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RARE B DECAYS AND CP VIOLATION*

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Abstract

We review the physics motivation for studying rare B decays and the increasing possibility that CP violation can be experimentally observed in the B meson system.

Introduction

We are interested in studying rare B decays for all the standard, nonstandard reasons: looking for flavor changing neutral currents, trying to find evidence — even indirect evidence from their virtual presence — for a fourth generation or supersymmetric partners of the known particles, *etc.* We are interested in studying CP violation in B decays for the same reason that CP violation is studied elsewhere: establishing its origin and character. In particular, we want to know whether it is due to a phase in the quark mixing matrix, *i.e.*, a mismatch between quark mass eigenstates and quark weak eigenstates, or comes from physics at a very much higher scale, *e.g.*, as a phase difference between the left-handed and right-handed sectors in a left-right symmetric electroweak gauge theory.

As we have just noted, the standard model allows for CP violation in the form of a phase originating in the quark mixing matrix, the Kobayashi–Maskawa (K–M) matrix.[1] When there are three generations of quarks and leptons, there is one CP violating phase and any difference of rates between a given process and its CP conjugate process has the form

$$\Gamma - \bar{\Gamma} \;\propto\; \text{coef.} \times \; s_1^2 s_2 s_3 s_\delta c_1 c_2 c_3 \quad , \tag{1}$$

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where we employ for definiteness the original parametrization of the matrix[1] in terms of three angles θ_i with $i = 1,2,3$, plus a phase δ and $s_\delta = \sin\delta$, $s_i = \sin\theta_i$ and $c_i = \cos\theta_i$. Our present experimental knowledge allows us to make the approximation: $c_1 c_2 c_3 \approx 1$, which is good to an accuracy of a few percent.

The combination of sines and cosines of K–M angles that occurs in Eq. (1) is mandatory for a CP violating effect with three generations. It is precisely this combination of factors that occurs in the determinant of the commutator of mass matrices introduced by Jarlskog,[2] to formulate a general condition for CP violation, if her basis-independent condition is restated in the K–M parametrization. We see explicitly from Eq. (1) that the presence of non-zero mixing for all three generations is required in order to have a CP violating effect. This is not surprising; we know that with only two generations there is no CP violation from the quark mixing matrix (all the potential phases can be absorbed into the quark fields) and this is exactly the situation we would be in if we set one of the mixing angles to 0 or $\pi/2$ and decoupled one of the generations from the other two.

When we form a CP violating asymmetry we divide a difference in rates by their sum:

$$\text{Asymmetry} = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} \quad . \tag{2}$$

If we do this for K decay, the decay rates for the dominant hadronic and leptonic modes all involve a factor of s_1^2, *i.e.*, essentially the Cabibbo angle squared. A CP violating asymmetry will then have the general dependence on K–M factors:

$$\text{Asymmetry}_{K\ Decay} \propto s_2 s_3 s_\delta \quad . \tag{3}$$

The right-hand-side is of order 10^{-3} (see the discussion below). This is both a theoretical plus and an experimental minus. The theoretical good news is that CP violating asymmetries in the neutral K system are naturally at the 10^{-3} level, in agreement with the measured value of $|\epsilon|$. The experimental bad news is that, no matter what the K decay process, it is always going to be at this level, and therefore difficult to get at experimentally with the precision necessary to sort out the standard model explanation of its origin from other explanations.

Note also that because CP violation must involve all three generations while the K has only first and second generation quarks in it (and its decay products only involve first generation quarks), CP violating effects must come about through heavy quarks in loops. There is no CP violation arising from tree graphs alone.

This is not the case in B decay (or B mixing and decay). First, the decay rate for the leading decays is very roughly proportional to s_2^2, which happens to be much smaller than the corresponding quantity (s_1^2) in K decay. But more importantly, we can look at decays which have rates that are K–M suppressed by factors of $(s_1 s_2 s_3)^2$ or $(s_1 s_3)^2$, just to choose two examples. By choosing particular decay modes, it is then possible to have asymmetries which behave like

$$\text{Asymmetry}_{B\ Decay} \propto s_\delta \quad . \tag{4}$$

With luck, this could be of order unity! Note, though, that we have to pay the price of CP violation somewhere. That price, the product $s_1^2 s_2 s_3 s_\delta$, is given in the CP violating difference of rates in Eq. (1). The K–M factors either are found in the basic decay rate, resulting in a very small branching ratio, or they enter the asymmetry, which is then correspondingly small. This is a typical pattern: the rarer the decay, the bigger the potential asymmetry. The only escape from this pattern comes from outside of K–M factors: to find a decay mode where the coefficient of the right-hand-side of Eq. (1) is large (because of a particular matrix element, or the value of m_t, or . . .).

The fact that asymmetries in K and B decay can be different by orders of magnitude is part and parcel of the origin of CP violation in the standard model. It "knows" about the quark mass matrices and can tell the difference between a b quark and an s quark. This is entirely different from what we expect in general from explanations of CP violation that come from very high mass scales, as in the superweak model or in left-right symmetric gauge theories. Then, all quark masses are negligible compared to the new, very high mass scale. Barring special provisions, there is no reason why such theories would distinguish one quark from another; we expect all CP violating effects to be roughly of the same order, namely that already observed in the neutral K system.

Over the past year, there have been several experimental results which bear on the likelihood that the standard model contains the explanation of CP violation and that it can be observed in the neutral B system. But before reviewing these experimental developments and their theoretical impact, I want to briefly survey the situation regarding rare B decays.

