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Additional B_d Decays with Large CP Violation and No Final State Phase Ambiguities*

Isard Dunietz

Stanford Linear Accelerator Center

Stanford University, Stanford, California, 94309, USA

and Art Snyder

Indiana University

Bloomington, Indiana 47401, USA

ABSTRACT

The B_d modes, $\bar{D}^oX^o$, generated by the quark process, $\bar{b}\to \bar{c}+u\ \bar{d}$, have a large CP asymmetry within the Cabibbo-Kobayashi-Maskawa (CKM) model. This asymmetry depends only on a ratio of CKM elements and not on final state phases. The CKM model predicts the same asymmetries for the $\bar{D}^oX^o$, ΨK_S and D^+D^- modes. We therefore advocate measuring the asymmetries of the modes $\bar{D}^oX^o$ and ΨK_S, D^+D^- separately, because a difference in them presents a violation of the CKM model. Since this note sums over many states and since opposite CP parities flip the sign of the asymmetry, a general prescription for deriving CP parities of two body modes is presented utilizing the helicity formalism.

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1. Introduction

Recently there has been interest in searching for CP violation with neutral B meson decays. The classic decay mode is $B_d \to \Psi K_S$.[1,2] The decay mode $B_d \to \pi^+\pi^-$ has also been studied in some detail.[2]

Here we suggest that decay modes, discussed earlier in the literature,[3,1,4,5] of the type $B_d \to \bar{D}^o X^o$ or $B_d \to \bar{D}^{*o} X^o$--generated by the quark process $\bar{b} \to \bar{c} + u\ \bar{d}$--may offer experimental sensitivity comparable to ΨK_S when the $\bar{D}^o$ or $\bar{D}^{*o}$ particle decays into a CP eigenstate, $(f)_{\mathcal{D}}$.[6] As in the ΨK_S case, the large amplitude due to the direct decay ($B_d \to \bar{D}^{(*)o} X^o \to (f)_{\mathcal{D}} X^o$) interferes with the large amplitude due to B_d - $\bar{B}_d$ mixing ($B_{d,phys} \to \bar{B}_d \to D^{(*)o} X^o \to (f)_{\mathcal{D}} X^o$) to yield a sizeable asymmetry.[7]

Furthermore, the prediction for this asymmetry is theoretically clean. Akin to the $B_d \to \Psi K_S$ mode, Section 2 shows that uncertainties in hadronic matrix elements and final state phases do not enter. Within the standard model of the electroweak interactions, in which CP violation arises from the complex Cabibbo-Kobayashi-Maskawa (CKM) matrix,[8] the interference term for $B_d \to (f)_{\mathcal{D}} X^o$ is the same as for $B_d \to \Psi K_S$, namely $|\mathrm{Im}\ \lambda| = \sin(2\beta)$, and satisfies[9]

$$0.08 \lesssim \sin(2\beta) \leq 1. \qquad (1.1)$$

The angle β is the angle between $V_{tb}^* V_{td}$ and $V_{cb}^* V_{cd}$,

$$\beta = -\arg\left(-\frac{V_{tb}^* V_{td}}{V_{cb}^* V_{cd}}\right).$$

To increase the data sample many different modes of the type $(f)_{\mathcal{D}} X^o$ can be summed over.[5] Since the asymmetries of final states with opposite CP parities differ by a minus sign, it will be crucial to distinguish between final states with different CP parities, so as not to dilute the signal.[10] Section 3 discusses how to extract CP parities of two body final states within the helicity formalism. Equipped with this knowledge, Section 4 lists the relevant decay modes of the form $(f)_{\mathcal{D}}X^o$.

Whether the decays $\overline{B}_d \to D^{(*)o}X^o \to (f)_{\mathcal{D}}X^o$ are a realistic complement to the ΨK_S mode depends on their branching ratios. Section 5 estimates their branching ratios within the framework of the BSW model,[11] but cautions the reader that final state interactions and other uncalculable effects render such estimates unreliable. Ultimately, measurements of the final states will determine whether those decays can substantially complement the ΨK_S mode.

Even if the $(f)_{\mathcal{D}}X^o$ modes are not competitive with the ΨK_S one, important information will be obtained by pursuing them. The standard model predicts the same CP violating interference term Im λ, for the $(f)_{\mathcal{D}}X^o$, ΨK_S and D^+D^- modes. If new physics were to occur within the D^o - $\overline{D}^o$ complex, the interference term of the $(f)_{\mathcal{D}}X^o$ modes could differ from the ΨK_S and D^+D^- ones,[12] and would present a violation of the standard model. Section 6 concludes.

2. Discussion

A detailed discussion of the decay $B_d \to \overline{D}^o\pi^o \to (\pi^+\pi^-)_D\,\pi^o$ clarifies our idea. Unless otherwise indicated, the discussion will hold true for other decay modes, listed in Section 4. Consider the process, $B_d \to \overline{D}^o\pi^o \to (\pi^+\pi^-)_D\,\pi^o$. Here the CP asymmetry to measure is

$$\mathrm{Asym} \equiv \frac{\Gamma(B_{d,phys} \to (\pi^+\pi^-)_D\,\pi^o) - \Gamma(\overline{B}_{d,phys} \to (\pi^+\pi^-)_D\,\pi^o)}{\Gamma(B_{d,phys} \to (\pi^+\pi^-)_D\,\pi^o) + \Gamma(\overline{B}_{d,phys} \to (\pi^+\pi^-)_D\,\pi^o)}. \quad (2.1)$$

Four amplitudes give rise to the decay $B_{d,phys} \to (\pi^+\pi^-)_D\,\pi^o$, when D^o - $\overline{D}^o$ mixing is neglected. Those amplitudes are:

1) $B_d \to \overline{D}^o\pi^o \to (\pi^+\pi^-)_D\,\pi^o$, (2.2)

2) $B_d \to D^o\pi^o \to (\pi^+\pi^-)_D\,\pi^o$, (2.3)

3) $B_{d,phys} \to \overline{B}_d \to D^o\pi^o \to (\pi^+\pi^-)_D\,\pi^o$, (2.4)

4) $B_{d,phys} \to \bar{B}_d \to \bar{D}^o\pi^o \to (\pi^+\pi^-)_D\,\pi^o.$ (2.5)

The amplitudes 2) and 4) are doubly Cabibbo-Kobayashi-Maskawa (CKM) suppressed in relation to 1) and 3), respectively.

A large interference between the main amplitudes 1) and 3) occurs, and the CP violating interference term is given by:

$$\mathrm{Im}\,\lambda = \mp \sin(2\beta). \tag{2.6}$$

The sign of Im λ depends on whether the final state, $(f)_{\mathcal{D}}X^o$, is CP even or odd. For CP even (odd) states, $\mathrm{Im}\,\lambda = -\sin(2\beta)$ $(\mathrm{Im}\,\lambda = +\sin(2\beta))$.[10] The final state of our example $(\pi^+\pi^-)_D\,\pi^o$ is CP odd.

