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First Search for CP violation in Tau Lepton Decay

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Abstract

We have performed the first search for CP violation in tau lepton decay. CP violation in lepton decay does not occur in the minimal standard model but can occur in extensions such as the multi-Higgs doublet model. It appears as a characteristic difference between the τ^- and τ^+ decay angular distributions for the semi-leptonic decay modes such as $\tau^- \to K^0\pi^-\nu$. We define an observable asymmetry to exploit this and find no evidence for any CP violation.

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To date CP violation has only been observed in the kaon system [1] and its origin remains unknown. In the minimal standard model (MSM) CP violation is restricted to the quark sector and cannot occur in lepton decay [2]. It can, however, occur in extensions to the MSM such as the three Higgs doublet model [3]. It appears that there is insufficient CP violation in the MSM to generate the apparent matter-antimatter asymmetry of the universe [4]. Searches for additional CP violation beyond the MSM may help reconcile this problem.

CP violation appears as a phase θ_{cp} in the gauge boson-fermion coupling constant, CP:$\theta_{cp} \rightarrow -\theta_{cp}$. The physical effects of such a phase are only manifest in the interference of two amplitudes with both relative CP-odd phase θ_{cp} and relative CP-even phase δ (the interference term is proportional to $\cos(\delta - \theta_{cp})$). In tau lepton decay the two amplitudes could come from the MSM vector boson exchange (W) and the extended standard model scalar (Higgs) exchange. The CP-odd phase comes from the imaginary part of the complex scalar coupling constant. The CP-even phase difference is provided by the final state interaction (strong) phase that is different for s-wave scalar exchange and p-wave vector exchange and only arises in semi-leptonic decay modes with at least two final state hadrons ($\tau^- \rightarrow h_1 h_2 \nu_\tau$). The final state interaction is described by the s-wave and p-wave form factors, $F_s = |F_s| e^{i\delta_s}$ and $F_p = |F_p| e^{i\delta_p}$ respectively so that the strong phase difference is $\delta_{strong} = \delta_p - \delta_s$. The CP-violating $s - p$ wave interference term is then proportional to $|F_p||F_s| g \cos(\delta_{strong} - \theta_{cp}) \cos\beta \cos\psi$, where β and ψ are physical decay angles measured in the hadronic rest frame ($\vec{p}_{h_1} + \vec{p}_{h_2} = 0$) [5]. The direction of the laboratory frame as viewed from the hadronic rest frame is $\vec{p}_{lab}$ and β is the angle between the direction of h_1 or h_2 and $\vec{p}_{lab}$. ψ is the angle between the tau flight direction and $\vec{p}_{lab}$. The ratio of scalar to vector coupling strength is g (i.e g is in units of $G_F/2\sqrt{2}$). Since the sign of θ_{cp} changes for the CP-conjugate τ^- and τ^+, we define an experimentally measurable asymmetry $A_{observed}(\cos\beta\cos\psi)$ in terms of the number of events from $\tau^\pm$ decay, $N^\pm(\cos\beta\cos\psi)$, in a particular interval of $\cos\beta\cos\psi$:

$$A_{observed}(\cos\beta\cos\psi) = \frac{N^+(\cos\beta\cos\psi) - N^-(\cos\beta\cos\psi)}{N^+(\cos\beta\cos\psi) + N^-(\cos\beta\cos\psi)} \propto |F_p||F_s| g \sin\delta_{strong} \sin\theta_{cp} \cos\beta\cos\psi$$

The asymmetry is linear in $\cos\beta\cos\psi$ and we do not expect an overall rate asymmetry [6] since

$$\int_{-1}^{+1} dx A_{observed}(x) = 0; x = \cos\beta\cos\psi$$

We select a $\tau^- \rightarrow K_S^0 h^- \nu_\tau$, $K_S^0 \rightarrow \pi^+\pi^-$ event sample since a mass dependent Higgs-like coupling would give the largest asymmetry in this mode and with three charged tracks in the final state the decay angles are well measured. Here h^- is a charged pion or kaon.