Rare B Decays

The benchmark process in rare B decays is $B \to K\mu\bar{\mu}$. In the standard model this decay proceeds through an "electromagnetic penguin" diagram and should occur with a branching ratio of a few times 10^{-6}. There does not seem to be any reason to expect important competition from long range effects and this process should be a clean test of one loop effects in the standard model.[3] The presence of a fourth generation[4] could increase the branching ratio appreciably to perhaps a few times 10^{-5}.

The same basic one-loop diagram can lead to a real photon and result in the decay $b \to s + \gamma$ at the quark level, or $B \to K^* + \gamma$, $B \to K^{**} + \gamma$, *etc.* at the hadron level. Here QCD corrections are absolutely critical: They change the GIM suppression in the amplitude from being in the form of a power law, $(m_t^2 - m_c^2)/M_W^2$, to the softer form of a logarithm, $ln(m_t^2/m_c^2)$. This corresponds to an enhancement by one to two orders of magnitude[5–7] over the rate expected from the simplest one-loop electroweak graph.[8]

The inclusive process at the quark level, $b \to s\gamma$, should occur with a branching ratio of roughly[3] 10^{-3}; exclusive modes like $B \to K^{*}\gamma$ and $B \to K^{**}\gamma$ are estimated at 5 to 10% of this.[5] Again a fourth generation could enhance this rate by an order of magnitude or so.[9] The extension to a supersymmetric world is more interesting. The obvious new diagrams come from putting the supersymmetric partners of the quarks and the W in the loop of the "electromagnetic penguin" diagram. Much more important,[10] however, is the transition from a "penguin" to a "penguino," the "penguin" diagram involving a gluino and a squark. Because it involves strong interaction couplings rather than weak ones, it competes (and interferes) with the QCD enhanced "electromagnetic penguin" and produces a branching ratio of order a few times 10^{-3}.

Turning away from one-loop processes, the decay $\bar{B}^{-} \to \tau^{-}\nu_{\tau}$ is predicted to occur at the level of a few times 10^{-5}. It would permit the direct measurement of the parameter f_B, which is an ingredient of the theoretical expression for ΔM_B (which results in $B - \bar{B}$ mixing).

Other potential rare decays that are commonly considered are those that are forbidden in the standard model.[11] Whereas most limits on flavor changing neutral currents involve first and second generation quarks and/or leptons, $B \to \mu\tau$ and $B \to K\mu\tau$ involve flavor changing neutral currents which connect the second and third generations. Some attempts to understand the origin of generations of quarks and leptons and/or the size of the elements of the K–M matrix predict the existence of these processes. For example, with horizontal gauge bosons it is possible to build a model where some of these processes occur at the level of $\sim 10^{-5}$ in branching ratio without contradicting existing experimental data.[11] However, something below 10^{-9} seems a more typical level at which to expect them, if they occur at all.

CP Violation

At the present time the three angles and one phase of the three generation KM matrix are limited by direct measurements of the *magnitudes* of the KM matrix elements $V_{ud}, V_{us}, V_{cd}, V_{cs}, V_{cb}$, and bounds on the magnitude of V_{ub}. This determines two of the angles (or combinations of the angles) fairly well, and bounds a third one.

Information on the CP violating phase comes about in two ways. First, there is an indirect chain: information on the magnitude of V_{td} can be extracted from the magnitude of $B-\bar{B}$ mixing (given m_t and hadronic matrix elements) and inserted in a relation that comes from unitarity and ties it to V_{cb}, V_{us}, and V_{ub}. Knowledge of the magnitudes of these K–M matrix elements allows us to gain information on the phase. The tightness of this constraint depends on the relative magnitudes of these quantities and the accuracy with which they are known. Given present accuracies and theoretical uncertainties in the extraction of some of the K–M matrix elements, this constraint is generally a fairly loose one.

A second and more direct way to get at the phase involves the one well-measured CP violation parameter, ϵ, in the neutral K system. It is assumed that ϵ arises from short distance effects, *i.e.*, the box diagram with virtual c and t quarks. This gives the relation:

$$\begin{aligned}\epsilon \approx \frac{e^{i\pi/4}}{\sqrt{2}} \frac{BG_F^2 f_K^2 m_K}{6\pi^2 \Delta M_K} \\ \times s_1^2 s_2 s_3 s_\delta[-\eta_1 m_c^2 + \eta_2 s_2(s_2 + s_3 c_\delta) m_t^2 + \eta_3 m_c^2 \ell n(m_t^2/m_c^2)] \quad .\end{aligned} \tag{5}$$

If everything else in this relation were known (which it is not), we would have a direct handle on the phase δ. The factors η_1, η_2, and η_3 are due to strong interaction (QCD) corrections. They are calculable and have the values 0.7, 0.6, and 0.4, respectively, given a renormalization scale of a few hundred MeV and typical quark masses.[12] Less well-determined is the infamous parameter B, which is the ratio of the actual value of the matrix element between K^0 and $\bar{K}^\circ$ states of the operator composed of the product of two V-A neutral, strangeness changing currents divided by the value of the same matrix element obtained by inserting the vacuum between the two currents. If we insert known experimental quantities, Eq. (5) becomes

$$|\epsilon| \approx \frac{0.314}{\mathrm{GeV}^2}\, B\; s_2 s_3 s_\delta \left[-\eta_1 m_c^2 + \eta_2 s_2(s_2 + s_3 c_\delta) m_t^2 + \eta_3 m_c^2 \ell n(m_t^2/m_c^2)\right] \quad . \tag{6}$$

Equations (5) and (6), as written, are strictly valid when $m_t^2 \leq M_W^2$, but numerical evaluation of the correct expression,[13] which we use in the analysis that follows, shows that even for $m_t \approx M_W$ the changes in the coefficients of the last two terms in brackets are not large.