Eq. (2.6) is derived as follows: The pure B_d decay, $B_d \to \bar{D}^o\pi^o$, can be parametrized as

$$A(B_d \to \bar{D}^o\pi^o) = V_{cb}^* V_{ud}\,|a|\,e^{i\delta}. \tag{2.7}$$

Because only one CKM combination, $V_{cb}^* V_{ud}$, contributes to this decay, the hadronic matrix elements and final state interaction phases can be represented as a complex number, $|a|\,e^{i\delta}$. Notice that this complex number includes final state interaction effects, such as the rescattering, $B_d \to D^-\pi^+ \to \bar{D}^o\pi^o$. The CP-conjugated mode leaves the final state phases unchanged and complex conjugates the CKM elements,

$$A(\bar{B}_d \to D^o\pi^o) = V_{cb} V_{ud}^*\,|a|\,e^{i\delta}. \tag{2.8}$$

The doubly CKM suppressed amplitudes will in general have different final state phases, but are negligible.[13] **The uncertainty due to final state phases is removed, because those amplitudes, where different final state phases could occur, have tiny CKM elements and are negligible.**

The amplitudes for the subsequent neutral D decays are given by

$$A(D^o \to \pi^+\pi^-) \sim V_{cd}^* V_{ud}\,, \tag{2.9a}$$

$$A(\bar{D}^o \to \pi^+\pi^-) \sim V_{cd} V_{ud}^*\,, \tag{2.9b}$$

where a common factor is suppressed (see Appendix A). Thus, the amplitudes for the decay chains are

$$A(B_d \to (\pi^+\pi^-)_D \pi^o) \sim V_{cb}^* V_{ud} V_{cd} V_{ud}^* . \qquad (2.10a)$$

$$A(\overline{B}_d \to (\pi^+\pi^-)_D \pi^o) \sim - V_{cb} V_{ud}^* V_{cd}^* V_{ud} . \qquad (2.10b)$$

The minus sign in Eq. (2.10b) arises because the final state is CP odd.[10] The interference term Im λ is[1–5]

$$\mathrm{Im}\,\lambda \equiv \mathrm{Im}\, \frac{V_{tb}^* V_{td} A(\overline{B}_d \to (\pi^+\pi^-)_D \pi^o)}{V_{tb} V_{td}^* A(B_d \to (\pi^+\pi^-)_D \pi^o)} . \qquad (2.11)$$

Henceforth we choose to work with the Wolfenstein parametrization,[14] where

$$\mathrm{Im}\,\lambda = - \mathrm{Im}\, \frac{V_{td}}{V_{td}^*} . \qquad (2.12)$$

Since in the Wolfenstein parametrization the four CKM elements,

$$V_{ud}, V_{us}, V_{cd}, V_{cs}, \qquad (2.13)$$

are real to excellent approximation, any $D^o \to (f)_D$ decay satisfies[15]

$$\frac{A(D^o \to (f)_D)}{A(\overline{D}^o \to (f)_D)} \approx \pm 1. \qquad (2.14)$$

The sign is plus (minus) for a CP even (odd) final state $(f)_D$.[10] For any hadronic CP eigenstate $(f)_D$, the interference term is

$$\mathrm{Im}\,\lambda = \pm \mathrm{Im}\, \frac{V_{td}}{V_{td}^*} . \qquad (2.15)$$

The sign is determined as discussed in the paragraph following Eq. (2.6). Similar arguments hold for $D^o(\text{excited}) \to (f)_{\mathcal{D}}$.

A note about the neglect of D^o - $\overline{D}^o$ mixing is in order. If D^o - $\overline{D}^o$ were present, then for each of the decay chains (2.2)-(2.5) there exists another one, where the time evolved $\overline{D}^o$ or D^o mixes into its antiparticle. For instance, in addition to

$$B_d \to \overline{D}^o \pi^o \to (\pi^+\pi^-)_D \pi^o, \qquad (2.2)$$

D^o - $\overline{D}^o$ mixing yields

$$B_d \rightarrow \bar{D}^o \pi^o \rightarrow D^o \pi^o \rightarrow (\pi^+\pi^-)_D\, \pi^o. \qquad (2.16)$$

Present limits on the square of the D^o - $\bar{D}^o$ mixing amplitude are $r_D < 0.37\%$ (90% CL),[16] and for our purposes can be neglected.[17]

To conclude the section, we recapitulate on the sign of Im λ. Final states $(f)_{\mathcal{D}} X^o$ which are CP even (odd) eigenstates have an interference term Im λ = – sin2β (+ sin2β).

3. CP Parities

The asymmetries of final states with opposite CP parities differ by a minus sign. It is crucial to distinguish between final states with different CP parities, so as not to dilute the signal. Then one can attempt to sum over many final states, bearing in mind their respective CP parities.[5]

We discuss generalities first and draw upon the helicity formalism.[18] Denote X_1, X_2 as arbitrary particles with spins s_1, s_2, helicities λ_1, λ_2, and intrinsic parities π_1, π_2, respectively. Consider the process

$$A \rightarrow X_1\, X_2, \qquad (3.1)$$

where A has spin j and spin projection m along an arbitrarily defined z-axis. Within the CM frame the state vector of the final state $X_1\, X_2$ is $|\, j, m; \lambda_1, \lambda_2>$. Parity upon this final state gives

$$P\, |\, j, m; \lambda_1, \lambda_2> = \pi_1\, \pi_2\, (-1)^{j-s_1-s_2}\, |\, j, m; -\lambda_1, -\lambda_2> . \qquad (3.2)$$

Denote the following linear superpositions of helicity eigenstates[18] as

$$|\, j, m; L, S> = \sum_{\lambda_1 \lambda_2} |\, j, m; \lambda_1, \lambda_2> \quad < j, m; \lambda_1, \lambda_2 |\, j, m; L, S>, \qquad (3.3)$$

where

$$< j, m; \lambda_1, \lambda_2 |\, j, m; L, S> = \left(\frac{2L + 1}{2j + 1} \right)^{1/2} C(LSj; 0, \lambda, \lambda)\, C(s_1 s_2 S; \lambda_1, -\lambda_2, \lambda), \qquad (3.4)$$

and

$$\lambda = \lambda_1 - \lambda_2. \qquad (3.5)$$

Here C denotes the Clebsch-Gordan coefficients.

