-prong topology with zero net charge where two charged tracks must form a K_S^0. Each event is divided into two hemispheres by requiring one charged track to be isolated by at least 90° from the other three tracks. The one-prong "tag" selects the τ candidate decaying into an electron, a muon, or a single charged hadron, and no more than one additional π^0. If the one-prong track is identified as a lepton we allow at most one photon candidate; when present this candidate must have energy less than 100 MeV. The other, "signal," τ decays into a K_S^0, a charged pion, and a neutrino. Each track must have a momentum smaller than $0.85E_{\mathrm{beam}}$ to minimize the background from Bhabha scattering and from muon pair production. The momenta of all charged tracks are corrected for the energy loss in the beam pipe and in the tracking system. The K_S^0 decay vertex must be within 15 cm from the e^+e^- interaction point and the K_S^0 invariant mass must be within 12.5 MeV$/c^2$ from the nominal value. Background from photon conversions is suppressed by requiring the cosine of the angle between two tracks to be smaller than 0.99. In addition, we require dE/dx information for the charged track accompanying the K_S^0 to be consistent with that of a pion.

To suppress the background from the $e^+e^- \rightarrow q\bar{q}$ events we require the invariant mass in the signal hemisphere to be less than the m_τ. To suppress background from two-photon interactions we require the missing mass scaled with the center-of-mass energy to be less than 0.65 and the scaled transverse momentum to be greater than 0.02. We also require the cosine of the angle between the beam pipe and the direction of the missing momentum to be less than 0.95. Here, missing mass is the invariant mass of the difference between the 4-vector of the e^+e^- system and that for the total sum of all detected particles. Missing momentum is defined as a negative vector sum of all the momentum vectors of detected particles. The efficiency of the above selection criteria is $(11.3 \pm 0.1)\%$. A total of 11 970 events have been selected from the available CLEO data sample.

We estimate the remaining background by applying the same selection criteria to Monte Carlo simulations. The overall contribution from $e^+e^- \rightarrow B\bar{B}$ and two-photon [19] processes is less than 0.2%. The background from $e^+e^- \rightarrow q\bar{q}$ is estimated to be $(1.9 \pm 0.2)\%$. The dominant background is due to misidentified τ decays, with the largest contributions coming from the $\tau \rightarrow KK^0\nu_\tau$ $[(15.2 \pm 1.7)\%]$ and $\tau \rightarrow \pi K\pi^0\nu_\tau$ $[(9.5 \pm 1.0)\%]$ decays. The total background from τ decays is estimated to be $(39.2 \pm 2.5)\%$, and from all sources, $(41.3 \pm 2.5)\%$. As a cross check of our signal selection procedure we calculate a branching fraction for $\tau \rightarrow (K\pi)_{I=1/2}\nu_\tau$ and obtain a value consistent with those in the Particle Data Group tables [20].

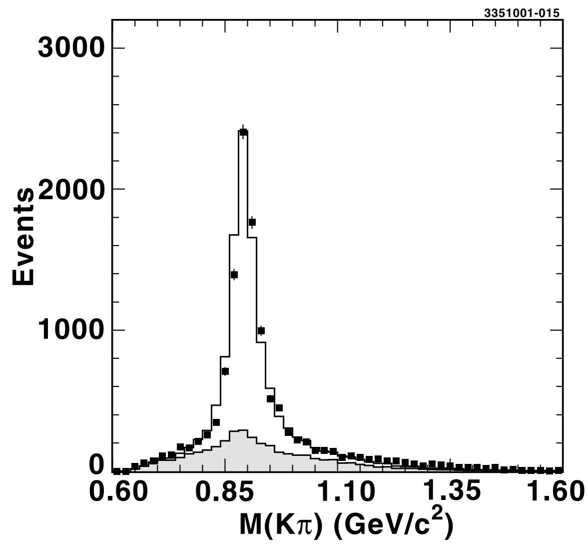

FIG. 1. The $(K_S^0\pi)$ invariant mass for data (squares), signal Monte Carlo prediction (solid line) and background (shaded histogram).

CP can be violated as a result of an interference between a vector [dominated by the $K^*(892)$] and a scalar [e.g., the $K_0^*(1430)$] resonances in the final state. To look for evidence of higher mass resonances we plot in Fig. 1 the invariant mass of the $(K_S^0\pi)$ system for the data, signal Monte Carlo, and backgrounds. We see no evidence for the $K_0^*(1430)$ resonance. We observe in the data a shift in the K^* mass peak of approximately 4.7 ± 0.9 MeV$/c^2$ with respect to the Monte Carlo simulation. This is under study but it does not affect the results presented in this paper.

In Fig. 2 we plot $\langle\xi\rangle$ separately for τ^- and τ^+ as a function of the $(K_S^0\pi)$ invariant mass for the data and for the Monte Carlo with maximum CP violation. A difference between the $\langle\xi\rangle$ distributions for τ^- and τ^+ would indicate CP violation. We expect the CP-violating effects to be maximal in the invariant mass range laying between the resonances, i.e., between 0.9 and 1.4 GeV$/c^2$. We observe no difference in the $\langle\xi\rangle$ distributions for the data and, therefore, no CP violation.