As we have already explained, the factor $s_1^2 s_2 s_3 s_\delta$ must appear in Eq. (5); it does. Our present knowledge of the elements of the K–M matrix permits the placing of an upper bound[14] on the quantity $s_2 s_3 s_\delta$ of about 2.5×10^{-3}. The parameter B has a long history of calculation and re-calculation, but a reasonable range seems to be

$$1/3 < B < 1 \quad .$$

The constraint on the mixing angles coming from ϵ and $B - \bar{B}$ mixing then depends on what we assume for the quantities B and m_t, as well as on the still uncertain value for $b \rightarrow u/b \rightarrow c$. If $m_t = 45$ GeV, then the magnitude of ϵ and the "large" observed[15] $B - \bar{B}$ mixing push the KM matrix elements into a corner: V_{ub} and V_{td} must be as large as possible, the phase is pushed beyond 90° and toward 180°, and B must be near the upper end of its allowed range. In the analysis of Harari and Nir[16] the phase $\delta' \approx 150°$ and

$$0.75 \times 10^{-3} \lesssim s_2 s_3 s_\delta \lesssim 1.25 \times 10^{-3} \tag{7}$$

is rather narrowly constrained.

As we go to larger values of m_t, a bigger range of angles is allowed. Increasing m_t to 60 GeV, we can have (for $B \approx 1/3$) the quantity $s_2 s_3 s_\delta \approx 2.5 \times 10^{-3}$, its maximum allowed value independent of m_t. As m_t increases still further, the constraint in Eq. (6) due to $|\epsilon|$ is seen to generally favor smaller values of $s_2 s_3 s_\delta$.

The parameter ϵ', which measures CP violation in the K decay amplitude itself, arises in the standard model from diagrams involving heavy quarks in loops, the so-called "penguin" diagrams. By inserting experimentally measured quantities, the contribution to ϵ' from the "penguin" operator contribution to $K \to \pi\pi$ can be written[17]

$$\epsilon'/\epsilon = 6.0\ s_2 s_3 s_\delta \left(\frac{Im\widetilde{C}_6}{-0.1}\right) \left(\frac{<\pi\pi|Q_6|K^0>}{1.0\ GeV^3}\right) \left(1 - \Omega_{\eta,\eta'} + \Omega_{em}\right) \quad , \tag{8}$$

where Q_6 is the "penguin" operator in the short distance expansion of the strangeness-changing weak Hamiltonian,[18] $Im\widetilde{C}_6$ is the imaginary part of the corresponding Wilson coefficient with the K–M factor taken out, and $\Omega_{\eta,\eta'}$ and Ω_{em} are corrections due to $\pi^0 - \eta$ and $\pi^0 - \eta'$ mixing, and to "electromagnetic penguins," respectively.

After various calculational mistakes were settled, the factor $(1 - \Omega_{\eta,\eta'} + \Omega_{em})$ may still result[19] in anything betweeen a $\sim 30\%$ decrease and a small increase in ϵ'/ϵ. The value of -0.1 for $Im\widetilde{C}_6$ is relatively stable from calculation to calculation if the renormalization scale is taken as a few hundred MeV, since the imaginary part depends on momentum scales from m_c to m_t where the short distance expansion is well justified. The value of the matrix element of Q_6 is much less certain. If it is large enough to explain the experimental magnitude of $A(K \to \pi\pi)$, *i.e.*, roughly 1 or 2 GeV^3, then, combined with the value of $s_2 s_3 s_\delta$ needed to fit $|\epsilon|$ (see above), it yields the prediction that ϵ'/ϵ is of order $+10^{-2}$. This was the basic observation in Ref. 18: If the "penguin" operator is to be an explanation of the $\Delta I = 1/2$ rule and thus the magnitude of $A(K \to \pi\pi)$, then ϵ'/ϵ should be at roughly the 1% level.

Over the past nine years there have been many calculations of ϵ'/ϵ. The prediction depends on the favorite values of the matrix element, of m_t, and of $s_2s_3s_\delta$ at the time. Because of this, one needs to be very careful in comparing the results of these calculations. This is particularly true with respect to the variation in the favorite value of m_t over the years. As m_t has risen, the predictions for ϵ'/ϵ have correspondingly gone down (because the constraint due to ϵ forces $s_2s_3s_\delta$ down as m_t goes up).[20]

This past year has seen two important new experimental results for ϵ/ϵ'. First came the preliminary result from a test run of the Fermilab experiment:[21]

$$\epsilon'/\epsilon = 3.5 \pm 3.0 \pm 2.0 \ \times 10^{-3} \quad ,$$

and then this past summer, the preliminary result from the CERN experiment[22]

$$\epsilon'/\epsilon = 3.5 \pm 0.7 \pm 0.4 \pm 1.2 \ \times 10^{-3} \quad .$$

Both experiments have the capability of eventually decreasing both their statistical and systematic error bars below the 10^{-3} level. We will have to wait and see if the central value of ϵ'/ϵ remains non-zero by many standard deviations when the combined error bars shrink to this level.

While we wait, we can ask in any case whether the present central value, if it persists, is consistent with the standard model. The answer is yes, particularly if the value of m_t is large.[23]

One perspective on this is gained by turning the situation around and instead of predicting ϵ'/ϵ, assuming that $\epsilon'/\epsilon = 3.5 \pm 1.4 \ \times 10^{-3}$, and then asking what combined Wilson coefficient, "penguin" matrix element, and electromagnetic corrections would produce such a result. In the future, when the experimental situation settles down with small error bars, this is what we will be doing: We will use ϵ'/ϵ to measure the magnitude of the "penguin" operator contribution to K decay, and then check how well this agrees with lattice gauge theory calculations of the same quantity.

