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On The Prospects of Observing CP Violation in Bottom and Charm Decays*

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ABSTRACT

A review is given on the phenomenology of CP violation in B and D decays that has been developed over the last few years. Since a firm data base on B decays is still lacking, semiquantitative scenarios are drawn. Within the Standard Model one predicts asymmetries that can be as large as $\mathcal{O}$ (10%) with a confidence level that ranges between hopeful and considerable. Even so, millions of produced B and D mesons are required to make such studies feasible. A B factory would be crucial in such an endeavor.

1. INTRODUCTION

Weak decays of bottom hadrons hold out the promise to discover the first CP violation outside K^0 decays: for some decay modes are expected to exhibit rather large CP asymmetries; we can also have greater confidence in the theoretical treatment of B than of K mesons. Even so our final conclusion will be that at least 10^6 produced B mesons are needed for meaningful searches for CP violation. Such numbers certainly imply a major, dedicated effort.

The Standard Model does not predict any observable CP violation in charm decays. Nevertheless "New Physics" could produce CP asymmetries on the percent level in D° decays. Its phenomenology closely parallels that for B° decays and is therefore included here.

There are two ways in which CP asymmetries can emerge:

(a) via particle – antiparticle mixing and
(b) via final state interactions.

2. MIXING AND CP ASYMMETRIES

— Mixing will manifest itself most clearly via decays of B° to "wrong sign" leptons. With the Pais–Treiman definitions[1]

$$r_B = \frac{\Gamma(B^\circ \to \ell^+ X)}{\Gamma(B^\circ \to \ell^- X)} \simeq \left|\frac{q}{p}\right|^2 \frac{x^2}{2+x^2},$$

$$\bar{r}_B = \frac{\Gamma(\overline{B}^\circ \to \ell^- X)}{\Gamma(\overline{B}^\circ \to \ell^+ X)} \simeq \left|\frac{p}{q}\right|^2 \frac{x^2}{2+x^2}, \quad (1)$$

$$\Delta x = \frac{\Delta m}{\Gamma}, \frac{q}{p} = \frac{1-\epsilon}{1+\epsilon}$$

one finds

$$y = \frac{N(B^\circ \overline{B}^\circ \to \ell^\pm \ell^\pm X)}{N(B^\circ \overline{B}^\circ \to \ell^+ \ell^- X)} \quad (2)$$

$$= \begin{cases} r & \text{for } \underline{\gamma}(4s) \to B\overline{B} \\ \dfrac{2r}{1+r^2} & \text{for } e^+e^- \to b\bar{b} \text{ continuum} \end{cases}$$

In deriving Eq. (2) one has integrated over all decay times from zero to infinity. It is instructive to consider also the time evolution of semileptonic B° decays

$$\Gamma(B^\circ(t) \to \ell^+ X) \propto \left|\frac{q}{p}\right|^2 e^{-\Gamma t}(1 - \cos \Delta m t) \quad (3)$$

$$\Gamma(\overline{B}^\circ(t) \to \ell^- X) \propto \left|\frac{p}{q}\right|^2 e^{-\Gamma t}(1 - \cos \Delta m t) \quad (4)$$

2.1 CP ASYMMETRIES IN SEMILEPTONIC DECAYS

If mixing occurs, *i.e.*, $r \neq 0$, then one can search for CP asymmetries in the semileptonic B decays:

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$$a_{SL}=\frac{N(B^\circ\overline{B}^\circ\to\ell^+\ell^+X)-N(B^\circ\overline{B}^\circ\to\ell^-\ell^-X)}{N(B^\circ\overline{B}^\circ\to\ell^+\ell^+X)+N(B^\circ\overline{B}^\circ\to\ell^-\ell^-X)}$$

$$=\frac{|q|^2-|p|^2}{|p|^2+|q|^2} \quad . \tag{5}$$

Unfortunately the prospects for ever measuring a nonvanishing asymmetry of this type are very discouraging. In the Standard Model one predicts[2]

$$a_{SL}(B_d)\sim 10^{-3}\,, \quad a_{SL}(B_s)\sim 10^{-4} \tag{6}$$

This asymmetry is defined for like-sign dileptons. Since one expects $r(B_d)\leq 4\%$, $r(B_s)\sim 30-100\%$ one concludes that the staggering number of at least 10^{10} produced B mesons were needed. It should be noted that most "New Physics" models, like Supergravity, $SU(3)\times SU(2)_L\times SU(2)_R\times U(1)$ or composite models allow for (without guaranteeing it)

$$a_{SL}(\text{"New Physics"})\ \sim O(10^{-2}) \tag{7}$$

Data samples of at least 10^6 produced B_s or 10^7 produced B_d mesons might allow us to search for such asymmetries.

