Direct CP violation in the angular distribution of $B\to J/\psi K^*$ decays

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We show that the study of certain observables in the angular distribution in $B\to J/\psi K^*$ provide a clear test for CP violation beyond the standard model (SM). These observables vanish in the SM, but in models beyond the SM some of them can be large enough to be measured at B factories. [S0556-2821(98)03923-X]

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The CLEO Collaboration has recently reported [1] the first full angular analysis of $B\to J/\psi K^*$ decays. Several CP conserving quantities have been studied. They found that the P wave component is small, $|P|^2=0.16\pm0.08\pm0.04$, which is good news for measuring mixing induced CP violation via $B\to J/\psi K^{*0}\to J/\psi K_S\pi^0$ decay [2]. Relative to the longitudinal amplitude A_0, the phases of the transverse and parallel amplitudes were found to be $\phi(A_T)=-0.11\pm0.46\pm0.03$ rad, and $\phi(A_{||})=3.00\pm0.37\pm0.04$ rad, respectively. These phases are consistent with 0 or π, indicating the absence of final state interaction (FSI) phase shifts if CP is conserved. It should be noted that the analysis in fact does not measure FSI phases alone, but a combination of FSI and CP violating weak phases. In order to have information about FSI and CP violating weak phases, the particle and antiparticle decays have to be separately measured. With increased luminosities in the near future at CLEO, the SLAC and KEK B factories, and other facilities, together with good K/π separation capabilties (particle identification), one can distinguish K^* from $\overline{K^*}$, hence B vs $\overline{B}$. One can then study direct CP violation in these decays even if the partial rate asymmetry is zero. In this paper we show that certain observables in the angular distribution in $B\to J/\psi K^*$ provide a clear test for CP violation beyond the standard model (SM).

All necessary information for the present study is contained in the full angular distribution for $B\to J/\psi K^*$ which is given by [3]

$$\frac{1}{\Gamma}\frac{d^3\Gamma}{d\cos\theta_{\rm tr}d\cos\theta_{K*}d\phi_{\rm tr}}=\frac{9}{32\pi}\Big\{2|A_0|^2\cos^2\theta_{K*}(1-\sin^2\theta_{\rm tr}\cos^2\phi_{\rm tr})+|A_{||}|^2\sin^2\theta_{K*}(1-\sin^2\theta_{\rm tr}\sin^2\phi_{\rm tr})$$
$$+|A_T|^2\sin^2\theta_{K*}\sin^2\theta_{\rm tr}-{\rm Im}(A_{||}^*A_T)\sin^2\theta_{K*}\sin 2\theta_{\rm tr}\sin\phi_{\rm tr}$$
$$+\frac{1}{\sqrt{2}}{\rm Re}(A_0^*A_{||})\sin 2\theta_{K*}\sin^2\theta_{\rm tr}\sin 2\phi_{\rm tr}+\frac{1}{\sqrt{2}}{\rm Im}(A_0^*A_T)\sin 2\theta_{K*}\sin 2\theta_{\rm tr}\cos\phi_{\rm tr}\Big\},\qquad(1)$$

where $A_T=P$ is the P wave decay amplitude, and A_0 and $A_{||}$ are two othorgonal combinations of the S and D wave amplitudes with the normalization $|A_T|^2+|A_0|^2+|A_{||}|^2=1$. The angles $\theta_{\rm tr}$ and $\phi_{\rm tr}$ are defined as polar and azimuth angles of the charged lepton in the J/ψ rest frame, with x axis along the direction of K^*, and x-y plane parallel to $K\pi$ plane. The angle θ_{K*} is defined as that of the K in the rest frame of K^* relative to the negative of the J/ψ direction in that frame. The angular distribution for $\overline{B}$ decay is similar, and we shall use $\overline{A}$ to indicate the corresponding amplitudes.

In the CLEO analysis, the phase for A_0 was taken to be zero. For convenience we will use the convention that each amplitude A_i has both CP conserving FSI phase ϕ_i and CP violating phase σ_i, i.e., $A_j=|A_j|e^{i(\phi_j+\sigma_j)}$ while $\overline{A}_T=-|A_T|e^{i(\phi_T-\sigma_T)}$, $\overline{A}_{||}=|A_{||}|e^{i(\phi_{||}-\sigma_{||})}$, and $\overline{A}_0=|A_0|e^{i(\phi_0-\sigma_0)}$.

