CP Violation and CLEO

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The validity of the Standard Model explanation of CP violation remains an unsettled experimental question. Using the CLEO II detector at the Cornell Electron Storage Ring a first observation of the Cabibbo suppressed decay $B^+ \to \overline{D}^0 K^+$, relevant for measuring the unitarity angle γ, has been made. A novel search for CP violation in tau lepton decays sensitive to non-Standard Model physics is also described.

Introduction

The verification or disproval of the Standard Model (SM) explanation of CP violation is one of the primary goals of particle physicists working at colliding beam facilities. CP violation in the SM is essentially described by the well known CKM matrix [1] which describes the coupling of left handed quarks to vector gauge bosons. Relationships between CKM matrix elements can in turn be described by triangle relationships such as that shown in figure 1, where the magnitude of the interior angles and the sides are related to CKM matrix elements.

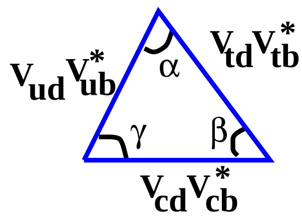

Figure 1: Unitarity triangle of the CKM matrix.

Verifying that the triangle sides and internal angles self-consistency form a triangle probes the SM explanation of CP violation while searching for CP violation in the leptonic sector, where there is no SM CP violation mechanism since there is no equivalent of the CKM matrix, probes non-SM physics. This report describes a branching fraction measurement of $\mathcal{B}(B^+ \to \overline{D}^0 K^+)$, which is part of the first verification goal, and describe a CP violation search in tau-lepton decays which addresses the second.

This work was performed with the CLEO II detector [2] at CESR. It collects data $\sim 2/3$ of the time at a center-of-mass energy matching the $\Upsilon(4S)$ peak and $\sim 1/3$ of the time 60 MeV below the peak for better estimates of continuum background. At the $\Upsilon(4S)$ only $B\overline{B}$ pairs are produced so that $E_B = E_{BEAM}$ and the B mesons are produced nearly at rest.

$\mathcal{B}(\mathbf{B}^+ \to \overline{\mathbf{D}^0}\mathbf{K}^+)$

The unitarity angle γ can be measured with time-integrated rate asymmetries from charged B meson decays [3]. Specifically, we can use the 6 decay reactions $B^\pm \to DK^\pm$, where $D = D^0, \overline{D}^0$, or $1/\sqrt{2}(D^0 \pm \overline{D}^0)$, i.e., flavor specific D mesons or a D which decays to a CP eigenstate ($D \to K_S, \pi^0, K_S\pi^+\pi^-, \ldots$). The relevant Feynman diagrams are shown in figure 2.

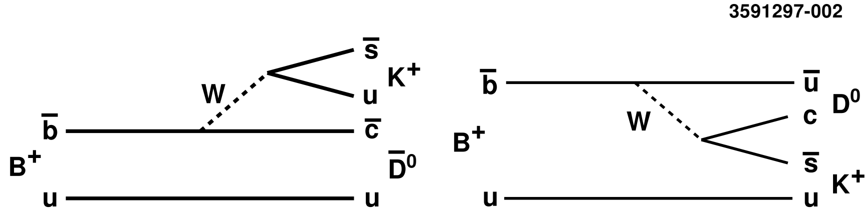

Figure 2: Major diagrams for the decays $B^+ \to \overline{D}^0 K^+$ and $B^+ \to D^0 K^+$.

A simple quantum mechanical relationship exists between these 6 decay amplitudes A:

$$\sqrt{2}A^{+}(B^{+} \to D_1^0 K^{+}) = \overline{A}(B^{+} \to D^0 K^{+}) + A(B^{+} \to D^0 K^{+})$$
$$\sqrt{2}A^{-}(B^{-} \to D_1^0 K^{-}) = \overline{A}(B^{-} \to D^0 K^{-}) + A(B^{-} \to D^0 K^{-}),$$

where the subscript 1 denotes the CP even D. (A similar relationship holds for the CP odd D.)

Two pairs of amplitudes are equal in magnitude so that the two algebraic relationships can be represented by two triangles as shown in figure 3. The angle γ is extracted from the two triangles after first measuring the decay amplitudes and with the help of other B and K decay results. A measurement of the magnitude of the base common to the triangles is equivalent to measuring the branching fraction $\mathcal{B}(B \to \bar{D}^0 K^{+})$.