2.2 CP ASYMMETRIES IN NONLEPTONIC DECAYS

For a final state f that is common to both B° and $\overline{B}^\circ$ decays (a property which is then shared by the CP conjugate channel $\bar{f}$) one defines a CP asymmetry[3]

$$A_{NL}=\frac{\Gamma(B^\circ\to f)-\Gamma(\overline{B}^\circ\to\bar{f})}{\Gamma(B^\circ\to f)+\Gamma(\overline{B}^\circ\to\bar{f})}$$

$$\simeq\frac{\sqrt{2r(1-r)}}{1+r}\ Im\ \frac{p}{q}\ \rho_f \tag{8}$$

$$\rho_f=\frac{A(\overline{B}^\circ\to f)}{A(B^\circ\to f)}$$

where $A(B^\circ\ \to\ f)$ denotes the amplitude for $B^\circ\to f$. A_{NL} vanishes both in the limit of small and of maximal mixing, *i.e.*, $r\ll 1$ and $r\simeq 1$, as is easily understandable, but considerably more slowly than one might expect naively.

In deriving Eq. (8) one has again integrated over all decay times. The actual time evolution is given by:

$$\Gamma(B^\circ(t)\to f)\propto e^{-\Gamma t}(1-\sin\Delta mt\ Im\ \frac{p}{q}\ \rho_f) \tag{9}$$

$$\Gamma(\overline{B}^\circ(t)\to\bar{f})\propto e^{-\Gamma t}(1+\sin\Delta mt\ Im\ \frac{p}{q}\ \rho_f) \tag{10}$$

A time dependance like in Eq. (9) or (10) by itself establishes CP violation. It is instructive to compare it with the time dependence in mixing transitions $B^\circ(t)\to\ell^+ + X$, Eqs. (3, 4).

2.3 EXAMPLES AND PREDICTIONS

The cleanest decay modes are generated by the quark transitions $b\to c\bar{c}s$, $c\bar{c}d$ since they can lead to CP eigenstates in the final state, $\bar{f}=\pm\ f$; *e.g.*, $B\to\psi\ K_s$. One can show[3] that in this case $p/q\ \rho_f$ can be calculated rather reliably in terms of KM parameters only.

For the decay modes $B_d\to\psi K_S, \psi K_S\pi^0, D\overline{D}$, $D\overline{D}K_S$ one predicts an asymmetry of 2–20%; the uncertainty is due to our ignorance concerning the KM angle U(bu) and the top mass (or the strength of B^0–$\overline{B}^0$ mixing). An asymmetry of 20% corresponds to a mixing signal $r_d\approx$ 2–4%. The estimated branching ratios range from order 10^{-3} to 10^{-2}.

The expected asymmetries in the decays $B_s\to\psi\phi$, F^+F^- are of order 10^{-3} to 10^{-2} only; however the existence of a fourth family could raise them to the 10% level.

Asymmetries of the type expressed in Eq. (8) can occur also when f is not a CP eigenstate,[3–6] although predictions are then beset with more uncertainties ($SU(4)$ breaking *etc.*); in $B_d\to D^+\pi^-$ one expects an asymmetry of order $10^{-3}-10^{-2}$; the mode $B_s\to D\phi$ on the other hand could conceivably exhibit an asymmetry of order 10-50%.

A comment is in order here: the CP asymmetries listed above do not depend on the intervention of final state interactions. The asymmetry is actually completely independent of final state interactions in those decays which are produced by the isospin conserving transition $b\to c\bar{c}s$; in some of the other cases final state interactions could change the pattern.

2.4 CP ASYMMETRIES IN D° DECAYS

The asymmetry defined in Eq. (8) is a generic one and can thus be applied to neutral D decays as well. The Standard Model does not predict any observable asymmetry; yet New Physics could produce mixing on the level $r_D \sim 1/2\%$ – which is still consistent with experimental bounds – leading to

$$A_{NL}(D^\circ) \simeq \sqrt{2r_D}\ Im\ \frac{p}{q}\ \rho_f \sim 0.1\ Im\ \frac{p}{q}\ \rho_f$$