The state $|\, j, m; L, S>$ describes a state with orbital angular momentum L and spin S. This was shown in the non-relativistic limit by Jacob and Wick and generalized to the relativistic case by McKerrell.[19] We do not dwell on the meaning of relativistic spin S in this report. All we need to appreciate is that the special linear superpositions of the helicity states, as given in Eq. (3.3), make sense relativistically. The states $|\, j, m; L, S>$ possess the following property:

$$P\,|\, j, m; L, S> = \pi_1\, \pi_2\, (-1)^L\, |\, j, m; L, S> . \qquad (3.6)$$

We now turn to discuss CP parities. For that, we concentrate on two cases for the decay modes X_1X_2 of a neutral parent particle A:

(1) The particles X_1 and X_2 are either CP eigenstates (such as, ρ^o, π^o, Ψ . . .) or themselves are not CP eigenstates but are observed in their decay into CP eigenstates (such as, $D^o \to \pi^+\pi^-$, $D^o \to (f)_D$, $K^{*o} \to \pi^o K_S \to \pi^o (\pi^+\pi^-)_K$, $K^o \to \pi^+\pi^-$, . . .). Their observed CP parities are denoted by $\eta\{X_1\}$, $\eta\{X_2\}$, respectively. So, if the particle X (X_1 and/or X_2) does not have an intrinsic CP parity, such as K^{*o} or D^o, then $\eta\{X\}$ denotes the CP parity of the final state, such as $\pi^o K_S$ or $(f)_D$. Sometimes we will be more explicit and denote, for instance, the CP parity of a $D^o \to (f)_D$ as $\eta\{(f)_D\}$.

(2) X_2 is the antiparticle of X_1, which can be charged or neutral.

Whereas the helicity eigenstates, $|\, j, m; \lambda_1, \lambda_2>$, are in general not CP eigenstates, the LS-eigenstates, $|\, j, m; L, S>$, are. Before showing this, we note that for the final state X_1X_2 to be a CP eigenstate, case (2) does not demand X_1 or X_2 to decay into a CP eigenstate when they are neutral (such as D^o), in contrast to case (1). Now we are ready to discuss CP parities.

Case (1):

The helicity eigenstates do not have, in general, a definite CP parity, since

$$CP \mid j, m; \lambda_1, \lambda_2> = \eta\{X_1\}\, \eta\{X_2\}\, (-1)^{j-s_1-s_2} \mid j, m; -\lambda_1, -\lambda_2> . \quad (3.7)$$

On the other hand, the LS-eigenstates do have a definite CP parity, because

$$CP \mid j, m; L, S> = \eta\{X_1\}\, \eta\{X_2\}\, (-1)^L \mid j, m; L, S> . \quad (3.8)$$

Case (2):

The state X_1X_2 is a particle-antiparticle system. The intrinsic (reflection) parity of the system π is -1 $(+1)$ for fermions (bosons). Again, CP transforms the helicity eigenstates according to

$$CP \mid j, m; \lambda_1, \lambda_2> = \pi\, (-1)^{2s_1} \mid j, m; -\lambda_2, -\lambda_1> . \quad (3.9)$$

In contrast the LS-eigenstates have a CP parity:

$$CP \mid j, m; L, S> = \pi\, (-1)^S \mid j, m; L, S> . \quad (3.10)$$

This concludes the general discussion.

To highlight several consequences, some less known than others, the remainder of this section focuses on a parent particle A that is spinless (such as B_d, B_s, D^o, . . .). Since the LS-eigenstates have definite CP parity, we choose them as basis states. Because the parent particle is spinless A ($j = m = 0$), $L = S$. Thus the CP parity for case (1) is $\eta\{X_1\}\, \eta\{X_2\}\, (-1)^L$, and that for case (2) is $\pi\, (-1)^L$. If the parent particle A predominantly decays into states that differ by <u>even</u> units of L, then the final state X_1X_2 has a dominant CP parity. Consequences:

(i) If the decay $A \to V_1V_2$, where the two final particles are vectors, is dominated by the $L = 0$ and 2 states versus the $L = 1$ state (or vice versa), then it will have a dominant CP parity. Denote the helicities of V_1 (V_2) as λ_1 (λ_2). Ref. 20 points out that the mode into the helicity component (λ_1, λ_2) = (0, 0) is a CP eigenstate, and can be isolated by measuring the Θ^* dependence. Here we stress that more can be learnt. For instance, if the helicity component (0, 0) were negligible, the state V_1V_2 might still be a prevalent CP eigenstate, because the S and D waves might dominate over the P one (or vice versa). Furthermore, even in the most general case, when no CP dominates, a detailed study of all the angular correlations, including the angle of the two decay planes, makes those V_1V_2 decay modes competitive with definite CP eigenstate ones.[21]

One example, which we are currently investigating, is the decays $B_d \rightarrow D^{*+}D^{*-}$, $D^{*o}\ \bar{D}^{*o}$, $D^{*o}\rho^o$, $D^{*o}\omega$, ΨK^{*o}.[21] Another example is the decays $D^o \rightarrow V_1V_2$, which occur close to threshold. One might argue that P- and D-waves are suppressed close to threshold. Then the V_1V_2 modes have a dominant CP parity. However, recent data suggests not only a large S-wave component, but also a large D-wave one in $D^o \rightarrow \bar{K}^{*o}\rho^o$ decay.[22] Still the P-wave has been found to be much smaller than the S- and D- waves and, therefore, the final state has a dominant CP parity when $\bar{K}^{*o}$ is observed in its CP eigenmode $K_S\pi^o$.

Ref. 22 teaches us an important lesson. Suppose we want to study CP violation in the mode $B_d \rightarrow \Psi K^{*o}$. This requires the K^{*o} to decay into its $\pi^o K_S$ mode, as the $K^+\pi^-$ mode is not accessible via the mixing-amplitude,

$$B_{d,phys} \rightarrow \bar{B}_d \rightarrow \Psi\ \bar{K}^{*o} \not\rightarrow \Psi\ (K^+\pi^-)_{K^*}\ .$$

In addition, we must also know the $B_d \rightarrow \Psi K^{*o}$ amplitudes into the various LS-states. Fortunately, the LS-amplitudes can be analyzed using a much larger data sample, namely all the available decay modes of the two vectors, including the $K^{*o} \rightarrow K^+\pi^-$ one. Actually, simplifications arise when the $K^{*o} \rightarrow K^+\pi^-$ mode is used to extract the various LS-amplitudes, as the amplitude that involves B_d - $\overline{B}_d$ mixing does not occur.

Similar arguments can be made for the decays $\overline{B}_d \rightarrow D^{*o}X^o$. Angular correlation studies to determine the LS-amplitudes can be performed on the much larger data sample, where the D^{*o} is allowed to decay into non-CP eigenstates.[23] Here B_d - $\overline{B}_d$ mixing would not interfere.

(ii) Consider case (1). If one of the particles is spinless (say $s_1 = 0$), then $L = S = s_2$. The final state has a definite CP parity of $\eta\{X_1\}\ \eta\{X_2\}\ (-1)^{s_2}$. An example is

$$\overline{B}_d \rightarrow D^oX^o \rightarrow (f)_D X^o. \tag{3.11}$$

The CP parity of this final state is $\eta\{(f)_D\}\ \eta\{X^o\}\ (-1)^{s_X}$. Here and henceforth, X^o denotes a particle with spin s_X that is either a CP eigenstate or decays into a CP eigenstate, with CP parity $\eta\{X^o\}$.