There are several ways for CP violation to manifest itself; the most familiar one is in partial rate asymmetries. Since there are three different decay amplitudes, partial rate asymmetries may show up in either of them [4]. These asymmetries can be studied by measuring the coefficients of the first three terms in Eq. (1) for B and $\overline{B}$ decays and comparing them. However, in the case under consideration such differences are very small and therefore difficult to measure. It is therefore interesting to see if there are other observables in the angular distribution which provide useful information about CP violation even if the partial rate asymmetries are zero.

It is clear that the coefficients $\alpha=-{\rm Im}(A_{||}^*A_T)$, $\beta={\rm Re}(A_0^*A_{||})$, and $\gamma={\rm Im}(A_0^*A_T)$ of the last three terms in the angular distribution, and similarly $\overline{\alpha}$, $\overline{\beta}$ and $\overline{\gamma}$ for $\overline{B}$

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decays, contain information about CP violation. Without separating B and $\overline{B}$ decays, however, which was the case for the CLEO analysis mentioned earlier, information on CP violation cannot be extracted. One must obtain the angular distributions for $B\to J/\psi K^*$ and $\overline{B}\to J/\psi \overline{K}^*$ decays separately and determine the coefficients for the interference terms in each case. The following three quantities then measure CP violation:

$$a_1=\alpha+\overline{\alpha}=2|A_T||A_{||}|\cos(\phi_{||T})\sin(\sigma_{||T}),$$

$$a_2=\beta-\overline{\beta}=-2|A_{||}||A_0|\sin(\phi_{||0})\sin(\sigma_{||0}),$$

$$a_3=\gamma+\overline{\gamma}=-2|A_T||A_0|\cos(\phi_{T0})\sin(\sigma_{T0}), \tag{2}$$

where $\phi_{ij}=\phi_i-\phi_j$ and $\sigma_{ij}=\sigma_i-\sigma_j$. Observables analogous to these, but integrated over various ranges of angles, have already been considered in Ref. [4]. We remark that similar analysis can be carried out for any two vector meson decay channels of B meson, such as $B\to D^*\rho$ and $B\to\phi K^*$, but it is probably more useful for tree-level dominated decays where the rate asymmetry is small.

We note that the CP violating observables $a_{1,3}$ do not require FSI phase differences and are especially sensitive to CP violating weak phases. The present CLEO data on angular distributions which provide information about FSI phases are proportional to the CP conserving quantities $\alpha-\overline{\alpha}\sim\sin(\phi_{||T})\cos(\sigma_{||T})$, $\beta+\overline{\beta}\sim\cos(\phi_{||0})\cos(\sigma_{||0})$, and $\gamma-\overline{\gamma}\sim\sin(\phi_{T0})\cos(\sigma_{T0})$. At present these data do not exclude a_1 (a_3) up to 0.50 (0.58), but the small FSI phase for $A_{||}$ measured by CLEO implies that a_2 is small.

In SM the decay amplitude for $B\to J/\psi K^*$ is due to the quark level effective Hamiltonian

$$H_{\rm eff}=\frac{G_F}{\sqrt{2}}V_{cb}V_{cs}^*\{C_1\overline{c}\gamma_\mu(1-\gamma_5)c\overline{s}\gamma^\mu(1-\gamma_5)b$$
$$+C_2\overline{s}\gamma_\mu(1-\gamma_5)c\overline{c}\gamma^\mu(1-\gamma_5)b\}, \tag{3}$$

where $C_1=-0.313$ and $C_2=1.15$ [5], and we have neglected the negligibly small penguin contribution. This effective Hamiltonian generates a common weak phase for all the amplitudes through the phase of $V_{cb}V_{cs}^*$, which is zero in the Wolfenstein parametrization. The quantities a_i therefore all vanish. However, in extensions of SM, these phases need not be the same, and the values for a_i may no longer vanish. Hence, the observables a_i provide good tests for CP violation beyond SM.