Thus a CP asymmetry on the percent level could be produced this way[7] and should be searched for. The best decay modes are those that lead to a CP eigenstate, *e.g.*, $f = K_s K^+ K^-,\ K^+K^-$. For small mixing, *i.e.*, $\Delta m \ll \Gamma$, one finds for the time evolution:

$$\Gamma(D^\circ(t) \to K^+K^-) \propto e^{-\Gamma t}(1 - (\Delta m t) Im\ \frac{p}{q}\ \rho_f) \tag{11}$$

since realistically t is at most a few times $(\Gamma)^{-1}$. Compare this with the time evolution for $D^\circ(t) \to K^-\pi^+$ *etc.*, decays in the limit of small mixing:

$$\Gamma(D^\circ(t) \to K^+\pi) \propto e^{-\Gamma t}$$
$$\times \Big\{(\Delta m t)^2 + (4 - 2\ \Delta\Gamma t) tg^4\theta_c |\hat{\rho}_f|^2 \tag{12}$$
$$+ 2\ tg^2\theta_c(\Delta\Gamma t)\ Re\ \frac{p}{q}\ \hat{\rho}_f - 4\ tg^2\theta_c(\Delta m t) Im\ \frac{p}{q}\ \hat{\rho}_f\Big\}$$

where

$$tg^2\theta_c\hat{\rho}_f = \frac{A(D^\circ \to K^+\pi^-)}{A(D^\circ \to K^-\pi^+)}\ .$$

2.5 SEARCH STRATEGIES

The examples given above exhibit a general feature: while the CP asymmetries can reach very large values one estimates that the branching ratios for the corresponding exclusive modes are at best small. In addition one has to identify the final state. A good example for these difficulties is provided by $B_d \to \psi K_s$. It is then very tempting to suggest searching for a difference between the inclusive rates $\Gamma(B_d \to \psi + X)$ and $\Gamma(\overline{B}_d \to \psi + X)$ since the corresponding branching ratio amounts to 1%. However it can be shown that

$$A_{NL}(B \to \psi K_s X) = -A_{NL}(B \to \psi K_L X) \tag{13}$$

and thus

$$A_{NL}(B \to \psi + X) \equiv 0 \tag{14}$$

The underlying reason is that the sign of the asymmetry in the decays B°, $\overline{B}^\circ \to f,\ \bar{f}$ depends on the CP parity of f. More specifically one finds for the asymmetry when summing over different final states f_i:

$$A_{NL}(B^\circ \to \sum_i f_i)$$
$$= \sum_i A_{NL}(B^\circ \to f_i)\, BR(B^\circ \to f_i)(-1)^{CP[f_i]} \tag{15}$$

where $(-1)^{CP[f_i]}$ denotes the CP parity of the final state f_i. The following lessons are obtained from Eq. (15):

(i) An indiscriminate summation over final states will lead to an at least partial cancellation of the asymmetry.

(ii) If the final state can contain a neutral kaon, one has to identify at least a K_s; otherwise the asymmetry is bound to vanish.

(iii) Adding the contributions from different decay modes with the appropriate sign, actually represents a simpler task than it appears at first: one can show that the decays $\overset{(-)}{B}{}^\circ \to \overset{(-)}{D}{}^\circ M^\circ \to (K_s N^\circ)_D M^\circ$ lead to even CP eigenstates for N, M being any neutral member of the pseudoscalar, vector or axial vector nonets:

$$CP|(K_s N)_{D^\circ} M\rangle = +\ |(K_s N)_{D^\circ} M\rangle$$

Thus all these channels contribute with the same sign! Using MARK III branching ratios for $D^\circ \to K_s N^\circ$ when available and theoretical guidance for other $D^\circ \to K_s N^\circ$ modes and for $B^\circ \to D^\circ M$ transitions one arrives at

$$BR(B^\circ \to (K_s N)_{D^\circ} M) \sim \mathcal{O}(1\%) \tag{16}$$

with a predicted asymmetry of order 10%.

(*iv*) One can be even bolder and use the inclusive transition $\overset{(-)}{B}_d \to \overset{(-)}{D} + \ldots \to K_s + \ldots$ to search for a CP asymmetry. Using the same procedure that leads to Eq. (16) one finds a dilution factor of only 1/2 for the asymmetry.

This problem of cancellations in inclusive transitions also arises when f is not a CP eigenstate.[3]

3. CP ASYMMETRIES AND FINAL STATE INTERACTIONS

The CP asymmetries discussed so far do not require the intervention of final state interactions although those could affect the observed pattern somewhat. However, final state interactions are essential for another type of asymmetries that can emerge also in the absence of mixing; the cleanest scenario is provided by charged B (or D) decays. One finds for the difference between the two CP conjugate widths

$$\begin{aligned}&\Gamma(B^- \to f^-) \; - \; \Gamma(B^+ \to f^+) \\ &\propto \; Im \; g_1^* g_2 \sin(\alpha_1 - \alpha_2) M_1 M_2\end{aligned} \tag{17}$$

where M_i, $i = 1, 2$ denotes two different transition amplitudes with the weak couplings g_i and strong phase shifts α_i already factored out.