If $m_t = 45$ GeV, there is not too much room to maneuver and still satisfy the constraint of getting the correct value of $|\epsilon|$. Using the limits in Eq. (7), Eq. (8) translates to

$$\left(\frac{Im\widetilde{C}_6}{-0.1}\right)\left(\frac{<\pi\pi|Q_6|K^0>}{1.0\ GeV^3}\right)(1-\Omega_{\eta,\eta'}+\Omega_{em}) = 0.47 \pm 0.19$$

for the biggest value allowed for $s_2 s_3 s_\delta$ in Eq. (7), and

$$\left(\frac{Im\widetilde{C}_6}{-0.1}\right)\left(\frac{<\pi\pi|Q_6|K^0>}{1.0\ GeV^3}\right)(1-\Omega_{\eta,\eta'}+\Omega_{em}) = 0.78 \pm 0.31$$

for the smallest. The corresponding values for $m_t = 60$ GeV are 0.23 ± 0.09 and 1.10 ± 0.44, respectively, as the range of allowed values of $s_2 s_3 s_\delta$ has opened up considerably.[24] Choosing still larger values of m_t generally makes more of ϵ come from the term involving m_t^2 in Eq. (6); if we keep $B > 1/3$, the maximum value of $s_2 s_3 s_\delta$ gets smaller. For example, when $m_t = 100$ GeV,

$$\left(\frac{Im\widetilde{C}_6}{-0.1}\right)\left(\frac{<\pi\pi|Q_6|K^0>}{1.0\ GeV^3}\right)(1-\Omega_{\eta,\eta'}+\Omega_{em}) = 0.40 \pm 0.15$$

for the biggest allowed value of $s_2 s_3 s_\delta$ and

$$\left(\frac{Im\widetilde{C}_6}{-0.1}\right)\left(\frac{<\pi\pi|Q_6|K^0>}{1.0\ GeV^3}\right)(1-\Omega_{\eta,\eta'}+\Omega_{em}) = 2.1 \pm 0.8$$

for the smallest.

The outcome of this exercise, recalling that a value for the matrix element of the "penguin" operator of 1 to 2 GeV^2 is large enough to make it a plausible explanation for the $\Delta I = 1/2$ rule, is that the "penguin" contribution to the $K \to \pi\pi$ amplitude is unlikely to be negligible. It may well be very important. It would seem that the wind is blowing in the direction of the standard model and the explanation of CP violation in terms of the K-M phase.

CP Violation in B Decay

The possibilities for observation of CP violation in B decays are much richer than for the neutral K system. The situation is even reversed, in that for the B system the variety and size of CP violating asymmetries in decay amplitudes far overshadows that in the mass matrix.[25]

To start with the familiar, however, it is useful to consider the phenomenon of CP violation in the mass matrix of the neutral B system. Here, in analogy with the neutral K system, one defines a parameter ϵ_B. It is related to p and q, the coefficients of the B° and $\bar{B}^\circ$, respectively, in the combination which is a mass matrix eigenstate by

$$\frac{q}{p} = \frac{1-\epsilon_B}{1+\epsilon_B} \quad .$$

The charge asymmetry in $B^\circ \bar{B}^\circ \to \ell^\pm \ell^\pm + X$ is given by[26]

$$\frac{\sigma(B^\circ \bar{B}^\circ \to \ell^+\ell^+ + X) - \sigma(B^\circ \bar{B}^\circ \to \ell^-\ell^- + X)}{\sigma(B^\circ \bar{B}^\circ \to \ell^+\ell^+ + X) + \sigma(B^\circ \bar{B}^\circ \to \ell^-\ell^- + X)} = \frac{|\frac{p}{q}|^2 - |\frac{q}{p}|^2}{|\frac{p}{q}|^2 + |\frac{q}{p}|^2} \tag{9}$$

$$= \frac{\mathrm{Im}(\Gamma_{12}/M_{12})}{1+\frac{1}{4}|\Gamma_{12}/M_{12}|^2} \tag{10}$$

where we define $< B^\circ|H|\bar{B}^\circ >= M_{12} - \frac{i}{2}\Gamma_{12}$. The quantity $|M_{12}|$ is measured in $B-\bar{B}$ mixing and we may estimate Γ_{12} by noting that it gets contributions from B° decay channels which are common to both B° and $\bar{B}^\circ$, *i.e.*, K–M suppressed decay modes. This causes the charge asymmetry for dileptons most likely to be in the ballpark of a few times 10^{-3}, and at best 10^{-2}. For the foreseeable future, we might as well forget it experimentally.

Turning now to CP violation in decay amplitudes, in principle this can occur whenever there is more than one path to a common final state. For example, let us consider decay to a CP eigenstate, f, like ψK_s°. Since there is substantial $B^\circ - \bar{B}^\circ$ mixing, one can consider two decay chains of an initial B° meson:

$$\begin{array}{ccc} B^\circ \to B^\circ & \searrow & \\ & & f \quad , \\ B^\circ \to \bar{B}^\circ & \nearrow & \end{array}$$

where f is a CP eigenstate. The second path differs in its phase because of the mixing of $B^\circ \to \bar{B}^\circ$, and because the decay of a $\bar{B}$ involves the complex conjugate of the K-M factors involved in B decay. The strong interactions, being CP invariant, give the same phases for the two paths. The amplitudes for these decay chains can interfere and generate non-zero asymmetries between $\Gamma(B^\circ(t) \to f)$ and $\Gamma(\bar{B}^\circ(t) \to f)$. Specifically,

$$\Gamma(\bar{B}^\circ(t) \to f) \sim e^{-\Gamma t}\left(1 - \sin[\Delta m\ t] Im\left(\frac{p}{q}\rho\right)\right) \tag{11a}$$

and

$$\Gamma(B^\circ(t) \to f) \sim e^{-\Gamma t}\left(1 + \sin[\Delta m\ t] Im\left(\frac{p}{q}\rho\right)\right) \quad . \tag{11b}$$