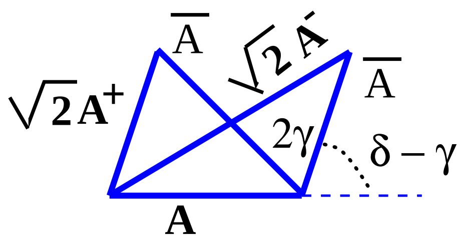

Figure 3: Triangle relationship for determining the unitarity angle γ. See text for explanation.

To measure $\mathcal{B}(B^{+} \to \overline{D}^0 K^{+})$ the 3 $\overline{D}^0$ decay modes $\overline{D}^0 \to K^{+}\pi^{-}, K^{+}\pi^{-}\pi^{+}, K^{+}\pi^{-}\pi^{+}\pi^{-}$ are used. The data sample consists of 3.3×10^6 $B\overline{B}$ pairs ($\int \mathcal{L}dt = 3.1\,\mathrm{fb}^{-1}$). Pions and kaons are identified by main drift chamber dE/dx measurements and for the relevant momentum region of 2.1 GeV–2.5 GeV the π/K separation is $1.5\,\sigma$. $\overline{D}^0$ candidates are then formed by demanding that the invariant mass of the putative $\overline{D}^0$ is close to that of a real $\overline{D}^0$. Afterwards, $\overline{D}^0$ and K's are combined using two important CLEO variables. The beam constrained mass $M_{BC} \equiv \sqrt{E_{beam}^2 - p_B^2}$ uses the kinematic constraint $E_B = E_{beam}$ and precise knowledge of the beam energy ($\sigma_{beam} \simeq 2.5\,\mathrm{MeV}$). Next, $\Delta E \equiv E_{\overline{D}^0} + \sqrt{p_K^2 + m_K^2} - E_{beam}$ is computed and a cut imposed. The resolution in ΔE is about 24 MeV and mode dependent.

The dominant background process is the Cabibbo favored decay $B^{+} \to \overline{D}^0 \pi^{+}$. Suppression is by ΔE and dE/dx cuts, and by cutting on the output $\mathcal{F}$ of an 11 variable Fisher discriminant. Overall selection efficiency for the $\overline{D}^0$ decay modes range from 17%–44%, depending on the mode.

Signal yields are determined mode-by-mode by an unbinned maximum likelihood method using a likelihood built from 7 probability density functions which account for signal signal events and 6 types of background events. The fit results are listed in table 1 for each of the 3 $\overline{D}^0$ decay modes. The signal yields N_{DK} are shown in the first row and the dominant background yields $N_{D\pi}$ are are shown in the second row. The third row shows the signal significance. Figure 4 shows the $-2\ln\mathcal{L}$ likelihood contours for each of the D decay modes.

Table 1: $B^+ \to \overline{D^0}\, K^+$ Likelihood Fit Results. Preliminary.

Mode:	$K^+\,\pi^-$	$K^+\,\pi^-\,\pi^0$	$K^+\,\pi^-\pi^+\pi^-$
N_{DK}	16.5 ± 5.9	13.5 ± 8.7	21.5 ± 7.8
$N_{D\pi}$	240 ± 15	379 ± 22	325 ± 20
N_{DK} significance	$4.2\,\sigma$	$1.8\,\sigma$	$3.8\,\sigma$
$N_{DK}/N_{D\pi}$	0.069 ± 0.026	0.035 ± 0.023	0.066 ± 0.025

