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.

We search and find no evidence for CP violation in τ decays into the Kπντ 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 < Im(Λ) < 0.067 at 90% C.L.

DOI: 10.1103/PhysRevLett.88.111803

PACS numbers: 11.30.Er, 12.60.Fr, 13.35.Dx

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
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 $\tau$ decays mediated by the $W$ and a scalar boson [7,8]. We search for $CP$ violation in $\tau$ 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 $\tau$ decays into $\pi^0\nu_\tau$ [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 $\tau$ decays into the $K\pi\nu_\tau$ final state. Although this decay mode has a smaller branching fraction, it is suppressed by the weaker $SU(3)_f$ 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 different value from zero would indicate $CP$ violation. Various $CP$-odd observables have different sensitivity to $CP$ violation. However, there is “optimal” observable $\xi$ 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 $\xi = P_{odd}/P_{even}$. In order to construct $\xi$ 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 $\xi$ 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 $\Lambda$. We assume that $CP$ symmetry is conserved at the $\tau$ pair production vertex. For this model, the matrix element for the $\tau^-$ decay into the $K\pi^-\nu_\tau$ final state is [10]

$$A(\tau^- \to K\pi^-\nu_\tau) \sim \tilde{u}(\nu)(1 - \gamma_5)u(\tau)f_VQ^\mu + \Lambda\tilde{u}(\nu)(1 + \gamma_5)u(\tau)f_SM^\mu,$$

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, $M = 1 \text{ GeV}/c^2$ is a constant providing a normalization of the scalar term, and $Q^\mu$ is

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

(1)

Here, $p_{\pi}, p_K, m_{\pi},$ and $m_K$ are the momenta and masses of the outgoing pion and kaon. The square of the matrix element is

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

(2)

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

$$Q^\mu = \frac{m_H^2 + (m_{\pi}^2 - m_K^2)^2}{4m_H^2} - \frac{m_{\pi}^2}{2},$$

(3)

$$Q^2 = 2m_{\pi}^2 + 2m_K^2 - [m_H^2 + (m_{\pi}^2 - m_K^2)]/m_H^2,$$

(4)

$$(q \cdot k) = (m_{\pi}^2 - m_H^2)/2,$$

(5)

$$Q^\mu = \left( \frac{m_H^2 + (m_{\pi}^2 - m_K^2)^2}{4m_H^2} - \frac{m_{\pi}^2}{2} \right)^{1/2} \cos\alpha,$$

(6)

where $m_H$ is an invariant mass of the $(\pi K)$ system. The angle between the pion and $\tau$ flight directions in the $(K \pi)$ rest frame is denoted as $\alpha$. The angle $\alpha$ is not measured directly, but can be expressed on average by the combination of the measurable angles of the directions of the $K$ and $\tau$ with respect to the $z$ axis [10,11]. The optimal observable $\xi$ is constructed from the above quantities.
kaons, we use the $\tau \to K_S^0 \pi^+ \nu_\tau$ decay. At CESR, the decay products of $\tau^-$ and $\tau^+$ 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 $90^\circ$ from the other three tracks. The one-prong “tag” selects the $\tau$ candidate decaying into an electron, a muon, or a single charged hadron, and no more than one additional $\pi^0$. 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,” $\tau$ decays into a $K_S^0$, a charged pion, and a neutrino. Each track must have a momentum smaller than $0.85E_{\text{beam}}$ 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 $12.5 \text{ MeV}/c^2$ from the nominal value. Background from photon conversions is suppressed by requiring the cosine of the angle between the beam pipe and the direction of the charged track accompanying the $K_S^0$ to be consistent with that of a pion.

To suppress the background from the $e^+e^- \to q\bar{q}$ events we require the invariant mass in the signal hemisphere to be less than the $m_\tau$. 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 11970 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 $e^+e^- \to BB$ and two-photon [19] processes is less than 0.2\%. The background from $e^+e^- \to q\bar{q}$ is estimated to be $(1.9 \pm 0.2)\%$. The dominant background is due to misidentified $\tau$ decays, with the largest contributions coming from the $\tau \to K\pi^0 \nu_\tau$ \((15.2 \pm 1.7)\%\) and $\tau \to \pi K\pi^0 \nu_\tau$ \((9.5 \pm 1.0)\%\) decays. The total background from $\tau$ 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 $\tau \to (K\pi)_{-1/2} \nu_\tau$ and obtain a value consistent with those in the Particle Data Group tables [20].

$CP$ can be violated as a result of an interference between a vector [dominated by the $K^+ (892)$] and a scalar [e.g., the $K_S^0 (1430)$] 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 $K_S^0 (1430)$ resonance. We observe in the data a shift in the $K^+$ mass peak of approximately $4.7 \pm 0.9 \text{ MeV}/c^2$ 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 $\tau^-$ and $\tau^+$ 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 $\tau^-$ and $\tau^+$ 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.