Here we have neglected any lifetime difference between the mass matrix eigenstates (thought to be very small) and set $\Delta m = m_1 - m_2$, the difference of the eigenstate masses, and $\rho = A(B \to f)/A(\bar{B} \to f)$, the ratio of the amplitudes, and we have used the fact that $|\rho| = 1$ when f is a CP eigenstate in writing Eqs. (11a) and (11b). From this we can form the asymmetry:

$$A_{\text{CP Violation}} = \frac{\Gamma(B) - \Gamma(\bar{B})}{\Gamma(B) + \Gamma(\bar{B})} = \sin[\Delta m\ t] Im\left(\frac{p}{q}\rho\right) \quad . \tag{12}$$

In the particular case of decay to a CP eigenstate, the quantity $Im\left(\frac{p}{q}\rho\right)$ is given entirely by the K–M matrix and is independent of hadronic amplitudes. However, to measure the asymmetry experimentally, one must know if one starts with an initial B° or $\bar{B}^\circ$, *i.e.*, one must "tag."

We can also form asymmetries where the final state f is not a CP eigenstate. Examples are $B_d \to D\pi$ compared to $\bar{B}_d \to \bar{D}\bar{\pi}$; $B_d \to \bar{D}\pi$ compared to $\bar{B}_d \to D\bar{\pi}$; or $B_s \to D_s^+ K^-$ compared to $\bar{B}_s \to \bar{D}_s^- K^+$. These is a decided disadvantage here in theoretical interpretation, in that the quantity $Im\left(\frac{p}{q}\rho\right)$ is now dependent on hadron dynamics.

It is instructive to look not just at the time - integrated asymmetry between rates for a given decay process and its CP conjugate, but to follow the time dependence,[27] as given in Eqs. (11a) and (11b). As a first example, Fig. 1 shows[28] the time dependence for the process $\bar{b} \to \bar{c}u\bar{d}$ (solid curve) in comparison to that for $b \to c\bar{u}d$ (dashed curve). At the hadron level this could be, for example, $B_d \to \bar{D}^-\pi^+$ in comparison to $\bar{B}_d \to D^+\pi^-$. The direct process is very much Kobayashi–Maskawa favored over that which is introduced through mixing, and hence the magnitude of the ratio of amplitudes, $|\rho|$, is very much greater than unity. The three parts of Fig. 1 show the situation for $\Delta m/\Gamma = 0.2$ (at the high end of theoretical prejudice before the ARGUS result[15] for B_d mixing), $\Delta m/\Gamma = 0.78$ (near the central value from ARGUS), and $\Delta m/\Gamma = 5$ (roughly the minimum value expected for the B_s in the three generation standard model, given the central value of ARGUS for B_d). In none of these cases are the dashed and solid curves distinguishable within "experimental errors" in drawing the graphs. This is simply because $|\rho|$ is so large that even with "big" mixing the second path to the same final state has a very small amplitude, and hence not much of an interference effect.

A much more interesting case is shown in Fig. 2 for the time dependence at the quark level for the process $\bar{b} \to \bar{c}c\bar{s}$ (solid curve) in comparison to that for $b \to c\bar{c}s$ (dashed curve). At the hadron level this could be, for example, B_d in comparison to $\bar{B}_d$ decaying to the same, (CP self-conjugate) final state, ψK_s°. As discussed before, $|\rho| = 1$

in this case. The advantages of having $\Delta m/\Gamma$ for the B_d° system as suggested by ARGUS (Fig. 2b) rather than previous theoretical estimates (Fig. 2a) are very apparent. When we go to mixing parameters expected for the B_s° system (Fig. 2c), the effects are truly spectacular. In fact, in this last case the time average asymmetry is washed out by the many oscillations in one lifetime and a study of the time dependence of the asymmetry is a necessity.

Figure 3 illustrates the opposite situation to that in Fig. 1; mixing into a big amplitude from a small one. We are explicitly comparing the quark level process $\bar{b} \to \bar{u}c\bar{d}$ (solid curve) to $b \to u\bar{c}d$ (dashed curve). At the hadron level this could be, for example, $B_d \to D^+\pi^-$ in comparison to $\bar{B}_d \to \bar{D}^-\pi^+$. The direct process is very much Kobayashi–Maskawa suppressed compared to that which occurs through mixing and hence the magnitude of the ratio of amplitudes, $|\rho|$, is very much less than unity. Here we have an example where too much mixing can be bad for you! As the mixing is increased (going from Fig. 3a to 3c), the admixed amplitude comes to completely dominate over the original amplitude, and their interference (leading to an asymmetry) becomes less important in comparison to the dominant term.

A second path to the same final state could arise in several other ways besides through mixing. For example, one could have two cascade decays that end up with the same final state, such as:

$$B_u^- \to D^\circ K^- \to K_s^\circ \pi^\circ K^-$$

and

$$B_u^- \to \bar{D}^\circ K^- \to K_s^\circ \pi^\circ K^- \quad .$$

Another possibility is to have spectator and annihilation graphs contribute to the same process.[29] Still another is to have spectator and "penguin" diagrams interfere. This latter possibility is the analogue of the origin of the parameter ϵ' in neutral K decay, but as discussed previously, there is no reason to generally expect a small asymmetry here. Indeed, with a careful choice of the decay process, large CP violating asymmetries are expected.