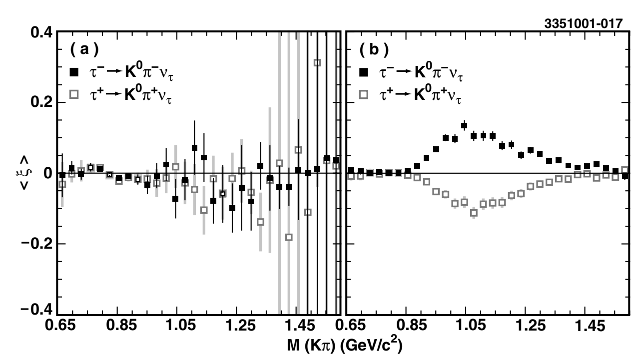

FIG. 2. Average value of the optimal observable as a function of the $(K_S^0\pi)$ invariant mass for (a) data and (b) Monte Carlo with maximum CP violation $\mathrm{Im}(\Lambda) = 1$.

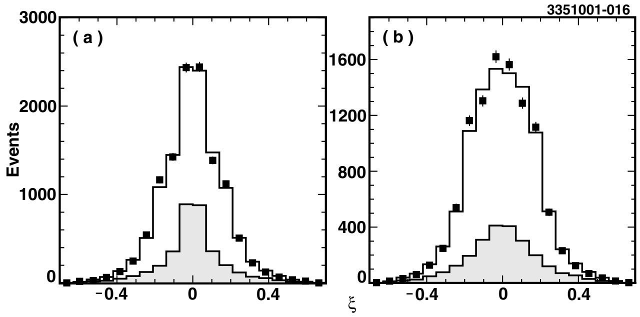

FIG. 3. The distribution of ξ for the data (squares) compared to the sum of the background (shaded histograms) and a standard model Monte Carlo prediction (a) for the whole data sample and (b) for the events with the mass of the $(K\pi)$ system ranging between 0.85 and 1.45 GeV/c^2.

To calculate the limit on the CP violation parameter Λ, we plot in Fig. 3 the ξ distribution for both the full data sample and for the restricted region of the $(K\pi)$ invariant mass $0.85 < M(K\pi) < 1.45$ GeV/c^2, where the sensitivity to CP violation is maximal. Here, we change the sign of ξ distribution for the τ^+ decays to add τ^- and τ^+ samples together. The corresponding average values of $\langle\xi\rangle$ for the data and for the signal and background Monte Carlo predictions are listed in Table I.

An average value of ξ in the signal Monte Carlo simulation is consistent with zero (Table I). Therefore, the selection criteria do not introduce artificial CP violating asymmetry.

To relate the observed mean value of the optimal observable $\langle\xi\rangle$ to the CP violating imaginary part of the coupling constant Λ, the $\mathrm{Im}(\Lambda)$ dependence of $\langle\xi\rangle$ must be known. The ξ is pure CP odd and, therefore, for small values of $\mathrm{Im}(\Lambda)$ the average $\langle\xi\rangle \simeq c_1\,\mathrm{Im}(\Lambda) + c_3\,\mathrm{Im}(\Lambda)^3$. We estimate c_1 and c_3 from the Monte Carlo generated with different values of $\mathrm{Im}(\Lambda)$. We use these coefficients to estimate the value of $\mathrm{Im}(\Lambda)$. The coefficients c_1, c_3, and the results for both the full sample and for the events within restricted $(K\pi)$ invariant mass range are given in Table II.

To estimate the limits on the CP violating parameter $\mathrm{Im}(\Lambda)$ we must first estimate the systematic errors. There are several possible sources of systematic errors that can contribute to this analysis. The resulting errors are multiplicative if the sources can modify the value of c_1 and additive if the sources can bias the central value of $\langle\xi\rangle$. We concentrate on c_1, because even large modifications of c_3 do not affect the result. Among the multiplicative sources we study effects due to uncertainty in the mass and width of $K_0^*(1430)\,(\pm 12\%)$, choice of the normalization constant $M(\pm 2\%)$, parametrization of the vector current ($\pm 3\%$), and Monte Carlo simulation ($\pm 9.3\%$). Additive systematic errors are estimated by studying track reconstruction efficiency for π^- and π^+ and by studying the bias in the asymmetry induced by the remaining background. The asymmetry in the track reconstruction efficiency is consistent with zero, and the uncertainty from the study contributes ± 0.009 to the uncertainty on $\mathrm{Im}(\Lambda)$. The asymmetries in the backgrounds are also consistent with zero as shown in Table I; the uncertainties on the background asymmetries become ± 0.017 on $\mathrm{Im}(\Lambda)$. The overall multiplicative error is estimated to be $\pm 15\%$, and the overall additive error on $\mathrm{Im}(\Lambda)$ is ± 0.019.