(iii) A nontrivial consequence are the two decay chains, where X^o is spinless:

(a) $$\overline{B}_d \rightarrow D^{*o}\,X^o \rightarrow [\gamma\, D^o]_{D^*}\,X^o \rightarrow [\gamma\,(f)_D]_{D^*}\,X^o \tag{3.12}$$

(b) $$\overline{B}_d \rightarrow D^{*o}\,X^o \rightarrow [\pi^o\, D^o]_{D^*}\,X^o \rightarrow [\pi^o\,(f)_D]_{D^*}\,X^o \tag{3.13}$$

Appendix B shows that both final states have definite CP parities, and that the CP parity of the final state in decay chain (a) is opposite to the one in decay chain (b),

(a) $$CP\,|\,[\gamma\,(f)_D]_{D^*}\,X^o\rangle = +\,\eta\{X^o\}\,\eta\{(f)_D\}\ |\,[\gamma\,(f)_D]_{D^*}\,X^o\rangle, \tag{3.14}$$

(b) $$CP\,|\,[\pi^o\,(f)_D]_{D^*}\,X^o\rangle = -\,\eta\{X^o\}\,\eta\{(f)_D\}\ |\,[\pi^o\,(f)_D]_{D^*}\,X^o\rangle. \tag{3.15}$$

Thus it is crucial to distinguish the mode $D^{*o} \rightarrow \pi^o\,D^o$ from $D^{*o} \rightarrow \gamma\,D^o$. This is possible if the detector has good calorimetry, such as the CsI detector recently installed by CLEO.[24]

(iv) Consider case (2) where both final state particles are spinless. The CP parity of the final state X_1X_2 (such as, D^+D^-, $\overline{D}^oD^o$, $\pi^+\pi^-$, $K^o\ \overline{K}^o$, K^+K^-,..) is even.[25]

4. Relevant Decay Modes

We first discuss the decays $B_d \to (f)_{\mathcal{D}}X^o$, when the final state is a CP eigenstate. We concentrate on two possibilities:

(1) The B_d decays into the lowest lying meson with $\bar{c}u$ quantum numbers, the $\bar{D}^o$, via $B_d \to \bar{D}^o X^o \to (f)_D X^o$. The meson X^o can be one of the following:

(a) pseudoscalars ($J^{PC} = 0^{-+}$) π^o, η, η',

(b) vectors ($J^{PC} = 1^{--}$) ρ, ω, ϕ,

(c) the $J^{PC} = 1^{++}$ resonances $a_1(1260)$, $f_1(1285)$, $f_1(1420)$,

(d) the $J^{PC} = 0^{++}$ resonances $a_0(980)$, $f_0(975)$, $f_0(1400)$,

(e) the $J^{PC} = 1^{+-}$ resonances $b_1(1235)$, $h_1(1170)$,

(f) the $J^{PC} = 2^{++}$ resonances $a_2(1320)$, $f_2'(1525)$, $f_2(1270)$.

The above-mentioned $\bar{D}^o$ decays into a CP eigenstate, $\bar{D}^o \to (f)_D$. The CP parity of the final state in the process

$$B_d \to \bar{D}^o X^o \to (f)_D X^o, \tag{4.1}$$

is

$$\begin{aligned} CP[(f)_D X^o] &= -CP[(f)_D] \qquad \text{if } X^o \text{ belongs to set (a)-(c),} \\ &= +CP[(f)_D] \qquad \text{if } X^o \text{ belongs to set (d)-(f).} \end{aligned}$$

Whereas X^o from set (a)-(c) contributes with the same sign to the CP asymmetry, the X^o from set (d)-(f) contributes with the opposite sign, for a given $(f)_D$. Note that all the particles and resonances X^o below ~900 MeV enter with the same sign to the CP asymmetry.

(2) The B_d decays into $\bar{D}^{*o}$, or higher resonances with $\bar{c}u$ quantum numbers. Consider, thus, $B_d \to \bar{D}^o(\text{excited})\, X^o \to (f)_{\mathcal{D}}X^o$. For a spinless,

excited $\bar{D}^o$, we allow the meson X^o to be anything listed in (a)-(f). For excited $\bar{D}^o$ with higher spin, such as $\bar{D}^{*o}$, the meson X^o must be spinless, to allow a definite CP parity for the final state. Then the meson X^o must be from (a) or (d) with J = 0.

Since a definite CP parity is required for the final state of a B_d meson, by necessity the $(f)_{\mathcal{D}}$ mode --arising from $\bar{D}^o$(excited) $\rightarrow (f)_{\mathcal{D}}$-- must have a definite CP parity too. This report focuses on the $\bar{D}^{*o}$,[26] which has two main decay modes,[27]

$$BR(\bar{D}^{*o} \rightarrow \bar{D}^o\pi^o) \approx BR(\bar{D}^{*o} \rightarrow \bar{D}^o\gamma) \approx 50\% . \qquad (4.2)$$

Here both the $\bar{D}^o\pi^o$ and the $\bar{D}^o\gamma$ are in a P-wave (see Appendix B). Thus if the subsequent $\bar{D}^o$ decays into a CP eigenstate, the final state of $\bar{D}^{*o} \rightarrow (f)_{D^*}$ is a CP eigenstate.

To summarize, two possibilities (1) and (2) for large clean CP violation were discussed. The remainder of this section lists the D^o modes $(f)_D$ into CP eigenstates:

(D1) Final states which include one neutral kaon, such as, $\bar{K}^o\pi^o$, $\bar{K}^o\eta$, $\bar{K}^o\eta'$, $\bar{K}^o\rho$, $\bar{K}^o\omega$, $\bar{K}^o\phi$, $\bar{K}^o$(c)-(f),[28] $\bar{K}^{*o}\pi^o$, $\bar{K}^{*o}\eta$, $\bar{K}^{*o}\eta'$, $\bar{K}^{*o}$ (d).[28]

(D2) Final states which include an $s\bar{s}$ quark pair, such as, $\phi\pi^o$, $\phi\eta$, K^+K^-, $\bar{K}^oK^o$, $\bar{K}^{*o}K^o$, $\bar{K}^oK^{*o}$.

(D3) Final states which include flavor neutral decays, such as, $\pi^+\pi^-$, $\{\pi^o, \eta, \eta', a_o, f_o\}$ $\{\pi^o, \eta, \eta', \rho, \omega$, (c)-(f)$\}$.[29, 28]

The two vector modes of a D^o might have a dominant CP parity as discussed in consequence (i) of Section 3. If the modes in (D4) and (D5) below are experimentally found to be predominant CP eigenstates, then they could also be used for $(f)_D$:

(D4) Final states, such as, $\rho^o\phi$, $\omega\,\phi$, $\omega\,\bar{K}^{*o}$, $\rho\,\bar{K}^{*o}$.

(D5) Final states which are a particle-antiparticle system, such as, $\overline{K}^{*o}K^{*o}$, $K^{*-}K^{*+}$, $\rho^+\rho^-$, $\rho^o\rho^o$, $\omega\omega$ . . .

For cases (D1)-(D4) the neutral kaon K^o is seen in its $\pi^+\pi^-$ decay, and the K^{*o} in its $K^o\pi^o$ mode. In contrast, case (D5) allows K^{*o} to be seen in its $K^o\pi^o$ and $K^+\pi^-$ modes, and K^{*+} in its $K^o\pi^+$ and $K^+\pi^o$ modes, because the final state $(f)_D$ is a particle-antiparticle system. In the next section, we estimate the combined B_d branching ratio to final states of the form (1) or (2).