The data used in this analysis have been collected from e^+e^- collisions at a center of mass energy ($\sqrt{s}$) of 10.6 GeV with the CLEO II detector at the Cornell Electron Storage Ring (CESR). The total integrated luminosity of the data sample is 4.8 fb^{-1}, corresponding to the production of 4.4×10^6 $\tau^+\tau^-$ events. The CLEO II detector has been described elsewhere [7].

We select events with a total of 4 charged tracks and zero net charge. Each track must have momentum transverse to the beam axis $p_T > 0.025 E_{beam}(E_{beam} = \sqrt{s}/2)$ and $|\cos\theta| < 0.90$ where θ is the polar angle with respect to the beam direction. The event is divided into two hemispheres by requiring one of the charged tracks to be isolated by at least 90^o from the other three (1 vs 3 topology). The isolated track is then required to have momentum greater than $0.05E_{beam}$ and $|\cos\theta| < 0.80$ to ensure efficient triggering and reduce backgrounds from two photon processes and beam gas interactions. To further reduce the two photon backgrounds and also continuum quark-antiquark production ($q\overline{q}$) we require that the net missing momentum of the event be greater than $0.03E_{beam}$ in the transverse plane and not point to within 18^o of the beam axis. We also require the total visible energy in the event to be between $0.7E_{beam}$ and $1.7E_{beam}$.

Events are permitted to contain a pair of *unmatched* energy clusters in the calorimeter (i.e, those not matched with a charged particle projection) in the 1-prong hemisphere with energy greater than 100 MeV consistent with π^0 decay. After π^0 reconstruction we reject events with remaining unmatched showers of greater than 350 MeV. We further reject events with showers of energy above 100 MeV in the 3 prong hemisphere or 300 MeV in the 1-prong hemisphere provided such showers are well isolated from the nearest track projection (by at least 30 cm) and have photon-like lateral profiles. These vetoes suppress backgrounds from $q\overline{q}$ events and tau feed-across (i.e., tau decay modes containing unreconstructed π^0's or K_L^0's).

The K_S^0 is identified by requiring two of the tracks in the 3-prong hemisphere to be consistent with the decay $K_S^0 \to \pi^+\pi^-$. We determine the K_S^0 decay point in the x-y plane (transverse to the beam direction) by the intersection of the two tracks projected onto this plane. This point must lie at least 5 mm from the mean e^+e^- interaction point (IP). We require that the distance between the two tracks in z (beam direction) at the decay point be less than 12 mm to ensure that the tracks form a good vertex in three dimensions. The distance of closest approach to the IP of the line defined by the x-y projection of the K_S^0 momentum vector must be less than 2 mm. The invariant mass of the pair of tracks, assumed to be pions, must be within 20 MeV of the known K_S^0 mass. We define a sideband region 30-100 MeV above and below the K_S^0 mass to use as a control sample.