The asymmetry (17) will vanish unless two conditions are satisfied simultaneously:

(i) Nontrivial phase shifts $\alpha_1, \neq \alpha_2$ have to be generated from the strong (or electromagnetic) forces.

(ii) The weak couplings g_1 and g_2 have to possess a relative complex phase. In the Standard Model this implies that the transition rates for such decay modes are suppressed by small mixing angles.

Conditions (i) and (ii) could be realized in many different scenarios; three typical ones are listed below:

(A) Interplay between two cascade processes:[3] Interference between the two different cascades $B^- \to D^\circ K^- + X \to K_s K^- XY$ and $B^+ \to \overline{D}^\circ K^+ + X \to K_s K^+ XY$ can lead to a difference in rate of up to $\mathcal{O}(1\%)$ with a combined branching ratio expected to be of order 10^{-3}.

(B) Interplay between quark decay and weak annihilation:[8] It is quite conceivable that in addition to quark decay weak annihilation could have a significant impact at least on some B decays. These two mechanisms can contribute coherently to modes such as $B^\pm \to \overset{(-)}{D}{}^{\circ *} D^\pm$. In that case there could be a CP asymmetry of order 1% [9]. This asymmetry however vanishes if weak annihilation is insignificant.

In both scenarios (A) and (B) soft interactions are invoked to generate nontrivial phase shifts. The strength of these effects cannot be predicted in a reliable way; instead one makes an ansatz that is understandably on the optimistic side. As a note of caution: these welcome effects disappear if only the leading terms in a $1/N$ approach, N being the number of colors, are retained.

(C) Interplay between quark decay and Penguin operators: Penguin operators possess both a real and imaginary part: thus they can generate the necessary phase shifts by themselves (although soft interactions could mask it, as it happens for $(\epsilon'/\epsilon)_K$). The interference of Penguins with quark cascades in modes like $B \to K\rho$, $K\pi$ will then by itself produce asymmetries which could reach the percent level[3,10] with an estimated branching ratio of $BR(B \to K\rho) \sim \mathcal{O}(10^{-4})$.

4. CONCLUSIONS

(i) The phenomenology of those CP asymmetries in neutral B decays that involve mixing has basically been developed. What is clearly lacking however is a firm data base on branching ratios, $B-\overline{B}$ mixing *etc.*, to decide which specific search has the best chance to succeed.

(ii) In the absence of such a data base one can draw various scenarios that lead to some qualitative conclusions:

(α) It is unlikely that CP violation in semileptonic B decays will ever be observed; even with allowance for "New Physics" data samples of at least 10^6 B_s or 10^7 B_d mesons are required.

(β) The CP asymmetry in $B \to \psi K_s$ decays is reliably predicted as of order 10%. However when one considers the combined branching ratios one realizes that such a search can realistically be done only at a hadronic machine.

(γ) Summing over final states in a discriminating fashion as described before will be of great help statistically while costing only a factor of two or so in the asymmetry. Yet even so one estimates that at least 10^6 produced B mesons are needed. Soon existing machines like SLC and LEP have therefore only a marginal chance to find a CP asymmetry in B decays.

(iii) There could be CP asymmetries on the 1% level in D° decays. Photoproduction of charm could serve as a "D factory" yielding millions of D decays.

(iv) The phenomenology of CP asymmetries in charged B decays has not been developed to the same degree. This is largely due to the fact that these asymmetries can emerge only if final state interactions intervene in a prescribed way. Those can be produced by soft interactions, yet then no reliable prediction can be made. One estimates typically that at least 10^7 produced B's are needed.

(v) A new element enters at this point: it is generally argued that Penguin transitions can be treated perturbatively in B decays. Then one can compute the relevant phase shifts with some confidence. This produces a CP asymmetry that in $B \to K\rho$ could reach the percent level. Since the branching ratio is not expected to exceed 10^{-4} such a study is beyond the reach of SLC or LEP. It might however be within the SSC capabilities.

It is obvious that these studies require a very major, dedicated and broad-based effort. Such an effort is however justified and even mandated considering the profound insights that would be gained into a long-standing mystery: the origin of CP violation.

To make real progress in this endeavor it seems highly desirable, if not even indispensable to have a B factory available that can produce millions of B mesons in a clean environment, preferably with the ability to observe the time evolution of B decays.

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