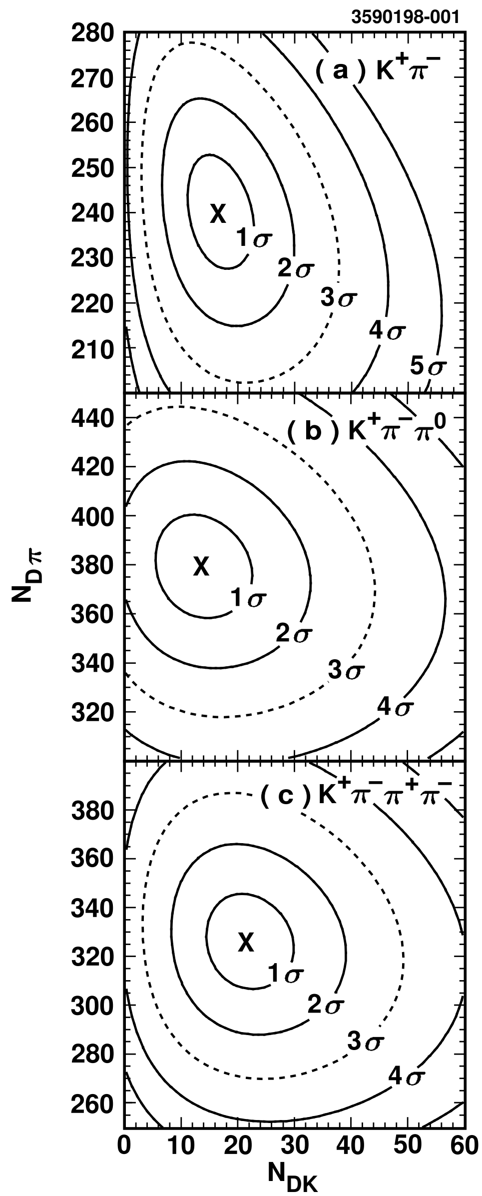

Figure 4: Contour plots of $-2\ln\mathcal{L}$ from the $B \to DK$ fit as a function of signal yield N_{DK} and dominant background yield $N_{D\pi}$. The 3σ contour is dashed.

Our result is the ratio R of branching fractions $R = \frac{\mathcal{B}(B^+ \to \overline{D^0} K^+)}{\mathcal{B}(B^+ \to \overline{D^0} \pi^+)} = 0.055 \pm 0.014 \pm 0.005$. The first error is statistical and the second is systematic. This preliminary result is consistent with $(f_K/f_\pi)^2 \tan^2\theta \approx 0.07$, expected from factorization for $a_2 \ll a_1$ [4]. Combining the result with a previous CLEO II result [7] for $\mathcal{B}(B^+ \to \overline{D^0}\pi^+)$ yields $\mathcal{B}(B^+ \to \overline{D^0}K^+) = (0.257 \pm 0.065 \pm 0.032) \times 10^{-3}$.

CP violation search in tau-lepton decays

CP violation in the SM is restricted to the quark sector and is forbidden in lepton decays. Furthermore, the SM explanation of CP violation does not appear to fully account for the large apparent discrepancy between matter and anti-matter in the present universe [5]. However, extensions to the SM, like the three Higgs doublet model [6], do permit CP violation in tau decay and may have cosmological significance. Hence, searches for CP violation in lepton decays are an interesting probe of non-SM physics.

CP violation is essentially an interference phenomenon that requires at least two quantum mechanical paths to the same final state. These paths (decay amplitudes) must have a "CP-odd" phase (one which acquires a relative negative sign under CP conjugation) and a "CP-even" phase (one which does not acquire a relative negative sign under CP conjugation). Interference between the corresponding amplitudes of the different paths then produces a physical effect proportional to $\cos(\delta - \theta_{CP})$, where δ and θ_{CP} are the CP-even and odd phases, respectively.

For the case of tau lepton decays, two such decay amplitudes could be provided by the SM vector boson (W) exchange and by a non-SM scalar (Higgs) exchange. The CP even phase δ is generated by final state or strong interactions which produce different phases for scalar (s-wave) and vector (p-wave) interactions. A non-zero δ would be produced only in semi-leptonic decays with at least two final state hadrons (eg, $\tau \to h_1 h_2 \nu_\tau$). The CP-odd phase θ would be generated by the imaginary part of the complex scalar coupling constant in the non-SM decay amplitude.

The overall effect of the interference between the two decay amplitudes is to produce a CP asymmetry A_{CP} in $\tau \to h_1 h_2 \nu_\tau$ decays:

$$A_{CP} = \frac{N^+(\cos\alpha) - N^-(\cos\alpha)}{N^+(\cos\alpha) + N^-(\cos\alpha)} \propto g \sin\delta \sin\theta_{CP} \cos\alpha,$$

where N^+ is the number of τ^+ decays that decay with $\cos\alpha$, where α is the angle between the tau flight direction and one of the final state hadrons, in the rest frame of the final state hadrons. Note that $A_{CP} \propto \sin\theta_{CP}$.