Within our experimental precision we observe no significant asymmetry of the optimal observable and, therefore, no CP violation in $\tau \to K\pi\nu_\tau$ decay. For a restricted range of the $(K\pi)$ mass (between 0.85 and 1.45 GeV/c^2) we obtain a value of the imaginary part of the scalar component in the τ decays as

$$\mathrm{Im}(\Lambda) = (-0.046 \pm 0.044 \pm 0.019)(1 \pm 0.15). \quad (7)$$

The first error is statistical and the second is additive systematic. The overall expression is multiplied by the multiplicative systematic error. The corresponding limits are

$$-0.172 < \mathrm{Im}(\Lambda) < 0.067, \quad (8)$$

at 90% C.L. This limit is an order of magnitude more restrictive than that obtained in the previous search [12] for CP violation in $\tau \to K\pi\nu_\tau$ decays. These results constrain the value of $\mathrm{Im}(\Lambda)$ at a comparable level to those from our study of $\tau^-\tau^+ \to (\pi^-\pi^0\nu_\tau)(\pi^+\pi^0\bar{\nu}_\tau)$ [9]. However, the current result is again about a factor of 10 more restrictive on the CP violating parameters of multi-higgs doublet models [7] than that obtained in the previous study.

Detailed interpretation of this result depends on a specific model. For example, in a 3-Higgs doublet model, $\Lambda = m_\tau/m_H^2(m_d YZ^* - m_u XZ^*)$, where m_d and m_u are the d and u quark masses, X and Y are Higgs couplings to quarks, and Z denotes Higgs coupling to leptons. An additional assumption of $X = Y$ gives a restriction $(-0.59 m_H^2\ \mathrm{GeV}^{-2}) < \mathrm{Im}(XZ^*) < 0.23 m_H^2\ \mathrm{GeV}^{-2}$.

TABLE I. Average value of the optimal observable for the full sample and for the restricted region of $(K\pi)$ mass.

Sample	$\langle\xi\rangle$, 10^{-3} (full)	$\langle\xi\rangle$, 10^{-3} (restricted)
Data	-1.5 ± 1.5	-1.7 ± 1.7
Signal MC	0.4 ± 1.0	0.5 ± 1.1
τ background MC	0.6 ± 1.6	0.7 ± 2.3
qq background MC	-18.1 ± 14.7	-23.1 ± 19.1
Data (background subtracted)	-2.0 ± 1.8	-2.3 ± 1.9

TABLE II. Coefficients c_1, c_3 and the values of $\mathrm{Im}(\Lambda)$ and 90% C.L. for both full sample and for the restricted region of the $(K\pi)$ invariant mass.

Coefficient	Full	Restricted
c_1	0.0368 ± 0.0018	0.0410 ± 0.0020
c_3	-0.0135 ± 0.0019	-0.0127 ± 0.0022
Results		
$\mathrm{Im}(\Lambda)$	-0.054 ± 0.049	-0.046 ± 0.044
90% C.L.	$(-0.134, 0.027)$	$(-0.119, 0.027)$

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[1] J. H. Christenson *et al.,* Phys. Rev. Lett. **13**, 138 (1964).
[2] V. Fanti *et al.,* Phys. Lett. B **465**, 335 (1999); A. Alavi-Harati *et al.,* Phys. Rev. Lett. **83**, 22 (1999).
[3] B. Aubert *et al.,* Phys. Rev. Lett. **87**, 091801 (2001).
[4] A. Abashian *et al.,* Phys. Rev. Lett. **87**, 091802 (2001).
[5] W. J. Marciano, hep-ph/0108181.
[6] R. Stroynowski, Nucl. Phys. (Proc. Suppl.) **B76**, 185 (1999).
[7] Y. Grossman, Nucl. Phys. **B426**, 355 (1994).
[8] S. Weinberg, Phys. Rev. Lett. **37**, 657 (1976).
[9] P. Avery *et al.,* Phys. Rev. D **64**, 092005 (2001); H. Hayashii, Nucl. Phys. (Proc. Suppl.) **B98**, 141 (2001).
[10] Y. S. Tsai, Nucl. Phys. (Proc. Suppl.) **C55**, 293 (1997).
[11] J. H. Kühn and E. Mirkes, Phys. Lett. B **398**, 407 (1997).
[12] S. Anderson *et al.,* Phys. Rev. Lett. **81**, 3823 (1998).
[13] D. Atwood and A. Soni, Phys. Rev. D **45**, 2405 (1992).
[14] J. F. Gunion, B. Grzadkowski, and X. G. He, Phys. Rev. Lett. **77**, 5172 (1996).
[15] Y. Kubota *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **418**, 32 (1998).
[16] T. S. Hill, Nucl. Instrum. Methods Phys. Res., Sect. A **320**, 66 (1992).
[17] S. Jadach, J. H. Kühn, and Z. Wąs, Comput. Phys. Commun. **76**, 361 (1993); CLEO has implemented the scalar in the $\tau \rightarrow K_s^0 \pi \nu_\tau$ decay in TAUOLA code.
[18] R. Brun *et al.,* GEANT 3.15, CERN DD/EE/84-1.
[19] V. M. Budnev *et al.,* Phys. Rep. C **15**, 181 (1975).
[20] D. E. Groom *et al.,* Eur. Phys. J. C **15**, 320 (2000).