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CP Violation in the B System†

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ABSTRACT

The observation of CP violating phenomena in the B system is likely to give us much-needed information about the parameters of the CKM matrix and perhaps even tell us whether or not the standard model explanation for CP violation is correct. In this paper I examine the possibilities for CP violation in B decays. Lepton asymmetries and final state interactions are discussed and their shortcomings noted. The most promising scenario involves hadronic decay asymmetries, using either time-integrated or time-dependent techniques. I review the bounds on the CKM matrix due to the measurements of ϵ and B_d-$\overline{B_d}$ mixing, and give estimates for the size of these asymmetries. There are a number of difficulties for experiments – these are examined and several of the proposed solutions presented. Finally, I emphasize that the number of B's required to see CP violation at the 3σ level is of order 10^8.

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1. Introduction

For more than 20 years, the origin of CP violation has been one of the fundamental questions in particle physics. To date, CP violating phenomena have only been seen in the kaon system. First of all, the observation of the decay $K_L \to \pi\pi$ [1] is evidence that ϵ, the CP-violating mixing parameter, is non-zero. More recently, the measurement of ϵ'/ϵ by the NA31 experiment at CERN [2] indicates that CP is also violated in kaon decays. This latter result, if confirmed, already rules out some models for CP violation, the superweak model for example. It is likely that the B system will provide us with more clues, and perhaps even tell us whether or not the standard model explanation for CP violation, the Cabibbo-Kobayashi-Maskawa (CKM) matrix, is correct. The results of the ARGUS [3] and CLEO [4] collaborations have indicated that $B_d\overline{B_d}$ mixing is significantly larger than expected. This has led to an enormous amount of interest in the implications for the CKM matrix and, as we shall see, has suggested that CP violating asymmetries in the B system could be quite large. In this paper, I will discuss the prospects for CP violation in the B system.

I will start off with a review of CP violation in the kaon system (Sec. 2). In Sec. 3, I discuss mixing in the B system, contrasting the effects with those found in the K system. CP violating phenomena in the B system are examined in Sec. 4. After briefly discussing the possibilities for seeing a CP asymmetry in the semi-leptonic decay mode, and for seeing CP violation via final state interactions, I then turn to a more promising possibility, that of CP violating asymmetries in hadronic decay modes. The size of these asymmetries depends crucially on the CKM matrix elements, and I review the limits which result from both the K system and from the ARGUS/CLEO result. Experimental problems in seeing such asymmetries are discussed. I then examine the possibility for observing CP violation via time-dependent measurements. Sec. 5 contains a summary and conclusions.

2. The K system - Mixing and CP Violation

There are two ways in which CP is violated in the kaon system. The first is through CP violation in the state, characterized by the mixing parameter ϵ. This enters when the weak states K_S, K_L are expressed as linear combinations of the strong (electromagnetic) states:

$$
\begin{aligned}
|K_S^0\rangle &= \frac{1}{\sqrt{2(1+|\epsilon|^2)}}\left[(1+\epsilon)|K^0\rangle - (1-\epsilon)|\overline{K^0}\rangle\right] \\
|K_L^0\rangle &= \frac{1}{\sqrt{2(1+|\epsilon|^2)}}\left[(1+\epsilon)|K^0\rangle + (1-\epsilon)|\overline{K^0}\rangle\right] ,
\end{aligned}
\qquad (1)
$$

where I have used the convention $CP|K^0\rangle = -|\overline{K^0}\rangle$; $CP|\overline{K^0}\rangle = -|K^0\rangle$. If ϵ were zero, the weak states would be CP eigenstates: K_S would have CP +; K_L would have CP −. Therefore a non-zero ϵ is evidence for $\Delta S = 2$ CP violation. In the standard model, CP violation is explained by an imaginary phase in the CKM mixing matrix, which enters into the vertices in the box diagram for mixing in the kaon system (Fig. 1). ϵ is (in principle) calculable from this diagram. However, as we shall see, there are large theoretical uncertainties. Experimentally, it has the value [5]

$$\epsilon = (2.275 \pm 0.021) \times 10^{-3} \ . \tag{2}$$

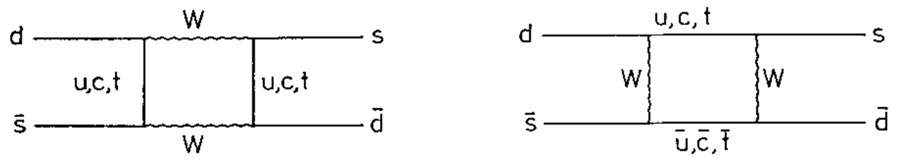

Fig. 1: Diagrams contributing to ϵ in the CKM model.