Since there is an undetected neutrino in the final state, the tau flight direction is unknown so that the angle α is unmeasurable and the above expression for A_{CP} is not directly usable. However, $\cos\alpha$ can be replaced by $\cos\beta\cos\psi$ [8], where these new experimentally accessible angles are also measured in the rest frame of the hadronic final state. The angle β is the angle between one of the hadrons h and the lab direction, and ψ is the cone angle the τ makes with the lab direction. Figure 5 shows the relevant geometry.

The preferred signal decay mode is $\tau \to K^0_S h, h = \pi, K$ since for a Higgs-like mass dependent coupling we expect a larger A_{CP} for a larger final state quark mass, and because the three final state charged tracks permit well measured decays angles. To simulate the expected experimental

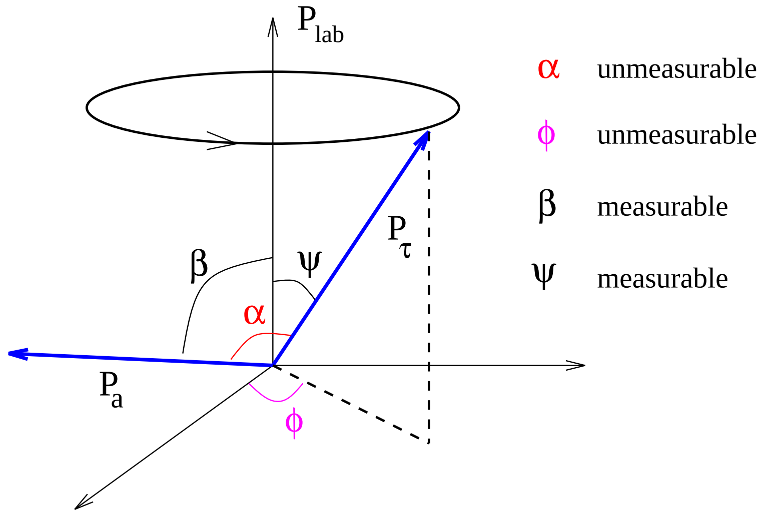

Figure 5: Experimentally accessible angles for measuring A_{CP}.

signature, we modified a standard Monte Carlo (MC) event generator [9] to include Higgs-like scalar couplings. Final state hadronic interactions were described by a Breit-Wigner p-wave form factor for the SM interaction and by a non-resonant s-wave form factor for the scalar decay. The primary MC input parameter is $Im(g)$, where g is the strength of the non-SM scalar coupling relative to the SM vector coupling.

Our initial data sample consists of 4.41×10^6 $\tau^+\tau^-$ pairs ($\int \mathcal{L}dt = 4.83\,\mathrm{fb}^{-1}$) collected at center of mass energy $\sqrt{s} = 10.6\,\mathrm{GeV}$. Events are selected used a 1 v. 3 charged track event topology and the K^0_S mesons are tagged by their displaced vertex. Other event selection cuts are straightforward. The overall selection efficiency determined by MC is 10%.

The K^0_S candidate invariant mass distribution after all selection criteria have been imposed is shown in figure 6. A peak at the K^0_S mass is seen and a control sample ("sideband region") is defined to be 30 MeV – 100 MeV on either side of the mass peak.

To increase statistical significance, we compute A_{CP} for all events in figure 6 using just two bins, $\cos\beta\cos\psi < 0$ and $\cos\beta\cos\psi > 0$. The measured asymmetries for signal and sideband region are listed in table 2. To account for possible detector response asymmetries which are difficult to simulate, a side band subtraction technique is used, $A_{expt} = A_{signal} - A_{side}$.

The expected asymmetry for a pure $\tau^- \to K^0_S\pi^-\nu_\tau$ sample was estimated from our modified MC event generator and included a full GEANT detector response simulation. Our estimate is that for a pure $K^0_S\pi^-$ signal, $A^{K^0_S\pi^-}_{MC}(\cos\beta\cos\psi \gtrless 0) = \pm 0.033 g \sin\theta_{CP}$.

