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SEARCH FOR CP VIOLATION IN B° [and D°] DECAYS II—A CLOSER LOOK*

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ABSTRACT

Recent findings from UA1 and ARGUS on $B^\circ - \bar{B}^\circ$ mixing brighten considerably the prospects of finding CP violation in B° decays. We sketch some semi-quantitative scenarios where we also address technical issues like the amount of time resolution that is necessary. We point out that searching for the reaction $\Upsilon(4s) \to B^\circ \bar{B}^\circ \to f_1, f_2$ where f_1, f_2 are CP eigenstates of the same CP parity has a good chance of revealing CP violation. The tight upper bound on $D^\circ - \bar{D}^\circ$ mixing, namely 0.5–1%, still allows for CP asymmetries of up to 5% in $\overset{(-)}{D^\circ} \to K^+K^-, K_s K^+ K^-$.

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I. Introduction

Searches for CP violation in B [and D] decays can be classified in the following way:

(A) The final state f is unambiguously due to either a B or a $\bar{B}$ decay. This is always true for final states in charged B decays; however, there are also interesting examples in B° decays: $B^\circ \to K^-\pi^+$ vs. $\bar{B}^\circ \to K^+\pi^-$, etc[1].

(B) The final state f is common to B° and $\bar{B}^\circ$ decays, like $\overset{(-)}{B^\circ} \to D^\mp\pi^\pm$; it can even be a CP eigenstate like $\overset{(-)}{B^\circ} \to \psi K_s, D^+D^-$.

This distinction is useful for understanding the physics involved as well as for technical reasons: in Case (A) the intervention of final state interactions is required to make CP violation observable. This could happen via "soft" hadronic interactions, resonances, etc., or via the presence of "Penguin" contributions; the decays $B \to K\pi, K\rho$ are expected to involve the latter scenario. By the same token, however, one realizes that predictions on branching ratios and even more on asymmetries are beset with considerable uncertainties. The advantages of this method lie in the very fact that these final states are flavour specific and therefore no additional flavour tagging is required.

In Case (B), on the other hand, it is the presence of mixing that makes CP violation observable. The recent findings of UA1 and ARGUS on like-sign di-leptons indicate a $B^\circ - \bar{B}^\circ$ mixing strength well suited for studies on CP asymmetries. The drawback of this case lies in its need for flavour-tagging.

In the following we will give a more detailed description of Method (B) after the more general introduction given by A. Sanda in the preceding article.[2]

II. Mixing and CP Violation in Nonleptonic B° Decays

If f denotes a decay mode common to B° and $\bar{B}^\circ$—a property then shared by its CP conjugate $\bar{f}$—one finds[3]

$$\Gamma\left(B^\circ \to f\right) \propto e^{-\Gamma t}\left\{(1+\cos\Delta m t) \mid \rho_f \mid^2 + \left(1-\cos\Delta m t\right) - 2\sin\Delta m t \,\mathrm{Im}\, \frac{p}{q}\rho_f\right\}$$

$$\Gamma\left(\bar{B}^\circ \to \bar{f}\right) \propto e^{-\Gamma t}\left\{(1+\cos\Delta m t) + \left(1-\cos\Delta m t\right) \mid \rho_f \mid^2 + 2\sin\Delta m t \,\mathrm{Im}\, \frac{p}{q}\rho_f\right\} \tag{1}$$

with $\rho_f = \frac{A(B^\circ \to f)}{A(\bar{B}^\circ \to f)}$, $\frac{p}{q} = \frac{1+\epsilon}{1-\epsilon}$; for simplicity we have set $\Delta\Gamma = 0, \mid p \mid^2 = \mid q \mid^2$ which should be excellent approximations.

Equation (1) shows that the CP asymmetries depend crucially on two quantities: Δm and $\mathrm{Im}\, \frac{p}{q}\rho_f$.

(a) Δm per se has no intrinsic connection to CP violation; it can be taken from data on like-sign di-leptons. From the ARGUS data one obtains for $B_d - \bar{B}_d$ mixing[4]

$$x_d = \frac{\Delta m}{\Gamma}(B_d) \simeq 0.78 \pm 0.16 \tag{2}$$

which is considerably larger than what was expected previously by most authors, namely $x_d \lesssim 0.2$. Thus, the requirement of mixing hardly suppresses the observable CP asymmetry if the preliminary ARGUS results hold up; even integrating over all decay times which introduces a factor $x/(1+x^2)$ produces a suppression by a factor of two only in that case.[3] $B_s - \bar{B}_s$ mixing is then expected to be near-maximal, *i.e.*,

$$r_s = \frac{\Gamma(B_s \to \ell^+ X)}{\Gamma(B_s \to \ell^- X)} \simeq \frac{x_s^2}{2 + x_s^2} \gtrsim 0.9 \tag{3}$$

or

$$x_s = \frac{\Delta m}{\Gamma}(B_s) \gtrsim 4 \tag{4}$$

$B_s - \bar{B}_s$ mixing would thus produce spectacular signatures *if the time resolution available is considerably better than* $\Gamma^{-1} \sim 10^{-12}$ *sec;* otherwise the integration over all decay times leads to a significant suppression $x_s/(1 + x_s^2) \lesssim 0.23$!