It is also possible to have CP violation in the decays of kaons, parametrized by the $\Delta S = 1$ CP violating parameter ϵ', which arises from different isospin phases in the amplitudes for the decays $K \to 2\pi$:

$$\begin{aligned} A_0 &= \langle \pi\pi,\ I = 0|H_W|K^0\rangle \\ A_2 &= \langle \pi\pi,\ I = 2|H_W|K^0\rangle \ , \end{aligned} \tag{3}$$

and

$$\epsilon' \propto \mathrm{Im}\left(\frac{A_2}{A_0}\right) \ . \tag{4}$$

In the standard model, it is expected that $\epsilon' \ll \epsilon$, and the NA31 group at CERN [2] recently measured ϵ'/ϵ to be

$$\left(\frac{\epsilon'}{\epsilon}\right) = (3.3 \pm 1.1) \times 10^{-3} \ . \tag{5}$$

Therefore, in the kaon system, CP violation with $\Delta S = 2$ is much larger than that with $\Delta S = 1$.

3. The B System - Mixing

In the B system, there are also two possibilities for CP violation. First of all, as in the kaon system, CP can be violated in the mixing between B and $\overline{B}$ mesons (Fig. 2). However, the B system differs from the kaon system in one crucial respect. Since B-mesons are so heavy, the phase space for their decays is quite large. Therefore both B and $\overline{B}$ have essentially the same lifetime, i.e. $\Delta\tau_B \ll \tau_B$. The calculation which yields the lifetime difference comes from the box diagram, and is similar to that which gives ϵ_B, the $\Delta B = 2$

CP-violating parameter in the B system [6]. Therefore ϵ_B is expected to be quite small in the standard model. This calculation has been done [7], and yields

$$\epsilon_B = \begin{cases} O(10^{-4}), & B_d, \\ O(10^{-5}), & B_s. \end{cases} \tag{6}$$

It therefore seems that the prospects for observation of $\Delta B = 2$ CP-violating phenomena are essentially hopeless.

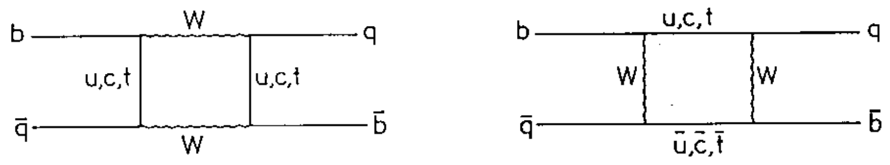

Fig. 2: Diagrams contributing to B^0-$\overline{B}^0$ mixing.

However, in the B system, the situation is reversed with respect to the kaon system, namely, CP violation in B decays ($\Delta B = 1$) can be large. For such phenomena, the relevant parameter is x, the ratio of the energy of the oscillation (i.e. the mass difference) and the total width for the B mesons:

$$x = \frac{\Delta M}{\Gamma} \quad \frac{\text{(transition energy)}}{\text{(mean total width)}} \ . \tag{7}$$

After all, mixing hardly matters if the particle decays before it has a chance to oscillate into its antiparticle. This can be seen explicitly - because of B-$\overline{B}$ mixing, a state which starts out as a pure B^0 or $\overline{B^0}$ will evolve in time to a mixture of B^0 and $\overline{B^0}$:

$$\begin{aligned} |B^0(t)\rangle &= f_+(t)|B^0\rangle + \frac{1-\epsilon_B}{1+\epsilon_B}\, f_-(t)\,|\overline{B^0}\rangle \\ |\overline{B^0}(t)\rangle &= \frac{1-\epsilon_B}{1-\epsilon_B}\, f_-(t)|B^0\rangle + f_+(t)\,|\overline{B^0}\rangle \ . \end{aligned} \tag{8}$$

Here, $|B^0\rangle$ represents a pure B^0 state at $t = 0$, $|\overline{B^0}\rangle$ represents a pure $\overline{B^0}$ state at $t = 0$, and

$$\begin{aligned} f_+(t) &= e^{-imt}e^{-\Gamma t/2}\cos(\Delta m t/2) \\ f_-(t) &= e^{-imt}e^{-\Gamma t/2}i\sin(\Delta m t/2) \ . \end{aligned} \tag{9}$$

From Eqn (9), it is clearly seen that the competition between Δm and Γ is the important consideration for seeing CP violation in B decays. For B_d-$\overline{B}_d$ mixing, the combined ARGUS and CLEO measurements give

$$x_d = 0.70 \pm 0.13 \ . \tag{10}$$

As we shall see, this is a large number, and leads to the possibility of substantial CP violating asymmetries in B decays, to which I now turn.

4. The B System - CP Violation

In the B system, CP violation is indicated by a difference in the rates for $B \to f$ and $\overline{B} \to \overline{f}$. In this section, I examine four possible scenarios for such a CP violating asymmetry.