5. Rate Estimates

We now wish to compare the statistical power of the $B_d \rightarrow (f)_{\mathcal{D}}X^o$ modes to that of the classic $B_d \rightarrow \Psi K_S$ one. This requires estimates of branching ratios and efficiencies. For purposes of the paper efficiency refers to the branching fraction to visible modes. We do not discuss the ability to vertex those modes, which is an important requirement for an asymmetric $\Upsilon(4S)$ machine but not for a symmetric $\Upsilon(4S)^+$ or polarized Z^o one. Specifically the efficiencies in Table 1 are obtained as follows. The neutral kaon is K_S half of the time, and K_S decays to $\pi^+\pi^-$ 2/3 of the time. The neutral K^{*o} decays to $K^o\pi^o$ 1/3 of the time. We assume the ρ^o is seen in its $\pi^+\pi^-$ decay, the η in its 2γ and $\pi^+\pi^-\pi^o$ decays, the ω in its $\pi^+\pi^-\pi^o$ decay, the η' in its $\rho^o\gamma$ decay, and the ϕ in its K^+K^- mode. The D^{*o} is seen in its $D^o\pi^o$ and $D^o\gamma$ decays, and the D^o in all its possible CP eigenstate modes.

We attempt to estimate the efficiency of D^o, ε_D. The measured rates for the definite CP eigenstates,

$$D^o \rightarrow \pi^+\pi^-, K^+K^-, \overline{K}^o\pi^o, \overline{K}^o\rho^o, \overline{K}^o\phi, \rho^o \overline{K}^{*o}, \qquad (5.1)$$

yield a total branching rate of 5%.[27,22] However, when each of the decay modes is weighed by its efficiency (as given in Table 1), the visible rate is lowered to $\varepsilon_D \approx 2\%$. We included the $\rho^o \overline{K}^{*o}$ mode, since it was shown to have a dominant CP parity (see consequence (i) of Section 3).

If experiment were to reveal that each of the V_1V_2 modes are dominated by a single CP parity, then we ought to include them in our analysis. As no experimental data is yet available, we use the BSW model--with $a_1 = 1.3$, $a_2 = -0.55$ and a D^o lifetime of $\tau_D = 0.42$ ps--for the following modes:

$$D^o \to \omega\,\phi,\ \omega\ \overline{K}^{*o},\ \rho^o\rho^o,\ K^{*-}K^{*+},\ \rho^+\rho^-,\ \omega\omega. \qquad (5.2)$$

We estimate a total branching rate of 5%, and a visible rate of $\varepsilon_D \approx 2\%$, for the V_1V_2 modes in Eq. (5.2). A note about efficiencies used in the calculation is in order. Whereas the efficiencies of the particles involved in modes from cases (D1)-(D4) are given in Table 1, the efficiencies for the ones from (D5) differ, as explained in the previous section. For (D5), the K^{*+} is seen in its $K^o\pi^+$ mode 2/3 of the time and in its $K^+\pi^o$ mode 1/3 of the time, $\varepsilon = 5/9$. The K^{*o} is seen in its $K^o\pi^o$ mode 1/3 of the time and in its $K^+\pi^-$ mode 2/3 of the time, $\varepsilon = 7/9$.

To summarize our findings about the D^o efficiencies. When definite CP eigenstates are used (Eq. (5.1)), $\varepsilon_D \approx 2\%$. When the V_1V_2 modes of Eq. (5.2) are proven to have dominant CP parities and are added, the efficiency of a D^o into CP eigenstates doubles to $\varepsilon_D \approx 4\%$, but is still 3% if vertexing of the D^o is required.

Bauer, Stech and Wirbel[11] obtained the rates of decays of B_d into the modes from sets (1) and (2) shown in Table 2. They calculated within the factorization approximation and obtained small branching ratios, neglecting annihilation diagrams and final state interactions. The modes in Table 2 have a combined "branching ratio X efficiency" of 3.1 X 10^{-4}. Folding in the efficiency of the D^{*o} and D^o of ~4%, a visible rate of 1.2 X 10^{-5} results for the decays of the form $B_d \to (f)_{\mathcal{D}}X^o$. Since the visible rate of 1.2 X 10^{-5} for the modes $(f)_{\mathcal{D}}X^o$ arises by the summation of many channels, a careful analysis is required to determine the CP parity and backgrounds of the individual final states $(f)_{\mathcal{D}}X^o$. In contrast, the ΨK_S is a single mode with definite CP parity, simple topology, minimal background and a large "branching ratio X efficiency" of $(3 \times 10^{-4}) \times 0.14 \times 2/3 = 2.8 \times 10^{-5}$. It appears that the ΨK_S mode is much favored over the $(f)_{\mathcal{D}}X^o$ ones.

Is the situation as hopeless for CP violation in the quark process $\bar{b} \rightarrow \bar{c} + u\ \bar{d}$? Not really, since the branching rates into modes of sets (1) and (2) could be enhanced over BSW estimates. Final state interactions can play a role in making the $\bar{D}^{(*)o}X^o$ modes. For instance, if at first mainly the $D^-\pi^+$ mode is made, final state interactions can still mix the $D^-\pi^+ \leftrightarrow \bar{D}^o\pi^o$. It is conceivable[30] that $BR(B_d \rightarrow \bar{D}^o\pi^o)$ is of the same order as the measured[31]

$$BR(B_d \rightarrow D^-\pi^+) \approx 0.25\%. \tag{5.3}$$

It is thus possible that one of the many modes from sets (1) or (2) could be enhanced. Ultimately, experiments will answer which modes are enhanced and which ones can be used for the asymmetry measurements.

A final comment. We are intrigued by the possibility that some of the $\bar{D}^{*o}X^o(J=1)$ modes, such as $\bar{D}^{*o}\rho^o$ or $\bar{D}^{*o}\omega$, could have large branching ratios. Those modes have no definite CP parity. However, the (0, 0) helicity component has a definite CP parity and can be extracted as advocated in Ref. 20. Even in the most general case, when no CP dominates, a detailed study of all the angular correlations, including the angle of the two decay planes, makes those decay modes competitive with definite CP eigenstate ones.[21]

6. Conclusion

Large CP violating effects are predicted with the decays $\overline{B}_d \rightarrow (f)_{\mathcal{D}} X^o$-- generated by the quark process $\overline{b} \rightarrow \overline{c} + u\ \overline{d}$. Similar to the ΨK_S mode, Section 2 showed that uncertainties in hadronic matrix elements and final state phases do not enter in calculating the CP violating interference term Im λ. To increase statistics one could sum over many modes $(f)_{\mathcal{D}} X^o$, listed in Section 4. Because the asymmetries flip sign for final states with different CP parities, we devoted Section 3 to discussions of CP parities of two body final states within the helicity formalism.