(b) The underlying CP violation enters via the factor Im $\frac{p}{q}\rho_f$. To estimate its size one has to rely on a theoretical model.

When f is a CP eigenstate—like $B_d \to \psi K_s, D\bar{D}K_s$ or $B_d \to D^\circ + \pi's \to (K_s + \pi's) + \pi's$—then $\frac{p}{q}\rho_f$ is, to an excellent approximation, a unit vector in the complex plane[3] and is given by a ratio of KM parameters alone; in other cases, this is not true any more but one can, with few exceptions, express reasonable order of magnitude estimates in this way. Thus, one finds for $(b\bar{d}) \to c\bar{c}s\bar{d}, c\bar{u}d\bar{d}$ transitions in the Wolfenstein representation of the KM matrix:

$$-\mathrm{Im}\ \frac{p}{q}\rho_f\bigg|_{B_d} \simeq \frac{2\eta(1-\rho)}{(1-\rho)^2 + \eta^2} \tag{5}$$

η, the CP violating phase, is inferred from ϵ_K; depending on the value of the top mass which has a very significant impact on η one finds

$$-\mathrm{Im}\ \frac{p}{q}\rho_f\bigg|_{B_d} \sim 0.2 - 0.6 \tag{6}$$

Therefore, quite generally one expects CP asymmetries of order 10 to 50% in nonleptonic B_d decays!

For nonleptonic B_s decays one finds instead for $(b\bar{s}) \rightarrow c\bar{c}s\bar{s}$ transitions like $B_s F^+ F^-, \psi\phi$

$$- \text{Im} \left. \frac{p}{q}\rho_f \right|_{B_s} \sim 0.1 \times \eta \sim \text{few percent} \tag{7}$$

unless there is a fourth family which can quite naturally bring CP asymmetries back up to the several ten percent level.

For KM suppressed transitions like $B_s \rightarrow D^\circ \phi$ the asymmetry can reach the 50% level even without a fourth family.[5]

To sum up this discussion: accepting the UA1 and ARGUS numbers at face value we conclude that the natural scale for CP asymmetries in nonleptonic B_d and B_s decays is given not by units of 10^{-3} or 1%, but by multiples of 10%. Furthermore, the intersting decay modes are not necessarily suppressed by small KM angles.

III. CP Violation in D° Decays

The Standard Model does not lead to CP asymmetries in D° decays that could realistically be observed; nevertheless it makes good sense to search for them anyway despite some tight bounds on $D^\circ - \bar{D}^\circ$ mixing. For the upper bound[6]

$$r_D = \frac{\Gamma(D^\circ \rightarrow \ell^- X)}{\Gamma(D^\circ \rightarrow \ell^+ X)} \lesssim 0.5\% \tag{8}$$

is translated into

$$x_D = \frac{\Delta m}{\Gamma}(D^\circ) \lesssim 0.1 \tag{9}$$

since $r = x^2/(2+x^2)$. For final states $f = K^+K^-, K_sK^+K^-$ which are CP eigenstates one obtains a simplification of Eq. (1):

$$\Gamma\left(\overset{(-)}{D^\circ}(t) \to K^+K^-, K_sK^+K^-\right) \propto e^{-\Gamma t}\left(1 \mp x_D \frac{t}{\tau_D}\mathrm{Im}\ \frac{p}{q}\rho_f\right) \tag{10}$$

It is possible to design models for New Physics, mainly those based on a non-minimal Higgs sector, where $x_D \sim 0.1$ and Im $\frac{p}{q}\rho_f \lesssim 0.5$. Thus

$$\mathrm{CP} - \mathrm{Asym.}\ (D^\circ(t) \to K^+K^-, K_sK^+K^-) \lesssim 0.05 \times \frac{t}{\tau_D} \tag{11}$$

represents not only a fascinating but even possible scenario. One should keep in mind also that the branching ratios are respectable, namely $BR(D^\circ \to K^+K^-) \simeq BR(D^\circ \to K_sK^+K^-) \sim 0.5\%$.