4.1 Lepton Asymmetries

The first possibility is via a lepton asymmetry [8]. B-$\overline{B}$ mixing is measured by looking for same sign dileptons: CP violation is indicated by a difference in the cross sections for producing positively and negatively charged dileptons:

$$A_l = \frac{N(l^+l^+) - N(l^-l^-)}{N(l^+l^+) + N(l^-l^-)} . \tag{11}$$

However, this is precisely the CP violation in the mixing matrix referred to earlier, i.e.,

$$A_l \simeq -4\,\mathrm{Re}\,\epsilon_B . \tag{12}$$

As was pointed out earlier, ϵ_B is expected to be very small in the B system, which leads to very small predicted asymmetries [9]:

$$A_l \leq \begin{cases} O(10^{-3}), & B_d, \\ O(10^{-4}), & B_s. \end{cases} \tag{13}$$

To see such a small asymmetry requires 10^9-10^{10} B's. However, it is clearly still worth looking for, since the observation of a larger CP violating asymmetry would be clear evidence of physics beyond the standard model.

4.2 $B^{\pm}$ - Final State Interactions

Another possibility is to look for CP violation in the decays of charged B's [10]. CP can be violated if two different amplitudes contribute to the decay of a B^- (B^+) into a final state f ($\overline{f}$).

$$\begin{aligned} A(B^- \to f) &= |A_1| e^{i\delta_1} e^{i\phi_1} + |A_2| e^{i\delta_2} e^{i\phi_2} \\ A(B^+ \to \overline{f}) &= |A_1| e^{i\delta_1} e^{-i\phi_1} + |A_2| e^{i\delta_2} e^{-i\phi_2} . \end{aligned} \tag{14}$$

Here, δ_i are the strong phase shifts (for example, isospin phases), and ϕ_i are the weak phases. The CP asymmetry is then

$$A_f^{+-} \propto \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2) . \tag{15}$$

As can be seen, a non-zero asymmetry requires (i) that there be a difference in the weak CP phases, and (ii) that the strong phases of the two amplitudes be different. Such an asymmetry is relatively easy to see experimentally. However, the calculations are unreliable, so that the theoretical interpretation of a positive signal would be difficult. Nevertheless, these CP asymmetries should still be searched for, although the implications for the CKM matrix would require more theoretical analysis.

4.3 Hadronic Decay Asymmetries

I now turn to the most likely prospect for CP violation in the B system - that of hadronic decay asymmetries. If we consider a non-leptonic final state f such that both B^0 and $\overline{B^0}$ can decay both to it and its CP conjugate state $\overline{f}$, then CP violation is manifested in a non-zero value of [11]

$$A_f = \frac{\Gamma(B^0(t) \to f) - \Gamma(\overline{B^0}(t) \to \overline{f})}{\Gamma(B^0(t) \to f) + \Gamma(\overline{B^0}(t) \to \overline{f})} . \tag{16}$$

Using Eqn (8), and integrating over time, we obtain

$$A_f = -\frac{2x\,\mathrm{Im}\lambda_f}{2 + x^2 + x^2|\rho_f|^2} , \tag{17}$$

where

$$\rho_f = \frac{A(\overline{B^0} \to f)}{A(B^0 \to f)} , \tag{18}$$

and

$$\lambda_f = \frac{1 - \epsilon_B}{1 + \epsilon_B}\, \rho_f . \tag{19}$$

Therefore a nonzero value of the imaginary part of λ_f would lead to a CP asymmetry. Note that λ_f, which is a product of $\Delta B = 2$ and $\Delta B = 1$ pieces, can be nonzero even if $\epsilon_B = 0$. Now, if f is not a CP eigenstate, then A_f depends on hadron dynamics in the ρ_f term, which leads to some theoretical difficulties in calculating the asymmetry. This is avoided by taking f to be a CP eigenstate. Furthermore, when only one combination of CKM matrix elements contributes to $B^0 \to f$, and another to $\overline{B^0} \to f$, then $|\rho_f| = 1$, i.e. ρ_f is a pure phase [12]. An example of this is shown in Fig. 3, where I have given the diagrams for B^0 and $\overline{B^0}$ decaying to ΨK_S. There,

$$\begin{aligned} A(B^0 \to f) &\sim V_{bc}^* V_{cs} , \\ A(\overline{B^0} \to f) &\sim V_{bc} V_{cs}^* . \end{aligned} \tag{20}$$