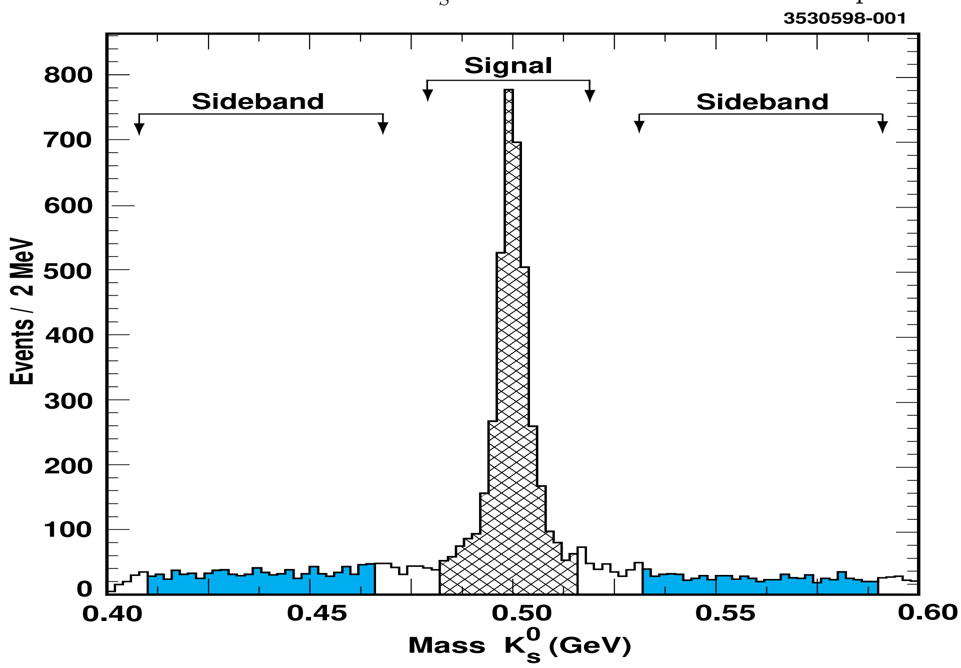

Figure 1 shows the invariant mass distribution after all selection criteria. Using this

FIG. 1. Invariant mass distribution for $K_S^0 \to \pi^-\pi^+$ in final data sample.

sample we measure the asymmetry for both signal and sideband in two intervals of $\cos\beta\cos\psi$, $A_{observed}(\cos\beta\cos\psi < 0)$ and $A_{observed}(\cos\beta\cos\psi > 0)$, given in Table I. Both signal and sideband exhibit similar non-zero asymmetries but with low statistical significance. The measured asymmetries are insensitive to small variations in the selection criteria. In addition to CP-violation, a non-zero asymmetry can arise from either a statistical fluctuation or a difference in detection efficiency for positive and negatively charged particles. A Monte Carlo simulation is used to estimate the expected CP violation in terms of the extended standard model scalar coupling parameters and we use the sideband sample to empirically estimate the asymmetry due to detector effects.

	$A_{observed}(\cos\beta\cos\psi < 0)$	$A_{observed}(\cos\beta\cos\psi > 0)$
Signal	0.058 ± 0.023	0.024 ± 0.021
Sideband	0.049 ± 0.030	0.034 ± 0.033

TABLE I. Observed asymmetries in signal and sideband regions

To estimate the expected CP-violating asymmetry for a pure $\tau^- \to K_S^0\pi^-\nu_\tau$ sample we use the KORALB Monte Carlo [8] to generate τ-pairs. It has been modified to include a scalar Higgs coupling in addition to the standard model W boson coupling, for the signal $K_S^0\pi^-$. We set $F_s = 1$ (i.e non-resonant decay) and F_p to be a Breit-Wigner for the $K^*(892)$ resonance so that $F_p >> F_s$ and the average strong phase difference $< \delta_{strong} >= \pi/2$. The GEANT code [10] is used to simulate detector response and assumes equal detection efficiencies for positive and negatively charged particles. We estimate $A^{K_S^0\pi^-}_{expected}(\cos\beta\cos\psi < 0) = -0.033 g \sin\theta_{cp}$ and $A^{K_S^0\pi^-}_{expected}(\cos\beta\cos\psi > 0) = +0.033 g \sin\theta_{cp}$ for a pure $\tau^- \to K_S^0\pi^-\nu_\tau$ signal. To compare this estimated asymmetry to the observed asymmetry we must take into account the effect of backgrounds since the signal region is not pure $K_S^0\pi^-$ and also estimate the asymmetry expected from charge dependent detection inefficiencies alone. Table II gives the estimated signal and sideband compositions by mode where the Lund Monte Carlo [9] has been used to generate the $q\overline{q}$ events.