There are many ways where new physics may change the phases σ_i. To lowest order they may arise from dimension 6 four quark operators, or from the dimension 5 color dipole operator $\overline{s}i\sigma_{\mu\nu}G^{\mu\nu}(1\pm\gamma_5)b$, where $G^{\mu\nu}$ is the gluon field strength. New physics contributions from $C_L\overline{c}\gamma^\mu(1\pm\gamma_5)c\overline{s}\gamma_\mu(1-\gamma_5)b$ type of interactions are proportional to the SM contribution, which just generate a common weak phase for all the amplitudes and therefore the a_i's are all zero. The observables a_i discussed here do not provide good tests for new physics of this type. Interactions of the form $C_R\overline{c}\gamma^\mu(1\pm\gamma_5)c\overline{s}\gamma_\mu(1+\gamma_5)b$, however, will generate different phases for A_T and $A_{||,0}$ because the $\overline{s}\gamma^\mu(1+\gamma_5)b$ contribution to A_T is proportional to C_R, but for $A_{||,0}$ it is proportional to $-C_R$. To a good approximation, one gets the weak phase $\sigma_T=-\sigma_{||,0}$, leading to nonzero values for a_i.

Let us consider, as an example, R-parity violating supersymmetric models. The exchange of charged sleptons or down type squarks can generate nonzero C_R with an arbitrary phase σ_R. The allowed value for C_R is constrained by experimental data on $b\to s\gamma$, but it still allows the C_R contribution to the $B\to J/\psi K^*$ amplitude to be as large as 20% of the SM contribution. Slightly stronger constraints can be obtained by assuming that $b\to c\overline{c}s$ is similar to $b\to c\overline{u}s$ from R-parity violating interactions. The upper bound of the weak phases are approximately given by [6]

$$\sigma_T=-\sigma_{||,0}\approx 0.1\sin\sigma_R. \tag{4}$$

Using the central values for the modulous of the amplitudes and assuming that the FSI phases are zero, we find

$$a_1\simeq 0.10\sin\sigma_R, \quad a_3\simeq -0.12\sin\sigma_R. \tag{5}$$

The contribution from the dimension 5 color dipole operator has been estimated by assuming that color octet operators contribute the amount as determined in generalized factorization approximation [2]. The magnitude of the color dipole coefficient as large as 10 times that of the SM one is not ruled out. In fact, charm counting and semileptonic branching ratio problems in B decays [7], and perhaps the large $B\to\eta' X_s$, may favor such a large value [8]. The weak phases σ_i can be as large as $0.1\sin\sigma_c$, where σ_c is the weak phase of the color dipole coupling. However, if the new color dipole interaction has the same $\overline{s}\sigma_{\mu\nu}(1+\gamma_5)b$ chiral structure as in SM, the phases are approximately equal and the values for a_i would be very small. For a color dipole of 10 times the SM strength but with $\overline{s}\sigma_{\mu\nu}(1-\gamma_5)b$ chiral structure, one obtains $\sigma_T\approx-\sigma_{||,0}$ leading to an upper bound of $0.1\sin\sigma_c$. This would generate a_1 and a_3 as large as $0.1\sin\sigma_c$ and $-0.12\sin\sigma_c$ respectively, quite similar to the R-parity violating case.

In all cases discussed above the weak phases for $\sigma_{||}$ and σ_0 are equal (or approximately equal). The asymmetry a_2 is therefore approximately zero in all cases we have considered, and does not seem to be a good quantity to study for CP violation using this method.

The sensitivety for $a_{1,3}$ is similar to the sensitivity to the phase angles of the amplitudes. It is interesting to note that the systematic error in CLEO analysis is already as low as 0.03 [1]. With increased statistics, $a_{1,3}$ as large as 0.10 should be accessible at CLEO, at CDF, and at future B factories. Since the errors are determined through a fit, it is not clear how the statistical error scales with actual number of events. The question can only be answered by actual studies, but naive scaling implies that one would need 10^8 events to be able to distinguish the deviations that we gave as illustration. Nevertheless, the needed number of events may be less, and measurement of the observables a_i will provide us with useful information about CP violation. We remark again that similar CP violating observables can be constructed for any $B \to VV$ decays, such as $B \to D^* \rho$, where preliminary evidence for FSI phases has recently been reported by CLEO [9].

In conclusion, we have shown that the study of the observables a_i in the angular distributions of $B \to J/\psi K^*$ and $\overline{B} \to J/\psi \overline{K}^*$ decays can provide good tests for CP violation beyond the standard model, since they are zero in SM. We have illustrated with supersymmetric models with R-parity violation, and models with large color dipole interactions, where these observables can be large enough to be measurable.

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