In general, $|\rho_f|$ will be equal to 1 whenever the (quark level) decays $b \to u\overline{u}d$, $b \to u\overline{u}s$, $b \to c\overline{c}d$, or $b \to c\overline{c}s$ occur. For these cases, A_f takes the familiar form

$$A_f = -\frac{x}{1 + x^2}\, \mathrm{Im}\lambda_f . \tag{21}$$

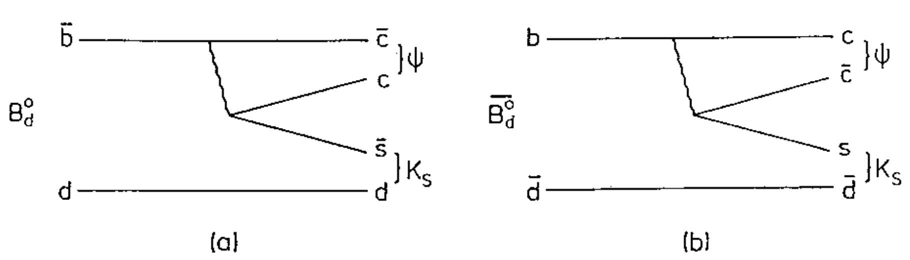

Fig. 3: Diagrams for (a) $B_d^0 \to \Psi K_S$ and (b) $\overline{B}_d^0 \to \Psi K_S$.

It can also be shown that $\frac{1-\epsilon_B}{1+\epsilon_B}$ is pure phase, assuming that ϵ_H is small, and that the box diagram is dominated by the t-quark [13]:

$$\frac{1-\epsilon_B}{1+\epsilon_B} = \frac{\xi_t}{\xi_t^*}\,, \qquad \xi_t = V_{tb}V_{t\alpha}^*\,, \alpha = d, s\,. \tag{22}$$

As mentioned earlier, the standard model explanation for CP violation is that it is due to a non-zero phase in the CKM matrix. How are the phases ρ_f and $\frac{1-\epsilon_B}{1+\epsilon_B}$ related to the CKM phase? A parametrization of the CKM matrix which is convenient when discussing B physics is the following [14]:

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\rho\lambda^3 e^{i\delta} \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho e^{-i\delta}) & -A\lambda^2 & 1 \end{pmatrix}\,. \tag{23}$$

This form of the CKM matrix is an approximation, accurate to $O(\lambda^3)$, where λ is the Cabibbo angle, $\lambda \simeq 0.22$. With this parametrization, the only two elements which have "large" ($O(\lambda^3)$) phases are V_{ub} and V_{td}. It is these phases which will give rise to substantial CP violating asymmetries in B decays. (There are other elements with smaller phases which are relevant to the kaon system, but I shall ignore them here.) CP violating asymmetries measure one or the other of these phases, or both. Using this parametrization, $\frac{1-\epsilon_B}{1+\epsilon_B}$ takes on two values:

$$\frac{1-\epsilon_B}{1+\epsilon_B} = \begin{cases} \frac{V_{tb}^*}{V_{tb}}\frac{V_{td}}{V_{td}^*} = \frac{V_{td}}{V_{td}^*} = e^{2i\phi} & (B_d) \\ \frac{V_{tb}^*}{V_{tb}}\frac{V_{ts}}{V_{ts}^*} = 1 & (B_s). \end{cases} \tag{24}$$

ρ_f also takes on two values, depending on how the b-quark decays:

$$\rho_f = \begin{cases} \frac{V_{ub}}{V_{ub}^*} = e^{2i\delta} & \text{(Cabibbo suppressed)} \\ \frac{V_{cb}}{V_{cb}^*} = 1 & \text{(Cabibbo allowed).} \end{cases} \tag{25}$$

Since λ_f is the product of ρ_f and $\frac{1-\epsilon_B}{1+\epsilon_B}$, there are three classes of model independent asymmetries which can be sizeable [15]. Each measures different combinations of KM matrix elements, all related to δ:

1) Cabibbo allowed B_d decays (e.g. $B_d \to \Psi K_S$)

$$\mathrm{Im}\lambda_1 \simeq \mathrm{Im}\frac{V_{td}}{V_{td}^*} = \sin 2\phi = \frac{2\rho\sin\delta(1-\rho\cos\delta)}{1+\rho^2-2\rho\cos\delta} \tag{26}$$

2) Cabibbo suppressed B_d decays (e.g. $B_d \to \pi^+\pi^-$)

$$\mathrm{Im}\lambda_2 \simeq \mathrm{Im}\frac{V_{td}}{V_{td}^*}\frac{V_{ub}}{V_{ub}^*} = \sin 2(\phi+\delta) = \frac{2\sin\delta(\cos\delta-\rho)}{1+\rho^2-2\rho\cos\delta} \tag{27}$$

3) Cabibbo suppressed B_s decays (e.g. $B_s \to \rho^0 K_S$)

$$\mathrm{Im}\lambda_3 \simeq \mathrm{Im}\frac{V_{ub}}{V_{ub}^*} = \sin 2\delta = 2\sin\delta\cos\delta \tag{28}$$

These are the only CP asymmetries in B decay which are completely calculable from the KM matrix, without additional (unreliable) hadronic information. I will now discuss the ranges of these asymmetries which are allowed by current data.