Table 3 lists the relative weights α of the asymmetry A_{CP} expected in the sample if we subtract the sideband asymmetry from the signal asymmetry. The relative abundance of a particular decay mode is indicated by the symbol f. Both α and f are estimated from MC on a mode by mode basis and all errors are statistical. To a good approximation, the table

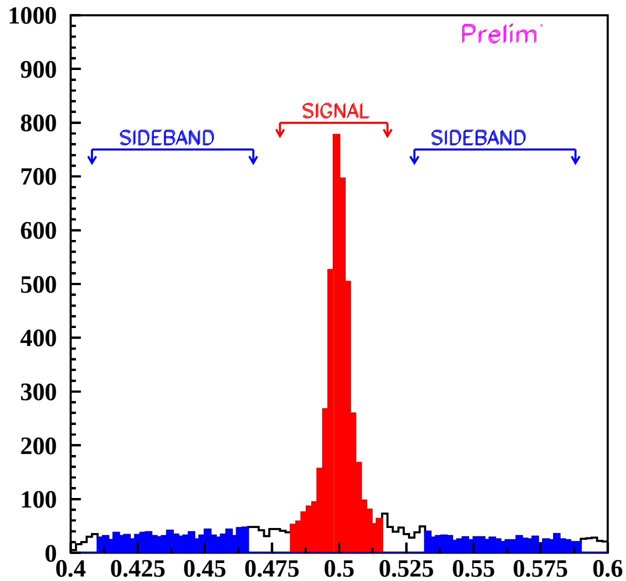

Figure 6: Invariant mass distribution of $K_S^0 \to \pi^-\pi^+$ candidates in data.

Table 2: Signal and sideband measured asymmetries. Preliminary.

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

shows that if a physics asymmetry exists, it should be suppressed in the sidebands and that backgrounds in the signal region tend to dilute the asymmetry rather than enhance it. In particular, the last entry in column six shows that the expected experimental asymmetry A_{expt} is approximately 50% of that expected from the $\tau^- \to K_S^0\pi^-\nu_\tau$ decay alone.

From table 2, the net measured asymmetry for the two bins is $A_{net}^- = 0.9 \pm 3.8\%$ and $A_{net}^+ = -1.0 \pm 3.9\%$. These numbers should be compared to the MC expectation after taking proper account of the dilution factor described above, $A^\pm = \pm 1.6 \sin\theta_{CP}\%$. The difference between expected and measured asymmetries constrain the imaginary part of the scalar's complex coupling to $g\sin\theta_{CP} < 1.7$ at the 90% confidence limit assuming that the scalar exchange proceeds through a non-resonant decay.

Our assumption that the sideband asymmetry is nearly zero was checked by measuring the asymmetry of the two bins in a large statistics sample [10] of the dominant sideband mode $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ using independent selections and cuts. The results were consistent with zero.

Conclusion

In summary, CLEO II has measured the branching fraction $\mathcal{B}(B^+ \to \overline{D}^0 K^+)$ which is a first step in eventually measuring the unitarity angle γ, and has searched for but found no evidence of CP violation in tau lepton decays.

Table 3: Monte Carlo estimated signal and sideband asymmetries. See text for explanation of symbols. All entries are preliminary.

Tau Mode	α^{mode}	f^{mode}_{signal}	$f^{mode}_{sideband}$	$(f^{mode}_{signal} - f^{mode}_{sideband}) \times \alpha$
$K^0_S(\pi^+\pi^-)\pi^-\nu_\tau$	1	0.525 ± 0.057	0.043 ± 0.005	0.482 ± 0.057
$K^0_S K^-\nu_\tau$	1/20	0.124 ± 0.036	0.009 ± 0.003	0.006 ± 0.002
$a_1\nu_\tau$	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	0.015 ± 0.004
$K^0_S K_L\pi^-\nu_\tau$	1/80	0.055 ± 0.018	0.003 ± 0.001	0.0007 ± 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	-0.007 ± 0.0004
$K^-\pi^+\pi^-\nu_\tau$	1/4	0.008 ± 0.003	0.043 ± 0.007	-0.009 ± 0.002
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 ± 0.03	0.48 ± 0.06

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