![Figure 1](image1.png)

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

![Figure 2](image2.png)

**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 $\text{Im}(\Lambda) = 1$. 
To calculate the limit on the $CP$ violation parameter $\Lambda$, we plot in Fig. 3 the $\xi$ 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 $\xi$ distribution for the $\tau^+$ decays to add $\tau^-$ and $\tau^+$ 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 $\xi$ 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 $\Lambda$, the $\text{Im}(\Lambda)$ dependence of $\langle \xi \rangle$ must be known. The $\xi$ is pure $CP$ odd and, therefore, for small values of $\text{Im}(\Lambda)$ the average $\langle \xi \rangle \approx c_1 \text{Im}(\Lambda) + c_3 \text{Im}(\Lambda)^3$. We estimate $c_1$ and $c_3$ from the Monte Carlo generated with different values of $\text{Im}(\Lambda)$. We use these coefficients to estimate the value of $\text{Im}(\Lambda)$. 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 $\text{Im}(\Lambda)$ 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\%). Additive systematic errors are estimated by studying track reconstruction efficiency for $\pi^-$ and $\pi^+$ 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 $\pm 0.009$ to the uncertainty on $\text{Im}(\Lambda)$. The asymmetries in the backgrounds are also consistent with zero as shown in Table I; the uncertainties on the background asymmetries become $\pm 0.017$ on $\text{Im}(\Lambda)$. The overall multiplicative error is estimated to be $\pm 15\%$, and the overall additive error on $\text{Im}(\Lambda)$ is $\pm 0.019$.

Within our experimental precision we observe no significant asymmetry of the optimal observable and, therefore, no $CP$ violation in $\tau \rightarrow K\pi \nu_{\tau}$ 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 $\tau$ decays as

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

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

$$-0.172 < \text{Im}(\Lambda) < 0.067,$$

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 $\tau \rightarrow K\pi \nu_{\tau}$ decays. These results constrain the value of $\text{Im}(\Lambda)$ at a comparable level to those from our study of $\tau^+ \tau^- \rightarrow (\pi^- \pi^0\nu_{\tau}) (\pi^+ \pi^0\bar{\nu}_{\tau})$ [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 $(-0.59 m_H^2 \text{ GeV}^{-2}) < \text{Im}(XZ^*) < 0.23 m_H^2 \text{ GeV}^{-2}$.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\langle \xi \rangle$, 10$^{-3}$ (full)</th>
<th>$\langle \xi \rangle$, 10$^{-3}$ (restricted)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>$-1.5 \pm 1.5$</td>
<td>$-1.7 \pm 1.7$</td>
</tr>
<tr>
<td>Signal MC</td>
<td>$0.4 \pm 1.0$</td>
<td>$0.5 \pm 1.1$</td>
</tr>
<tr>
<td>$\tau$ background MC</td>
<td>$0.6 \pm 1.6$</td>
<td>$0.7 \pm 2.3$</td>
</tr>
<tr>
<td>$qq$ background MC</td>
<td>$-18.1 \pm 14.7$</td>
<td>$-23.1 \pm 19.1$</td>
</tr>
<tr>
<td>Data (background subtracted)</td>
<td>$-2.0 \pm 1.8$</td>
<td>$-2.3 \pm 1.9$</td>
</tr>
</tbody>
</table>
TABLE II. Coefficients $c_1$, $c_3$ and the values of Im($\Lambda$) and 90% C.L. for both full sample and for the restricted region of the $(K\pi)$ invariant mass.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Full</th>
<th>Restricted</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_1$</td>
<td>0.0368 $\pm$ 0.0018</td>
<td>0.0410 $\pm$ 0.0020</td>
</tr>
<tr>
<td>$c_3$</td>
<td>$-$0.0135 $\pm$ 0.0019</td>
<td>$-$0.0127 $\pm$ 0.0022</td>
</tr>
<tr>
<td>Results</td>
<td>Im($\Lambda$)</td>
<td>$-$0.054 $\pm$ 0.049</td>
</tr>
<tr>
<td></td>
<td>90% C.L.</td>
<td>($-$0.134, 0.027)</td>
</tr>
</tbody>
</table>

We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. This work was supported by the National Science Foundation, the U.S. Department of Energy, the Research Corporation, and the Texas Advanced Research Program.

[17] S. Jadach, J. H. Kühn, and Z. Was, Comput. Phys. Commun. 76, 361 (1993); CLEO has implemented the scalar in the $\pi \to K^0 \pi \nu$ decay in TAUOLA code.