In addition to the phase, δ, and the Cabibbo angle, λ, there are two other parameters in the CKM matrix in Eqn (23), A and ρ. These are, in principle, obtainable from B decay. The B lifetime fixes A (through V_{bc}) to be $A = 1.05 \pm 0.17$ [16]; B semileptonic decays give (conservatively) $\rho < 0.9$ [17], and the preliminary ARGUS result for V_{ub} [18] yields $\rho > 0.3$. Note that CLEO has not confirmed this ARGUS result [4], so the lower bound is not firm. In any case, we do not take any fixed value of ρ in our analysis, but allow it to vary in the range $0 \le \rho \le 0.9$. Now, δ is constrained by the measurements of ϵ and x_d (the current measurement of ϵ' does not yield constraints better than those of ϵ and x_d [19]). The theoretical expression for ϵ is given by [20]

$$\epsilon = \frac{G_F^2 f_K^2 M_K M_W^2}{6\sqrt{2}\pi^2\Delta M_K} B_K \left(A^2\rho\lambda^6\sin\delta\right)\left(y_c\{\eta_3 f_3(y_c,y_t)-\eta_1\} + \eta_2 y_t f_2(y_t) A^2\lambda^2(1-\rho\cos\delta)\right)\,, \tag{29}$$

where $y_i = m_i^2/M_W^2$, f_2 and f_3 are weakly dependent functions of the top and charm masses, and the η_i are QCD corrections. The two important unknowns in Eqn (29) are the top quark mass and the bag parameter, B_K. The mass of the top quark is constrained by both experimental and theoretical considerations. Direct searches [21] put a lower limit $m_t > 41$ GeV, while the upper bound $m_t \lesssim 180$ GeV results from the study of radiative corrections within the standard model [22]. B_K encapsulates our present ignorance of the matrix element of $(\bar{d}\gamma^\mu(1-\gamma_5)s)^2$ between K^0 and $\overline{K^0}$. A reasonable range is $1/3 \leq B_K \leq 1$, with $B_K = 1$ corresponding to the vacuum insertion approximation. Theoretically, x_d receives its dominant contribution from the presence of top quarks in the box diagram and one finds [23]

$$x_d = \tau_B \frac{G_F^2}{6\pi^2} M_B M_W^2 \left(f_{B_d}^2 B_{B_d}\right) \eta_B y_t f_2(y_t) \left\{A^2\lambda^6 \left(1+\rho^2-2\rho\cos\delta\right)\right\} , \qquad (30)$$

where η_B is a QCD correction factor. Here the hadronic uncertainty is hidden in the factor $f_{B_d}^2 B_{B_d}$, whose meaning is analogous to that of the corresponding quantities in the kaon system, except that here also f_B is not measured. There are a large number of estimates for this quantity, most of which differ from one another, but $(100\ \text{MeV})^2 \leq f_{B_d}^2 B_{B_d} \leq (200\ \text{MeV})^2$ includes most of them. We now fit the theoretical expressions to the experimental numbers, at 90% c.l. Fig. 4 shows the allowed region in the ρ-δ plane for