IV. Search Strategies in Nonleptone B° Decays

The main problem for searching for these CP violations lies not in the expected size of the asymmetry, but in much more mundane aspects like branching ratios and reconstruction efficiencies. For example, $B_d \to \psi K_s$ or $\psi K_s\pi^\circ$ are expected to command branching ratios of at most 10^{-3}, $B_s \to D^\circ\phi$ at most 10^{-4}. $B_s \to F^+F^-$ on the other hand presumably possesses a large branching ratio of a few percent. Yet the expected low reconstruction efficiency for this mode makes it a somewhat unpromising candidate.

There is actually a general rule of thumb: channels with an expected CP asymmetry of 10% or more typically command branching ratios of 10^{-3}, 10^{-4} only (or even less); modes with branching ratios of up to one percent should not exhibit asymmetries exceeding one percent.

There might of course be notable exceptions to this general rule and therefore one should keep an open mind. Alternatively, one can wonder whether there are not smarter ways to exploit available data. In particular, is it not possible to increase statistics by summing over final states? For example, a "large" inclusive rate has been found

$$BR(B \to \psi + X) \sim 1\%$$

Unfortunately, one can show[3] that

$$\text{Asym. } (B_d \to \psi K_s X) = -\text{Asym. } (B_s \to \psi K_L X) \tag{12}$$

holds; thus a CP asymmetry in $B \to \psi K X$ is averaged out when one sums over K_s *and* K_L! Therefore, one has to identify at least the K_s.

There are, however, two examples where ***inclusive*** studies have a decent chance to work:

(*a*) $B_s \to \psi + X$: The rate for this process should be largely saturated by $B_s \to \psi\phi, \psi\eta, \psi\eta'$. One can show that the expected asymmetry has the *same* sign in these processes. Searching for CP violation in $B_s \to \psi + X$ thus represents a sound procedure.

(*b*) $B_d \to K_s + \pi' s$: Consider the process

$$\overset{(-)}{B_d} \to \overset{(-)}{D^\circ} M \to (K_s N)_D M \tag{13}$$

where M and N denote ***arbitrary*** members of the pseudoscalar, vector or axialvector nonets; *i.e.*, $N, M = \pi, \eta, \ldots, \rho, \omega, \phi, \ldots, A_1, \ldots$. Then one can again show that all these channels contribute to the expected CP asymmetry with the same sign and can thus safely be summed over.

The crucial question then concerns the size of the combined branching ratios. Using preliminary MARK III data where available and theoretical guidance where not one estimates very roughly

$$BR(D^\circ \to K_s N) \lesssim 8\% \tag{14}$$

For $B_d \to D^\circ M$ even less is known experimentally; yet again one can guestimate

$$BR(B_d \to D^\circ M) \sim 1\% \tag{15}$$

and thus

$$BR(B_d \to D^\circ M \to (K_s N)_D M) \sim 10^{-3} \tag{16}$$

This number is small, but not hopelessly so, in particular when one keeps in mind that the CP asymmetry could be as large as 50% as discussed before.

A simplification of this procedure consists in comparing the inclusive reactions $B_d \to K_s + X$ with $\bar{B}_d \to K_s + X$: using again MARK III data on D branching ratios and a modicum in theoretical guidance one arrives at a dilution for the expected asymmetry by only a factor of two, *i.e.*,

$$\mathrm{CP-Asym.}\ (B_d \to K_s X) \sim 10 - 25\% \tag{17}$$

These are just examples; once we have learned more about the relevant branching ratios and detection efficiencies we will be able to design and evaluate other search strategies.

V. Searching for CP Violation in $e^+e^-, p\overset{(-)}{p} \to B\bar{B}$

So far we have dealt with isolated B° [and D°] decays. This is, however, not quite realistic since the heavy flavour hadrons are produced pairwise. In the case of charm this complication can rather elegantly be overcome by relying on $D^{*\pm} \to D\pi^\pm$ cascades. For bottom decays there is no such easy solution: since the mode f one is studying is common to B° and $\bar{B}^\circ$ decays one needs some information on the initial state to determine whether $B^\circ \to f$ or $\bar{B}^\circ \to f$ occurred—otherwise no CP asymmetry can be defined. Thus, one has to study *correlations* of the type $B^\circ\bar{B} \to f\ell^+X$ vs. $\bar{B}^\circ B \to \bar{f}\ell^-X$. This need for flavour-tagging the "other" bottom decay increases the technical difficulty for such studies.