Note that not only do these routes to obtaining a CP violating asymmetry in decay rates not involve mixing, but they do not require one to know whether one started with a B or $\bar{B}$, *i.e.*, they do not require "tagging." These decay modes are in fact "self-tagging" in that the properties of the decay products (through their electric charges or flavors) themselves fix the nature of the parent B or $\bar{B}$.

Even with potentially large asymmetries, the experimental task of detecting these effects is a monumental one. When the numbers for branching ratios, efficiencies, *etc.* are put in, it appears that 10^7 to 10^8 produced B mesons are required to end up with a significant asymmetry (say, 3σ), depending on the decay mode chosen.[25] This is beyond the samples available today (of order a few times 10^5) or in the near future ($\sim 10^6$). On the other hand, it is possible to envision such samples at new electron-positron colliders, fixed target experiments, and at hadron colliders, especially the SSC.[25] A great deal of experimental work needs to be done to explore both technique and physics to achieve the goal of observing CP violation in the B system. A good start has already been made. With the excitement within the experimental community that has been growing over the past few years, it begins to seem likely that in the next five years we will see the experimental situation develop to the point that this physics is capable of being attacked.

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14. This is more easily seen in the parametrization of HARARI, H. & M. LEURER. 1986. Phys. Lett. **181B**: 123, where $[s_{23}s_{13}s_{\delta'}/s_{12}]_{HL} = [s_2s_3s_\delta]_{KM}$, and the maximum is obtained from $s_{\delta'} < 1$ and taking the experimental upper bounds on s_{23} and s_{13}.

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20. This is seen, for example, in Fig. 1 of Gilman and Hagelin, Ref. 17, where there is roughly a factor of two decrease in the predicted value of ϵ'/ϵ when m_t is increased from 30 to 55 GeV.

21. WINSTEIN, B. invited talk at the Division of Particles and Fields Meeting, Salt Lake City, January 14–17, 1987 (unpublished).

22. MANNELLI, I. invited talk at the International Symposium on Lepton and Photon Interactions at High Energies, Hamburg, July 27–31, 1987 and CERN preprint CERN-EP/87-177, 1987 (unpublished).

23. SHIFMAN, M. A. invited talk at the International Symposium on Lepton and Photon Interactions at High Energies, Hamburg, July 27–31, 1987 (unpublished) presents an affirmative answer also, but with smaller "error bars" on the theoretical uncertainties in the matrix element than I would venture.

24. In calculating the allowed range using Eq. (6), we allow not only the K–M matrix elements to vary within experimental and theoretical uncertainties, but also for m_c to lie between 1.3 and 1.7 GeV. The biggest value of $s_2 s_3 s_\delta$ is now 2.5×10^{-3}, as large as allowed independent of the constraint due to ϵ. Hence the value 0.23 ± 0.09 for the combination of Wilson coefficient, "penguin" operator matrix element, and electromagnetic corrections is the smallest allowed value corresponding to $\epsilon'/\epsilon = 3.5 \pm 1.4 \times 10^{-3}$. I thank H. Harari and Y. Nir for discussions on this point.

25. FOLEY, K. J. *et al.*, to be published in the Proceedings of the Workshop on Experiments, Detectors, and Experimental Areas for the Supercollider, Berkeley, California, July 7–17, 1987, and SLAC preprint SLAC–PUB–4426, 1987 (unpublished) review the current status of CP violation in B decay and give references to previous work.

26. PAIS, A. & S. B. TREIMAN. 1975. Phys. Rev. **D12:** 2744; OKUN, L. B. *et al.*. 1975. Nuovo Cim. Lett. **13:** 218.

27. The importance of this has been particularly emphasized by DUNIETZ, I. & J. L. ROSNER. 1986. Phys. Rev. **D34:** 1404.

28. These graphs were constructed by R. Kauffman, in accord with the paper of Dunietz and Rosner, Ref. 27, but with somewhat different parameters: $s_1 = 0.22, s_2 =$

$0.09, s_3 = 0.05$ and $\delta = 150°$ and the values of $\Delta M/\Gamma$ given in the text and figure captions.

29. This possibility has been particularly emphasized by CHAU, L. L. & H. Y. CHENG. 1985. Phys. Lett. **165B**: 429.

FIGURE CAPTIONS

1. The time dependence for the quark level process $\bar{b} \to \bar{c}u\bar{d}$ (solid curve) in comparison to that for $b \to c\bar{u}d$ (dashed curve). At the hadron level this could be, for example, $B_d \to \bar{D}^- \pi^+$ in comparison to $\bar{B}_d \to D^+\pi^-$. The three subgraphs correspond to (a) $\Delta m/\Gamma = 0.2$, (b) $\Delta m/\Gamma = 0.78$, and (c) $\Delta m/\Gamma = 5$.

2. The time dependence for the quark level process $\bar{b} \to \bar{c}c\bar{s}$ (solid curve) in comparison to that for $b \to c\bar{c}s$ (dashed curve). At the hadron level this could be, for example, $B_d \to \psi K_s^\circ$ (dashed curve) in comparison to $\bar{B}_d \to \psi K_s^\circ$ (solid curve). (The curves are interchanged for the ψK_s° final state because it is odd under CP.) The three subgraphs correspond to (a) $\Delta m/\Gamma = 0.2$, (b) $\Delta m/\Gamma = 0.78$, and (c) $\Delta m/\Gamma = 5$.

3. The time dependence for the quark level process $\bar{b} \to \bar{u}c\bar{d}$ (solid curve) in comparison to that for $b \to u\bar{c}d$ (dashed curve). At the hadron level this could be, for example, $B_d \to D^+\pi^-$ in comparison to $\bar{B}_d \to \bar{D}^-\pi^+$. The three subgraphs correspond to (a) $\Delta m/\Gamma = 0.2$, (b) $\Delta m/\Gamma = 0.78$, and (c) $\Delta m/\Gamma = 5$.