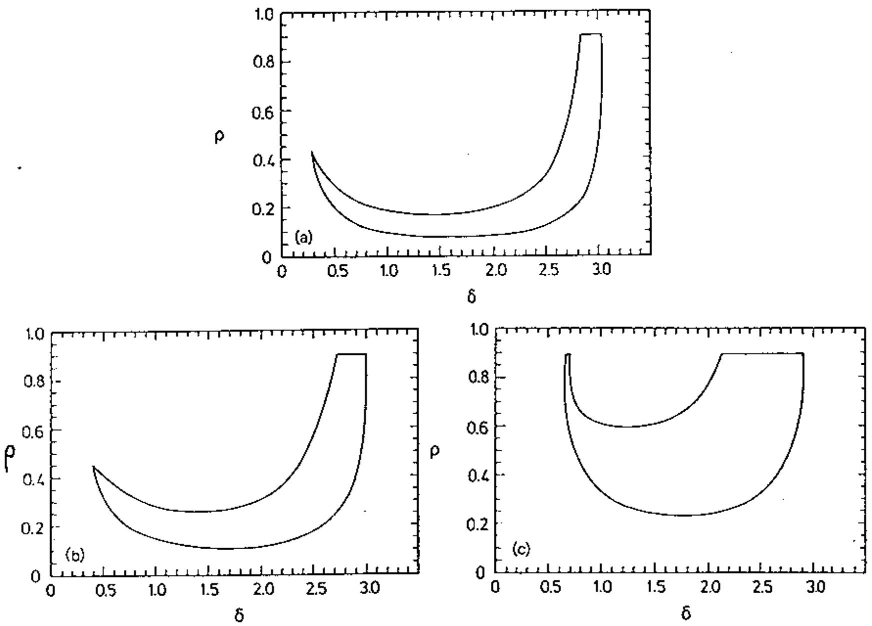

Fig. 4: The domain in ρ-δ space (δ in radians), within which the standard model is compatible with the measurements of ϵ and x_d (90% c.l.). We allow m_t to vary between 41 GeV and 180 GeV, and $(f_{B_d}^2 B_{B_d})^{1/2}$ between 100 MeV and 200 MeV: (a) $B_K = 1$, (b) $B_K = 2/3$, (c) $B_K = 1/3$.

the values $B_K = 1/3$, $2/3$ and 1, but allowing m_t and $f_{B_d}^2 B_{B_d}$ to vary over their entire ranges. As is clear from the figures, the allowed area for the CKM matrix parameters is quite sensitive to the value of B_K taken.

For the CP violating asymmetries (Eqs (26)-(28)), we will take B_K to be 2/3 for the purpose of illustration. In this case the allowed regions are shown in Fig. 5.

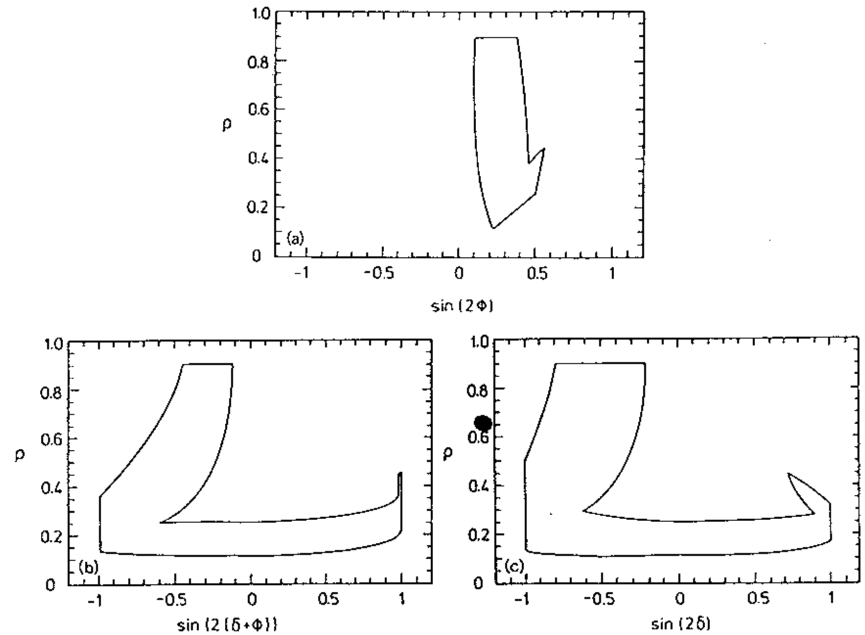

Fig. 5: Varying $(f_{B_d}^2 B_{B_d})^{1/2}$ and m_t, 100 MeV $\leq (f_{B_d}^2 B_{B_d})^{1/2} \leq$ 200 MeV and 41 GeV $\leq m_t \leq$ 180 GeV, and fixing $B_K = 2/3$, the areas within which the standard model is compatible with the measurements of ϵ and x_d (90% c.l.) are shown for the following parameter spaces: (a) $(\sin 2\phi, \rho)$, (b) $(\sin 2(\delta+\phi), \rho)$, (c) $(\sin 2\delta, \rho)$.

The region for $\mathrm{Im}(\lambda_1)$ is the smallest, with a maximum value of about 0.4 allowed. On the other hand, $\mathrm{Im}(\lambda_2)$ and $\mathrm{Im}(\lambda_3)$ are allowed quite sizable values. However, recall that the asymmetries are reduced by a factor $x/(1+x^2)$ (Eqn (21)). For B_d mesons, this is a factor of about 0.5. But for B_s mesons, this factor can be quite a bit smaller. Within the standard model, one expects

$$\frac{x_s}{x_d} \simeq \left|\frac{V_{ts}}{V_{td}}\right|^2 , \qquad (31)$$

which is $O(\lambda^{-2})$, leading to a conservative lower limit of $x_s > 3$ [15]. This gives a reduction factor of 0.3, but it is likely to be considerably smaller. Therefore, unless x_s is smaller than expected in the standard model, B_d decays, both Cabibbo allowed and Cabibbo suppressed, appear to be the best prospects for seeing CP violation in the B system via time-integrated methods.