Section 5 compared the $(f)_{\mathcal{D}} X^o$ modes to the classic ΨK_S one. Whereas a visible rate within the BSW model of $\sim 10^{-5}$ for the $(f)_{\mathcal{D}} X^o$ modes arises by the summation of many channels, the ΨK_S mode--a single mode with definite CP parity and simple topology--has a visible rate of $\sim 3 \times 10^{-5}$. The BSW model predicts that the $(f)_{\mathcal{D}} X^o$ modes are not competitive with the ΨK_S one. Final state interactions may enhance some of the $D^{(*)o} X^o$ modes, and may make the $(f)_{\mathcal{D}}$ X^o modes more competitive. Only future experiments will tell. This note focused on final states $(f)_{\mathcal{D}} X^o$ that are CP eigenstates. We can increase statistics by including final states that do not have a definite CP parity, but are mixtures of CP even and odd eigenstates. This increment can be achieved by utilizing all the information one could gain from angular correlations.[20,21]

Even if the $(f)_{\mathcal{D}} X^o$ modes are not competitive with the ΨK_S one, important information will be obtained by pursuing them. The standard model predicts the same CP violating interference term Im λ, for the $(f)_{\mathcal{D}} X^o$, ΨK_S and $D^+ D^-$ modes. If new physics were to occur within the D^o - $\overline{D}^o$ complex, the interference term of the $(f)_{\mathcal{D}} X^o$ modes could differ from the ΨK_S and $D^+ D^-$ ones,[12] and would present a violation of the standard model. This idea will be pursued in the future.

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Appendix A

In principle, three weak phases $\xi_i = V_{ci}^* V_{ui}$ contribute to the $D^o \to \pi^+\pi^-$ decay. Unitarity of the 3 X 3 CKM matrix, however, reduces the number of independent weak phases to two,

$$A(\overline{D}^o \to \pi^+\pi^-) = \xi_d^* |a_d| e^{i\delta_d} + \xi_s^* |a_s| e^{i\delta_s}, \tag{A1}$$

$$A(D^o \to \pi^+\pi^-) = \xi_d |a_d| e^{i\delta_d} + \xi_s |a_s| e^{i\delta_s}, \tag{A2}$$

where $|a_i|$, δ_i (i = d, s) are the respective hadronic matrix elements and final state interaction phases. Experiment informs us that[14,27]

$$\xi_s / \xi_d = -1 + i\, O(\lambda_c^4), \qquad | \xi_s / \xi_d | \approx 1, \tag{A3}$$

where $\lambda_c = 0.22$ is the Cabibbo angle.

The s-term, $\xi_s |a_s| e^{i\delta_s}$, represents rescattering effects, such as $D^o \to K^+K^- \to \pi^+\pi^-$, and penguin diagrams, $c \to u\, g$. Clearly, the decay $D^o \to \pi^+\pi^-$, is dominated by the d-term, $\xi_d |a_d| e^{i\delta_d}$. Even without this physical insight, we show that[32]

$$\frac{A(\overline{D}^o \to \pi^+\pi^-)}{A(D^o \to \pi^+\pi^-)} \approx \frac{V_{cd} V_{ud}^*}{V_{cd}^* V_{ud}} \tag{A4}$$

holds--barring a fine tuning--because the weak phases of the d- and s-terms are almost the same. The amplitudes for the $\pi^+\pi^-$ mode of the $\overline{D}^o$ and D^o are

$$A(\,\overline{D}^o \to \pi^+\pi^-) = \xi_d^* \left(|a_d|\, e^{i\delta_d} + \left(\frac{\xi_s}{\xi_d}\right)^* |a_s|\, e^{i\delta_s} \right), \qquad \text{(A5)}$$

$$A(D^o \to \pi^+\pi^-) = \xi_d \left(|a_d|\, e^{i\delta_d} + \frac{\xi_s}{\xi_d} |a_s|\, e^{i\delta_s} \right). \qquad \text{(A6)}$$

Because of Eq. (A3), the large parentheses in Eqs. (A5)-(A6) cancel to excellent approximation when the ratio $A(\,\overline{D}^o \to \pi^+\pi^-\,)\,/\,A(\,D^o \to \pi^+\pi^-\,)$ is taken. Thus, Eq. (A4) holds.

Since the asymmetries that we expect for $B_d \to (f)_{\mathcal{D}} X^o$ are of the order of $\mathrm{Im}\,\lambda =$ 10%-100%, we neglect the small asymmetries in the D^o modes advocated by Golden and Grinstein,[33]

$$|\,A(\,\overline{D}^o \to \pi^+\pi^-\,)\,| \neq |\,A(\,D^o \to \pi^+\pi^-\,)\,|\,. \qquad \text{(A7)}$$

Those small D^o-asymmetries arise precisely because of the imaginary part of ξ_s / ξ_d.

Appendix B

Consider the decay chains

(a) $\overline{B}_d \to D^{*o} X^o \to [\gamma\, D^o]_{D^*} X^o \to [\gamma\, (f)_D]_{D^*} X^o$

(b) $\overline{B}_d \to D^{*o} X^o \to [\pi^o\, D^o]_{D^*} X^o \to [\pi^o\, (f)_D]_{D^*} X^o$.

X^o is a spinless particle that is either a CP eigenstate or decays into a CP eigenstate with CP parity $\eta\{X^o\}$. This appendix proves that the final states of the former decay chain have a CP parity of $+\eta\{X^o\}\,\eta\{(f)_D\}$, the latter have $-\eta\{X^o\}\,\eta\{(f)_D\}$. It will be necessary to determine whether the D^* mode was a $\pi^o D^o$ or a $\gamma\, D^o$, else the asymmetry will be washed out.

First, let us focus on the $D^{*o} \to \gamma\, D^o \to \gamma\, (f)_D$ decay chain. The mode $D^{*o} \to \gamma\, D^o$ occurs via the parity conserving electromagnetic interaction. Since the intrinsic parity of a D^{*o} is (-1), the state $\gamma\, D^o$ must be in the combination:

$$| \gamma D^o> = \frac{1}{\sqrt{2}} \{ | \gamma(-1)\ D^o> - P\ | \gamma(-1)\ D^o> \}. \qquad (B1)$$

Here the state vector $| \gamma(\lambda)\ D^o> = | j = 1, m; \lambda, \lambda_D = 0>$ is given within the helicity basis, where j = 1 is the spin of the vector D^{*o}, and $\lambda = \pm 1$ is the helicity of the photon. With the aid of Eq. (3.2), parity gives

$$P\ | \gamma(\lambda)\ D^o> = +\ | \gamma(-\lambda)\ D^o> . \qquad (B2)$$

The configuration in which the $\gamma\, D^o$ finds itself is given by

$$| \gamma D^o> = \frac{1}{\sqrt{2}} \{ | \gamma(-1)\ D^o> - | \gamma(+1)\ D^o> \}. \qquad (B3)$$