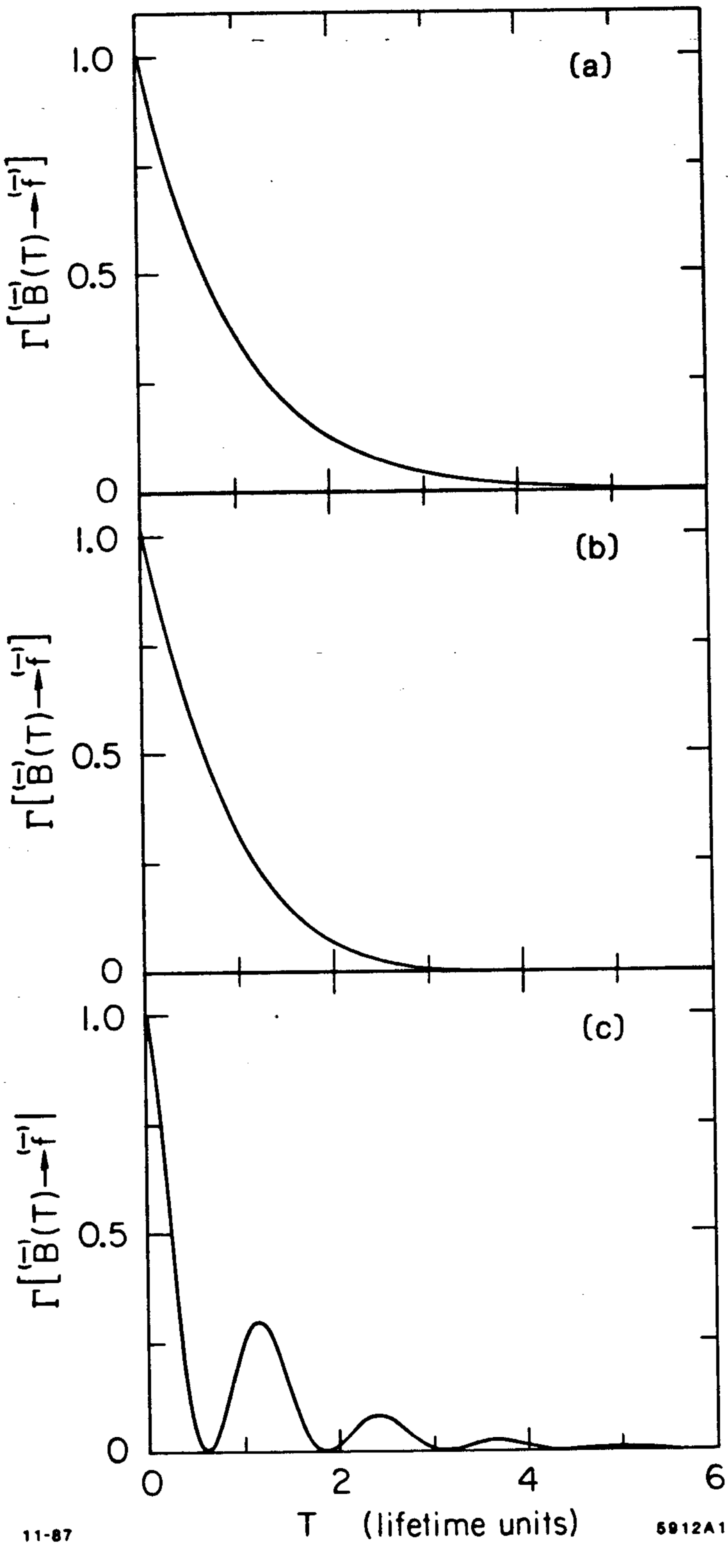

Fig. 1

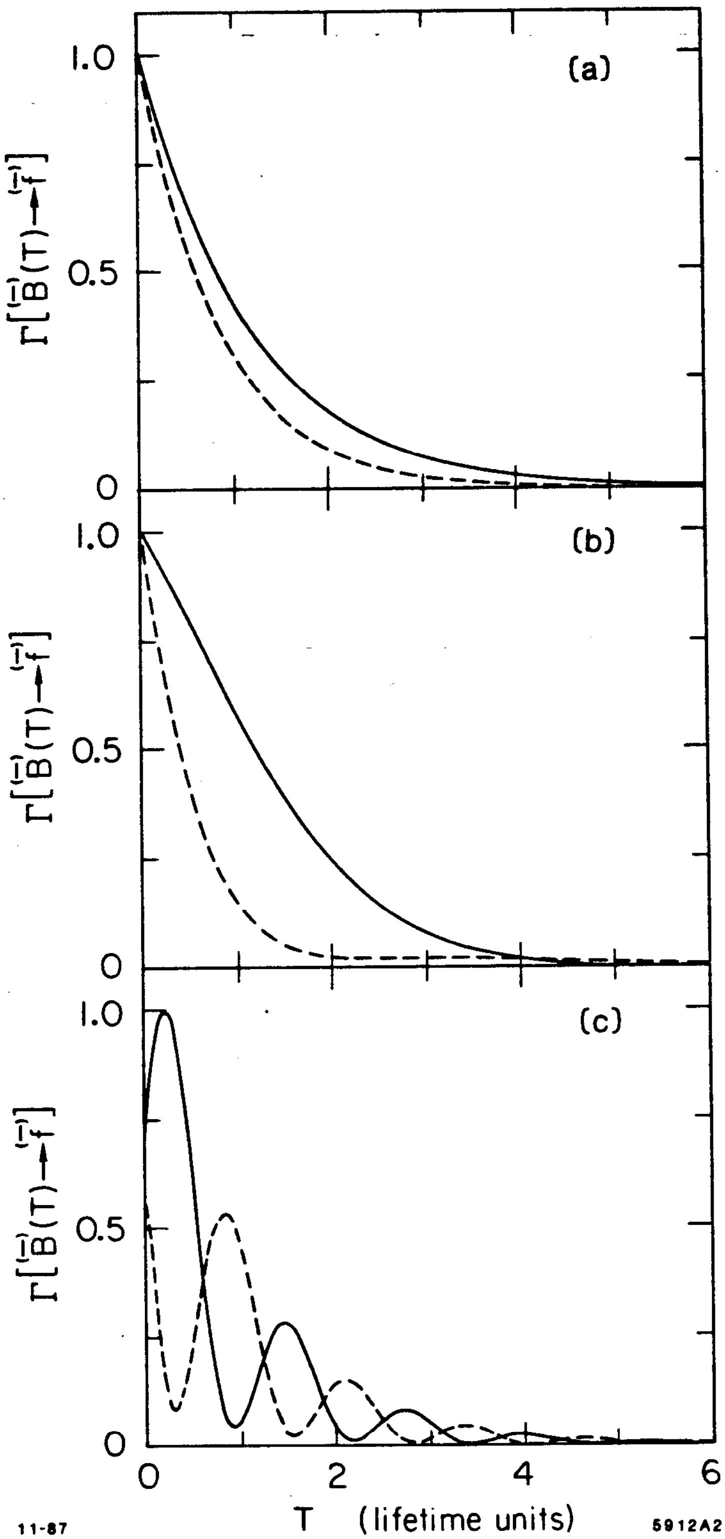