There are more complications when considering the experimental side of things. Let us first consider threshold e^+e^- machines, such as DORIS, CESR, or a possible B-factory. The hadronic CP asymmetries were calculated assuming that one knew whether it was a B or $\overline{B}$ which decayed. However, since pure B or $\overline{B}$ beams do not exist, one has to "tag" on the other B in order to know whether it was B or $\overline{B}$ which decayed. This is done at such machines by looking for its semileptonic decay. Using the semileptonic tag, the (pre-time-integrated) branching ratios for a $B\overline{B}$ pair to decay into a final state f and a leptonic tag are [24]

$$B.R.(B(t)\overline{B}(\bar{t})|_{C=\mp 1} \to f + (Dl\bar{\nu}X)_{\rm tag}) \propto e^{-\Gamma(t+\bar{t})}\left\{1 - \sin\left(\Delta m(t \mp \bar{t})\right) {\rm Im}\lambda_f\right\} , \quad (32)$$

$$B.R.(\overline{B}(t)B(\bar{t})|_{C=\mp 1} \to f + (\overline{D}l\nu X)_{\rm tag}) \propto e^{-\Gamma(t+\bar{t})}\left\{1 + \sin\left(\Delta m(t \mp \bar{t})\right) {\rm Im}\lambda_f\right\} . \quad (33)$$

The important point is that for $C = -1$, i.e. for the $B\overline{B}$ pair in an odd relative angular momentum state, the asymmetry vanishes when the times t and $\bar{t}$ are treated symmetrically. This is precisely the case at the $\Upsilon(4s)$, so that the $\Upsilon(4s)$ *cannot be used to see time-integrated CP asymmetries.* Above the $\Upsilon(4s)$, an L-even state can be produced from the decay of a $B\overline{B^*}$ + c.c. state. Unfortunately, the cross section is quite a bit smaller at this energy. There has also been a suggestion to use asymmetric e^+e^- beams at the $\Upsilon(4s)$. This would have the effect of separating the decay vertices, so that it might be possible to avoid integrating over the whole time distribution, and thereby partially evade the suppression of CP asymmetries from the L-odd state [25]. Although it is not clear whether or not this can be done, we will see that an asymmetric $\Upsilon(4s)$ machine could be quite useful for the measurement of time-dependent CP violating effects.

At hadron machines, there is an additional possibility for tagging. If the B^0 or $\overline{B^0}$ is produced along with a charged B, then the charge of the $B^\pm$ tags the neutral B. However, this requires full reconstruction of the charged B, which is quite difficult. For seeing asymmetries, fixed target machines, such as TEV II or UNK, may have some advantages over hadron colliders. Both types of machines produce enormous numbers of B's, and both have quite large backgrounds. However, in fixed target experiments, the produced B's are quite boosted, so that they travel a considerable distance before decaying. This will help in reducing some of the background. For example, experiment E771 at Fermilab has suggested looking for $B_d \to \Psi X$ [26]. One background problem comes from Ψ's produced

at the vertex. However, since the B's are boosted, it is possible to look for $\mu^+\mu^-$ pairs coming from a secondary vertex, which is a clear signal of a Ψ coming from a B decay. Nevertheless, it is not yet certain whether the background can be reduced sufficiently to see clear evidence for CP violation.

Regardless of which machine is used, the number of B's required to see CP violation is quite large. The effective branching ratios (which include efficiencies for detecting secondary decays) are all of order 10^{-5}. To see CP violation at a 3σ level requires at least 100 B's. And the tagging will cost at least a factor of 10. Therefore the observation of CP violation will require at least 10^8 $B\overline{B}$ pairs. Although this number is quite large, it is quite typical of all of this type of time-integrated CP violating asymmetries. The one consolation is that the situation would be worse if the asymmetries were smaller than 10%. Fortunately, as Fig. 5 shows, the standard model appears to favour large asymmetries.

4.4 Time-dependent CP Asymmetries

Finally, there is the possibility of time-dependent CP asymmetries [27]. The probability of obtaining a final CP eigenstate f at time t for a beam which at $t = 0$ was pure B^0 is

$$N_f(t) = N_f(0)e^{-\Gamma t}\left[1 - {\rm Im}\lambda_f \sin\Delta m t\right] ; \quad (34)$$

For $\overline{B^0}(t)$, it is

$$N_f(t) = N_f(0)e^{-\Gamma t}\left[1 + {\rm Im}\lambda_f \sin\Delta m t\right] . \quad (35)$$

First of all, if the time development of such a decay, for either case, were measured, a simple deviation from an exponential would signal CP violation. More importantly, however, there can be some quite spectacular effects. In Fig. 6a are shown the two curves for $B_d(\overline{B_d}) \to f$ ($f = \Psi K_S$, for instance), for the ARGUS/CLEO result $x_d = 0.70$, and ${\rm Im}(\lambda_f)$=0.3.