There is one important caveat to be kept in mind when analyzing these correlations: in the reaction $e^+e^- \to \Upsilon(4s) \to B^\circ\bar{B}^\circ$ no CP asymmetry of the type described above can occur *if* one integrates over *all* decay times. The reason for this is that the $B^\circ\bar{B}^\circ$ pair is produced in a charge conjugation odd state. There are two ways to overcome this no-go result:

1. One studies $e^+e^- \to B^\circ\bar{B}^{\circ *}$ + h. c. $\to B^\circ\bar{B}^\circ\gamma$; for the $B^\circ\bar{B}^\circ$ pair then exists in a charge conjugation even state.

2. One acquires some capability for resolving the lifetime evolution by either going somewhat above $B\bar{B}$ threshold or by using asymmetric e^+e^- collisions.[7] Due to popular demand we present the distribution of the gap ℓ between the two B decay vertices as a function of the velocity β of the B mesons, all measured in the $B\bar{B}$ CM system:

$$\frac{d\sigma(B^\circ\bar{B}^\circ\,|_{c=-} \to \overset{(-)}{f}\,\overset{(-)}{\ell^+}X)}{d\ell} \propto \frac{\ell}{\beta^2}e^{-\Gamma(\ell/\beta)}\left\{\left(1-\frac{\beta}{\Delta m\ell}\sin\frac{\Delta m\ell}{\beta}\right)|\rho_f|^2 + \left(1+\frac{\beta}{\Delta m\ell}\sin\frac{\Delta m\ell}{\beta}\right) \mp \frac{2\beta}{\Delta m\ell}\left(1-\cos\frac{\Delta m\ell}{\beta}\mathrm{Im}\,\frac{p}{q}\rho_f\right)\right\} \tag{18}$$

There is yet another way to employ correlations in the quest for CP violation: let f_1 and f_2 be two CP eigenstates of the *same* CP parity. Then, in principle, by observing *just one event* of the type

$$\Upsilon(4s) \to B^\circ\bar{B}^\circ \to f_1f_2 \tag{19}$$

one has established CP violation.[8] For the initial state has even CP parity whereas the final state, due to its p-wave configuration, has odd CP parity. One finds for the rate:

$$\text{rate }\left(\Upsilon(4s) \to B^\circ(t)\bar{B}^\circ(t) \to f_1f_2\right) \propto e^{-\Gamma(t+\bar{t})}\left(1-\cos\Delta m(t-\bar{t})\right) \times \left|1-\left(\frac{p}{q}\right)^2\rho_1\rho_2\right|^2 \tag{20}$$

with $\rho_i = \frac{A(B^\circ\to f_i)}{A(\bar{B}^\circ\to f_i)}$.

For small mixing this rate is proportional to $(\frac{\Delta m}{\Gamma})^2$ and thus highly suppressed. Yet no such suppression intervenes if the ARGUS findings hold up.

When considering $b \to c\bar{c}s, c\bar{u}d$ transitions one finds for the last factor

$$\left|1-\left(\frac{p}{q}\right)^2\rho_1\rho_2\right|^2 \simeq \frac{4\left(2\eta(1-\rho)\right)^2}{\left((1-\rho)^2+\eta^2\right)^2} \sim 1[0.2] \tag{21}$$

for $m_t \simeq 60[130]$ GeV. Therefore, this factor which is intrinsically connected to CP violation does not produce a large suppression.

Therefore, the rate is basically given by $BR(B \to f_1)BR(\bar{B} \to f_2)$. Searching just for $\Upsilon(4s) \to B^\circ \bar{B}^\circ \to (\psi K_s)(\psi K_s)$ is hopeless due to the tiny combined branching ratios. Yet summing over appropriate final states as discussed in Section IV greatly improves the prospects since one estimates:

$$\sum_{a,b} BR(B \to f_1^a)(\bar{B} \to f_2^b) \simeq 10^{-6} - 10^{-4} \tag{22}$$

Two features of this procedure should be kept in mind:

1. No time resolution is necessary; thus, it is well suited for e^+e^- collisions at bottom threshold.
2. One is searching merely for a rate, *not* an asymmetry.

VI. Summary

Important things are typically hard to come by. The question of CP violation is an extremely important issue and therefore very hard to address. However, if indeed $B_d - \bar{B}_d$ mixing is sizeable and $B_s - \bar{B}_s$ mixing near-maximal—as suggested by UA1[9] and ARGUS data—then the prospects for discovering CP violation in neutral B° decays improve very considerably. Considering the scant database available at the moment it is too early to try to identify the "best" procedure. Various scenarios have to be contemplated and analyzed. Some require good time resolution, in particular in studies of B_s decays, others do not. Much more "bread-and-butter" physics has to be done before really quantitative predictions can be made.

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