Even though the subsequent D^o modes into CP eigenstates $(f)_D$ occur through the parity non-conserving weak interactions, still the final state $\gamma\ (f)_D$ has the configuration

$$| \gamma (f)_D> = \frac{1}{\sqrt{2}} \{ | \gamma(-1)\ (f)_D> - | \gamma(+1)\ (f)_D> \}. \qquad (B4)$$

Eq. (3.7) shows that this configuration has definite CP parity

$$CP\ | \gamma\, (f)_D> = -\eta\{(f)_D\}\ | \gamma\, (f)_D>, \qquad (B5)$$

where the observed CP parities are $\eta\{\gamma\} = 1$ and $\eta\{(f)_D\}$. As a result, the final state in the decay chain (a) has the CP parity

$$CP\ | [\gamma\, (f)_D]_{D^*}\, X^o> = +\,\eta\{X^o\}\,\eta\{(f)_D\}\ | [\gamma\, (f)_D]_{D^*}\, X^o>. \qquad (B6)$$

Let us turn now to decay chain (b). In contrast to (a), the decay $D^{*o} \rightarrow \pi^o D^o \rightarrow \pi^o\ (f)_D$ yields the CP parity

$$CP\ | \pi^o\, (f)_D> = +\,\eta\{(f)_D\}\ | \pi^o\, (f)_D>. \qquad (B7)$$

Thus, the CP parity of the final state of decay chain (b) is

$$CP\ | [\pi^o\, (f)_D]_{D^*}\, X^o> = -\,\eta\{X^o\}\,\eta\{(f)_D\}\ | [\pi^o\, (f)_D]_{D^*}\, X^o>. \qquad (B8)$$

We see it differs by a minus sign from Eq. (B6), so one must be able to distinguish the modes $D^{*o} \rightarrow \pi^o\, D^o$ from $D^{*o} \rightarrow \gamma\, D^o$.

Another derivation of the CP parities of decay chains (a)-(b) utilizes the LS-formalism. The intermediate state $D^{*o}X^o$ of the decay chains (a)-(b) has spin S = 1. Since the total angular momentum is zero, L = S = 1. This state is represented within the LS-formalism as

$$| D^{*o}X^o> = | j_B = m_B = 0; L = S = 1>, \qquad (B9)$$

and has a CP parity of

$$CP\, | D^{*o}X^o> = \eta\{D^{*o}\}\, \eta\{X^o\}\, (-1)^L\, | D^{*o}X^o>. \qquad (B10)$$

Now $\eta\{D^{*o}\}$ depends on what mode D^{*o} decays into. Because the process $D^{*o} \rightarrow \gamma\, D^o$ is parity conserving, the state $\gamma\, D^o$ must be in a "P-wave",

$$| \gamma\, D^o> = | j = 1, m; L^* = 1, S^* = 1>. \qquad (B11)$$

Here, the superscript-stars distinguish the L and S values of the γD^o state from the $D^{*o}X^o$ one. (The transformation rules between helicity and LS-states show that the γD^o state in Eq. (B11) is identical to the one in Eq. (B3).) From Eq. (3.8), CP on γD^o yields

$$CP\, | \gamma\, D^o> = \eta\{\gamma\}\, \eta\{D^o\}\, (-1)^{L^*}\, | \gamma\, D^o> = -\, \eta\{D^o\}\, | \gamma\, D^o>, \qquad (B12)$$

where we used $\eta\{\gamma\} = +1$. Thus,

$$\eta\{D^{*o}\} = -\eta\{D^o\} = -\eta\{(f)_D\}\, . \qquad (B13)$$

When this result is applied to Eq. (B10), we again obtain Eq. (B6).

We turn our attention to the other decay mode of the D^{*o}. The state $\pi^o D^o$ of the process $D^{*o} \rightarrow \pi^o\, D^o$ is an LS-eigenstate,

$$| \pi^o\, D^o> = | j = 1, m; L^* = 1, S^* = 0>. \qquad (B14)$$

Apply CP on $\pi^o D^o$ to get $\eta\{D^{*o}\} = \eta\{D^o\} = +\, \eta\{(f)_D\}$ and we have proven Eq. (B8) again.

References

1 I. I. Bigi and A. I. Sanda, Nucl. Phys. **B193**, 85 (1981).

2 SLAC report, 1989, edited by D. Hitlin, SLAC-353.

3 A. B. Carter and A. I. Sanda, Phys. Rev. Lett. **45**, 952 (1980); Phys. Rev. **D23**, 1567 (1981).

4 L. Wolfenstein, Nucl. Phys. **B246**, 45 (1984)

5 I. I. Y. Bigi and A. I. Sanda, Nucl. Phys. **B281**, 41 (1987).

6 A remark on notation. The generic CP eigenstate, that a D^o or an excited D^o decays into, is denoted by $(f)_{\mathcal{D}}$. Here script $\mathcal{D}$ denotes the generic parent D^o or D^o(excited). On the other hand, the CP eigenstate $(f)_D$ denotes the final state of the D^o itself. At times we denote the CP eigenstate from a D^{*o} as $(f)_{D^*}$.

7 The convention is used that B^o has $\bar{b}$ content and that $B^o{}_{phys}$ refers to a time evolving B^o meson and not to a B^o mass eigenstate.

8 M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).

9 C.O. Dib, I. Dunietz, F.J. Gilman and Y. Nir, Phys. Rev. **D41**, 1522 (1990).

10 Bigi and Sanda, Refs. 1 and 5; Wolfenstein, Ref. 4; appendix of I. Dunietz and J. L. Rosner, Phys. Rev. **D34**, 1404 (1986).

11 M. Bauer, B. Stech and M. Wirbel, Z. Phys. **C34**, 103 (1987).

12 In analogy to Y. Nir and D. Silverman, SLAC report, 1990, SLAC-PUB-5209, we would get additional relations by using the quark subprocess, $\bar{b} \to \bar{c} + u\, \bar{d}$ with the B_d and B_s systems. The B_s modes governed by that quark subprocess, such as $B_s \to \bar{D}(^*)^o K_S \to (f)_{\mathcal{D}} K_S$ or $B_s \to \bar{D}^o\ \bar{K}^* \to (f)_D (\pi^o K_S)_{K^*}$, are predicted to have a tiny CP violating interference term Im λ within the standard model. Measuring a large Im λ with those modes would present a violation of the standard model.

13 Similarly if we parametrize the highly CKM suppressed mode as, $A(B_d \to D^o\pi^o) = V^*_{ub} V_{cd} |b| e^{i\tau}$, then its CP-conjugated mode is given by $A(\overline{B}_d \to \overline{D}^o\pi^o) = V_{ub} V^*_{cd} |b| e^{i\tau}$. Even though $\tau \neq \delta$ is likely, and thus τ represents different final state phases, those highly CKM suppressed amplitudes are negligible to the process at hand.