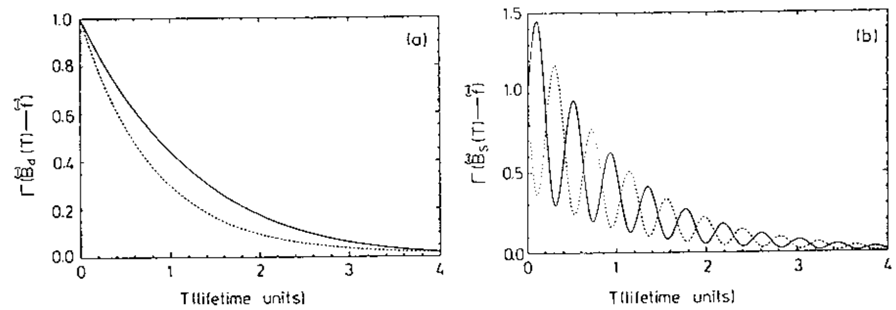

Fig. 6: The time dependence for $B \to f$ (dotted line) and $\overline{B} \to f$ (solid line) are shown: (a) $B_d(\overline{B_d}) \to f_d$, $x_d = 0.70$, ${\rm Im}\lambda_f = 0.3$, (b) $B_s(\overline{B_s}) \to f_s$, $x_s = 15.0$, ${\rm Im}\lambda_f = -0.6$.

Depending on the detector, it might be possible to separate the two curves, although this could be difficult. However, for the B_s system, the effects can be extremely large. Fig. 6b contains the graphs for $B_s(\overline{B_s}) \to f$ (e.g. $f = \rho K_S$) for $x_s = 15$ and $\mathrm{Im}(\lambda) = -0.6$. Here the differences between the two curves are enormous, and because of the large value of x_s, there are many oscillations within a few lifetimes.

Experimentally, there are some quite difficult problems, of course. To get the time dependence of the B's, extremely good vertex resolution is required. Furthermore, as written, these decays occur in the rest frame of the decaying B. The transformation to this frame requires complete reconstruction of the B, and with very good energy resolution. Finally, these decays also need tagging, and the rates are, as ever, quite small. Therefore, for the same reasons as in the time-integrated case, the number of $B\overline{B}$ pairs needed to see CP violation via time-dependent measurements is at least 10^8.

There are several possibilities for such experiments. The most important requirement is simply that the B travel a significant average distance before decaying, in order to be able to obtain reasonable time resolution. One possibility is to look at $B\overline{B}$ pairs produced at a Z factory [28]. Here the average decay length is a few millimeters. In addition, with polarization, the forward-backward asymmetry could be used to separate B and $\overline{B}$. Secondly, fixed target machines could also be used for such time-dependent measurements. For example, at TEV II, a B travels an average of 7000 microns before decaying, while at UNK, it could travel up to several centimeters. Finally, there is the possibility of using an asymmetric e^+e^- collider at the $\Upsilon(4s)$ [29]. Although the $B_d\overline{B}_d$ pair is produced essentially at rest in the centre-of-mass frame, the asymmetric energies give the B's a boost in the lab frame. Therefore, time-dependent measurements may be possible.

5. Summary and Conclusions

In conclusion, there are a number of possibilities for the observation of CP violating phenomena in the B system. Lepton asymmetries are predicted to be quite small in the standard model but should still be searched for as evidence of new physics. CP violation due to final state interactions is rather easy to see experimentally but, because of hadronic uncertainties, would be difficult to interpret in terms of implications for the CKM matrix. Within the standard model, the most promising possibility is looking for CP asymmetries in nonleptonic decays. There are two ways to search for these, using time-integrated and time-dependent means. In the time-integrated case, there are three classes of such asymmetries – B_d decays, both Cabibbo allowed and Cabibbo suppressed, and Cabibbo suppressed B_s decays. The CP asymmetries for B_d decays are predicted to be rather large. However, due to the (expected) large value of x_s, the asymmetries for the B_s decays should be quite small. Therefore, in the standard model, decays of B_d's are the best place to search for such CP asymmetries. Time-dependent methods look for differences in the

time distributions of B and $\overline{B}$ mesons decaying to a final state f. Depending on the parameters of the CKM matrix, it may or may not be possible to see such differences in the decays of B_d mesons. However, decays of B_s mesons should yield spectacular effects. Regardless of whether time-integrated or time-dependent methods are used, the number of $B\overline{B}$ pairs required to see a CP asymmetry at the 3σ level is at least 10^8. Therefore the observation of CP violation in the B system will take a lot of work. But the reward, namely the possibility of determining whether or not the CKM matrix explains CP violation, is most certainly worth it.

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