The backgrounds arise from our inability to distinguish kaons and pions in the desired momentum range, lack of K_L^0 identification, particles that fall outside the fiducial region of the detector, and charged track mismeasurement. We note that the signal and sidebands are composed of different modes and it is unlikely that both samples would exhibit a similar CP-asymmetry as the strong phases, and possibly the coupling strengths are different for each mode. Also the samples exhibit an overall rate asymmetry not expected from CP-violating interference effects [6]. However the effect of charge dependent detection inefficiencies would be expected to be similar as both samples satisfy the same kinematic selection criteria.

Studies of pions from an independent $K_S^0 \to \pi^+\pi^-$ sample indicate that at low momentum the reconstruction efficiency for π^+ is slightly greater than π^- and also the reconstruction of a K_S^0 in close proximity to a π^+ is slightly more efficient than for a π^-. The hadronic

Tau Mode	α_{mode}	f^{signal}_{mode}	$f^{sideband}_{mode}$	$(f^{signal}_{mode} - f^{sideband}_{mode}).\alpha_{mode}$
$K^0_S(\pi^+\pi^-)\pi^-\nu_\tau$	1	0.525 ± 0.057	0.043 ± 0.005	0.4820 ± 0.0570
$K^0_S K^-\nu_\tau$	1/20	0.124 ± 0.036	0.009 ± 0.003	0.0060 ± 0.0020
$a_1^-\nu_\tau$	1/80	0.106 ± 0.003	0.620 ± 0.013	-0.0064 ± 0.0002
$K^0_S\pi^-\pi^0\nu_\tau$	1/4	0.066 ± 0.016	0.006 ± 0.002	0.0150 ± 0.0040
$K^0_S K^0_L\pi^-\nu_\tau$	1/80	0.055 ± 0.018	0.003 ± 0.001	$0.0007 \pm 0\ .0002$
$K^0_S K^-\pi^0\nu_\tau$	1/20	0.030 ± 0.008	0.003 ± 0.001	0.0014 ± 0.0004
$\pi^+\pi^-\pi^-\pi^0\nu_\tau$	1/20	0.028 ± 0.002	0.167 ± 0.007	-0.0070 ± 0.0004
$K^-\pi^+\pi^-\nu_\tau$	1/4	0.008 ± 0.003	0.043 ± 0.007	-0.0090 ± 0.0020
others	0	0.012 ± 0.002	0.071 ± 0.017	0
$q\bar{q}$	0	0.044 ± 0.003	0.037 ± 0.003	0
Total	-	1.00 ± 0.07	1.00 ± 0.00	0.48 ± 0.06

TABLE II. Signal and sideband mode composition. $f^{signal,sideband}_{mode}$ is the fraction of the total signal or sideband sample for a particular mode. α_{mode} is the approximate magnitude of asymmetry expected relative to the $\tau^- \to K^0_S\pi^-\nu_\tau$ mode. The last column gives the dilution factor expected in the asymmetry when the measured asymmetry in the sideband control sample is subtracted from the measured asymmetry in the signal sample.

interaction of π^+ with the CsI crystals produces more fake electromagnetic clusters than from a π^- which may then be used as veto clusters. These effects are more pronounced at lower momentum (< 1 GeV) and thus for $\cos\beta\cos\psi < 0.0$ since the pion from $\tau^- \to K^0_S\pi^-\nu_\tau$ tends to be of lower momentum in this region. The sidebands may be used as a control sample to estimate these combined effects in our signal region in a simple empirical way providing we assume that any CP-violating effects are suppressed in the sideband modes.

The samples consist of a sum of modes, each a fraction $f^{signal,sideband}_{mode}$ of the total signal or sideband sample, with a possible CP-violating asymmetry suppressed by a factor α_{mode} relative to the $\tau^- \to K^0_S\pi^-\nu_\tau$ signal mode. The suppression factor α_{mode} arises from two effects and is given for each mode in Table II. First from the mass dependence of the Higgs coupling and second due to the dilution of the p-wave nature of the standard model final state. For example, the $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ mode is dominated in the standard model decay by an s-wave $\tau^- \to a_1^-\nu_\tau \to \rho^0\pi^-\nu_\tau$ intermediate state which dilutes the $s-p$ wave interference by a factor of ≈ 4 in addition to a mass suppression of m_u/m_s relative to the $K^0_S\pi^-$ mode.