14 L. Wolfenstein, Phys Rev. Lett. **51**, 1945 (1983).

15 Barring, of course, the extreme fine tuning, as discussed for the $D^o \to \pi^+\pi^-$ example in Appendix A.

16 J. C. Anjos et al., Phys Rev. Lett. **60**, 1239 (1988).

17 If large CP violating effects were to occur within the D^o - $\overline{D}^o$ system, then we would not be allowed to neglect those effects and a careful analysis would be required. However, within the standard model such CP violating effects are not expected, because long distance contributions probably dominate over those short distance ones that have a different weak phase. When long distance effects are prevalent, the "real" CKM elements of Eq. (2.13) are involved. Thus, the dispersive M_{12} and absorptive Γ_{12} D^o-mass matrix have the same phase and negligible CP violation occurs in the D^o - $\overline{D}^o$ system.

18 M. Jacob and G. C. Wick, Ann. Phys. (N. Y.) **7**, 404 (1959); J. D. Richman, Caltech report, 1984, CALT-68-1148; A. D. Martin and T. D. Spearman, "Elementary Particle Physics" (North Holland, Amsterdam, 1970).

19 A. McKerrell, Nuovo Cimento **34**, 1289 (1964).

20 B. Kayser, M. Kuroda, R. D. Peccei, and A. I. Sanda, UCLA report, 1989, UCLA/89/TEP/60.

21 I. Dunietz, A. Snyder and W. Toki, SLAC report in preparation.

22 J. Adler et al., SLAC report, 1989, SLAC-PUB-5130.

23 More statistics to measure the different LS-amplitudes are available when modes related via isospin, such as $B_u \to \Psi K^{*+}$, are studied. A careful analysis is required to disentangle the various LS-amplitudes when using the $D^{*o}\rho^{o}$, $D^{*+}\rho^{-}$ and $D^{*o}\rho^{-}$ modes, because different isospin amplitudes are involved.

24 E. Blucher et al., IEEE Trans. Nucl. Sci. **32**, 716 (1985).

25 Consider a two body state made out of a neutral spinless particle and its antiparticle, $P^o \, \overline{P}^o$. Suppose the $P^o \, \overline{P}^o$ state has total angular momentum j = L. Assuming only CPT invariance, one can show that the $P^o \, \overline{P}^o$ state is CP even; see, for instance, M. Goldhaber and C. N. Yang, in "Evolution of Particle Physics," edited by M. Conversi (Academic Press, New York, 1970), pp. 171-175. Consider the mode $(f_1)_P \, (f_2)_P$ of the $P^o \, \overline{P}^o$ state, where both f_1 and f_2 are CP eigenstates. If the mode $(f_1)_P \, (f_2)_P$ is CP odd (in determining the CP parity do not forget the factor $(-1)^L$ coming from angular momentum), then we witness CP violation within the $P^o - \overline{P}^o$ complex (i.e. the mass eigenstates P_L, P_H are not CP eigenstates). To clarify the idea, consider the following academic examples:

Example (1). Suppose we study CP violation in $B_d \to (f)_D \, X^o$ and we observe the decay channel $\overline{B}_d \to D^o X^o \to (K^o \, \overline{K}^o)_D \, X^o \to ((2\pi)_K \, (3\pi^o)_K)_D \, X^o$. We ought to count this $K^o \, \overline{K}^o$ system as having even CP parity, even though the extremely rare "academic" mode, $((2\pi)_K \, (3\pi^o)_K)_D$, is CP odd. This odd mode could arise because of CP violation within the K_L.

Example (2). The mere observation of a $\bar{B}_d \to \bar{D}^o D^o \to (2\pi)_D\ (\pi^o K_S)_D$, where the K_S is seen in its 2π mode, would prove CP violation within the D^o - $\bar{D}^o$ complex.

Example (3). Suppose we could prepare a $\bar{B}^o B^o$ state with total angular momenta that differ by <u>even</u> units. If the final state of the decay $\bar{B}^o B^o \to (f_1)_B (f_2)_B$ is CP odd, then we witness CP violation in the B^o - $\bar{B}^o$ complex. Such is the case for the Υ(4S), as pointed out by Wolfenstein, Ref. 4. Another case would be $\Upsilon(4S)^+ \to \gamma^* \to \bar{B}^{o*} B^o \to \gamma\ \bar{B}^o B^o \to \gamma\ (f_1)_B (f_2)_B$. Since the $\bar{B}^o B^o$ state is here in an L = even configuration, an observation, where f_1 and f_2 have opposing CP parities, would prove CP violation within the B^o - $\bar{B}^o$ complex.

26 If other $\bar{D}^o$ resonances occur appreciably in B_d decays, one would want to investigate them also.

27 Particle Data Group, G. P. Yost et al., Phys. Lett. **204B**, 1 (1988).

28 Where kinematically allowed.

29 We mean any final state that is made from two particles--one being taken from the first bracket and one from the second.

30 We thank Helen Quinn for discussions.

31 D. L. Kreinick, in Proceedings of the 1989 International Symposium on Lepton and Photon Interactions at High Energies, Stanford University, August 1989, edited by M. Riordan, p. 129.

32 I.I. Bigi, in Proceedings of the Tau-Charm Factory Workshop, May 23-27, 1989, SLAC, edited by L. V. Beers, p. 169.

33 M. Golden and B. Grinstein, Phys. Lett. **222B**, 501 (1989).

TABLE 1

The efficiencies of various final state particles. Here ε_D is the D^o branching fraction into visible CP eigenstates (see text).

particle	ε, efficiency
π^o, $\pi^\pm$, $K^\pm$	100%
K^o	33%
K^{*o}	11%
ρ^o	100%
η	60%
ω	90%
η'	30%
ϕ	50%
D^o	ε_D
D^{*o}	100% X ε_D

TABLE 2

Branching rates for various CP eigenstate modes of a B_d. The theoretical decay widths (second column) are taken from BSW (Ref. 11). The theoretical branching rates (third column) use $a_2 = -0.24$ and a B_d lifetime of 1.2 ps. The visible branching rates into CP eigenstates, $B_d \to (f)_{\mathcal{D}} X^o$, (fourth column) is obtained by multiplying the theoretical branching rate (third column) with the efficiencies given in Table 1.

B_d decay	Width (BSW) 10^{10} sec^{-1}	BR (BSW)	BR visible $X \varepsilon_D$
$B_d \to \bar{D}^o \pi^o$	$0.11\ a_2^2$	7.6×10^{-5}	7.6×10^{-5}
$B_d \to \bar{D}^{*o} \pi^o$	$0.16\ a_2^2$	1.1×10^{-4}	1.1×10^{-4}
$B_d \to \bar{D}^o \rho^o$	$0.06\ a_2^2$	4.1×10^{-5}	4.1×10^{-5}
$B_d \to \bar{D}^{*o} \eta^o$	$0.07\ a_2^2$	4.8×10^{-5}	2.9×10^{-5}
$B_d \to \bar{D}^o \omega$	$0.06\ a_2^2$	4.1×10^{-5}	3.7×10^{-5}
$B_d \to \bar{D}^o \eta'$	$0.03\ a_2^2$	2.1×10^{-5}	6.2×10^{-6}
$B_d \to \bar{D}^{*o} \eta'$	$0.04\ a_2^2$	2.8×10^{-5}	8.3×10^{-6}