Fig. 2

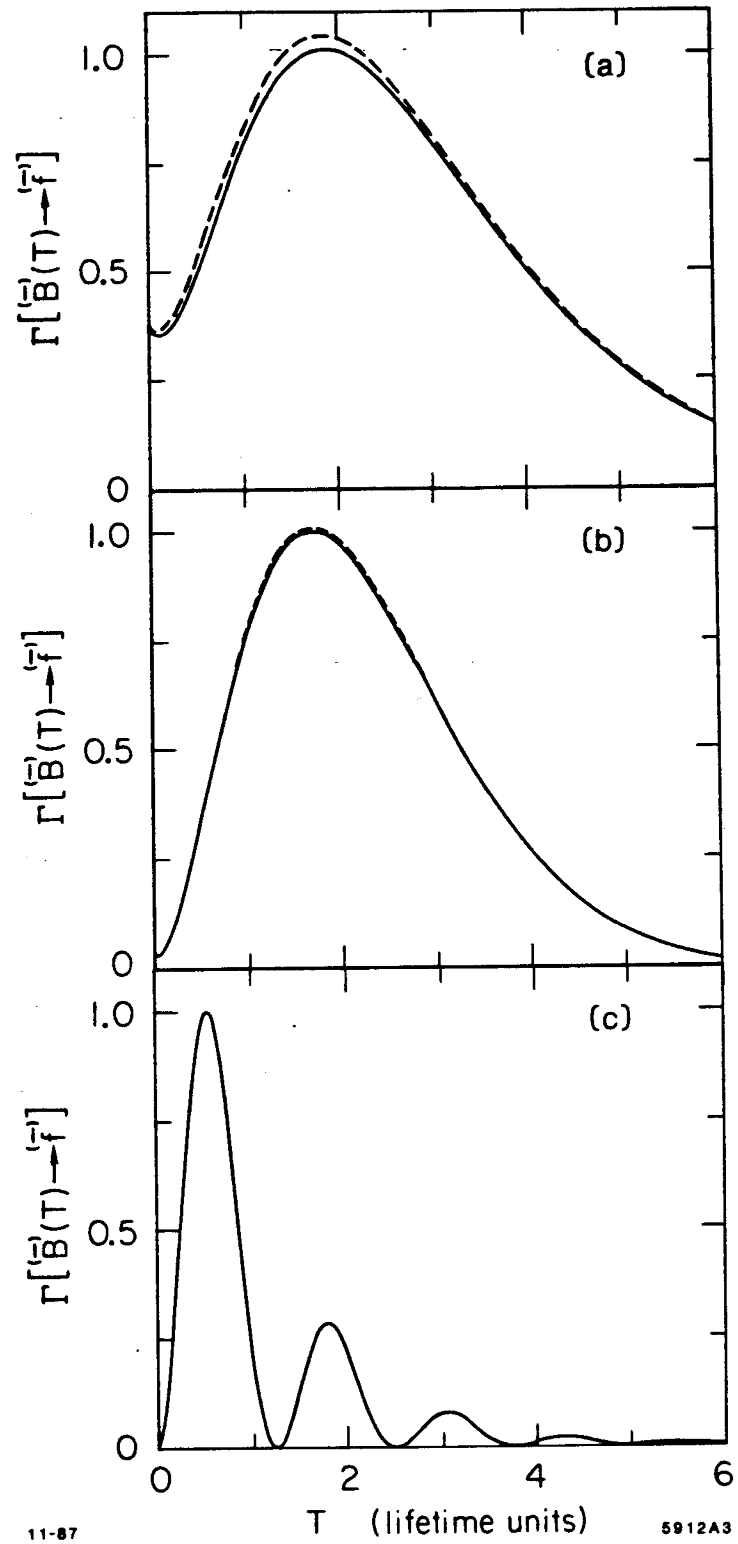

Fig. 3