If we assume that in the absence of any true CP violation a charge dependent detector inefficiency would produce an asymmetry $A_{detector}$ common to all modes then the observed asymmetry, assuming the asymmetries are small (i.e $\ll 1$), is given by

$$A^{signal,sideband}_{observed} = \Sigma_{mode} f^{signal,sideband}_{mode} \alpha_{mode} A^{K^0_S\pi^-}_{expected} + A_{detector}$$

From Table II we see that the sideband should have negligible asymmetry with respect to the signal under the assumption of a mass dependent coupling and can be used as a control sample to subtract the charge dependent detector asymmetries common to both signal and sideband.

$$A_{observed}^{subtracted} = A_{observed}^{signal} - A_{observed}^{sideband} = 0.48 A_{expected}^{K_S^0\pi^-}$$

If a true CP violation exists the subtracted quantity should still exhibit significant but diluted asymmetry while detector effects should be removed. From Table I the measured subtracted asymmetry is $A_{observed}^{subtracted}(\cos\beta\cos\psi < 0) = 0.009 \pm 0.038$, $A_{observed}^{subtracted}(\cos\beta\cos\psi > 0) = -0.010 \pm 0.039$ which is consistent with no CP violation. This can be compared with a revised Monte Carlo estimate that takes into account the dilution factor of 0.48, $A_{expected}(\cos\beta\cos\psi < 0) = -0.016 g \sin\theta_{cp}$, $A_{expected}(\cos\beta\cos\psi > 0) = 0.016 g \sin\theta_{cp}$. To cross check our assumption of suppressed CP violation in the sidebands we measure the asymmetry in an independent high-purity high-statistics data sample of the dominant sideband mode, $\tau^- \to a_1^- \nu_\tau$, using the selection criteria of reference [11]. We find $A_{observed}^{a_1}(\cos\beta\cos\psi < 0) = -0.0013 \pm 0.0047$, $A_{observed}^{a_1}(\cos\beta\cos\psi > 0) = -0.0023 \pm 0.0047$ giving no evidence for CP violation. The higher track momentum and cluster veto thresholds combined with the absence of a K_S^0 requirement from this sample removes the contribution to the asymmetry from charge dependent detection inefficiencies but a true CP-violating effect should remain. We note that by measuring the CP-violating asymmetry in the dominant sideband mode as zero our results are approximately valid for a non-mass dependent coupling. However, we cannot fully relax this assumption due to the difficulty of empirically isolating a sample of each background mode in which to measure the asymmetry.

In conclusion we find no evidence for CP violation in tau decay. We may compare the observed to expected asymmetries to set a constraint of $g \sin\theta_{cp} < 1.7$ at the 90 % confidence level assuming $F_s = 1$. At the forthcoming B-factory experiments we anticipate substantial improvements in sensitivity both from the increased statistical precision and detector improvements. The addition of K_L^0 detection, K^-/π^- separation and improved precision tracking will significantly decrease backgrounds.

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[6] In the most general case we do not expect an overall rate asymmetry. The angular dependence of an s, p, d etc.,-wave amplitude is given by the Legendre polynomials $P_{m=0,1,2}(x)$ so that the angular dependence of a CP-violating interference term is given by $P_m(x)P_n(x)$ and since

$$\int_{-1}^{+1} dx P_m(x) P_n(x) = \frac{2}{2n+1}\delta_{mn}$$

we can only have a non-zero rate asymmetry if $m = n$ in which case the strong phases of the two amplitudes will be equal ($\sin\delta_{strong} = 0$) so that the overall rate asymmetry will be zero.

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