# PROSPECTS IN $B$ PHYSICS* 

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#### Abstract

The status of B physics is reviewed with emphasis on the prospects for further developments, including the study of CP violating effects in the B meson system.


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## INTRODUCTION

The story of $B$ physics, or more properly the story of the $b$ quark, began at Fermilab 11 years ago with the discovery of the upsilon resonance. ${ }^{[1]}$ In the original paper, the peak near an invariant mass of 9.4 GeV was shown to be too broad to be due to a single resonance, given the resolution inherent in the spectrometer: The existence of at least two narrow states, and more probably three, was pointed out. Later experiments using hadron-hadron and electron-positron collisions were able to rcsolve the original peak into the $\Upsilon, \Upsilon^{\prime}$, and $\Upsilon^{\prime \prime}$ resonances. Furthermore, not only do the first three $\Upsilon$ states themselves form a narrow and clean system to study, but they decay radiatively into a set of other narrow states, $\chi_{b}$ and $\chi_{b}^{\prime}$.

Thus there is a whole set of related resonances around 10 GeV in mass. We can understand their quantum numbers, masses and many other properties if they are composed of a spin $1 / 2$ quark, the $b$ (or bottom or beauty) quark bound together with its corresponding antiquark, the $\bar{b}$. Each would have a mass of about 5 GeV . The set of such bottomonium states that would be expected is shown in Fig. 1, with a checkmark indicating those that are already found experimentally.

All the states of bottomonium that we discussed in the opening paragraph can decay via the strong or electromagnetic interaction either into a member of the bottomonium family or (by having the $b$ and $\bar{b}$ quarks annihilate) into " $b$-less" matter. When we reach the $\Upsilon^{\prime \prime \prime}$ or $\Upsilon(4 S)$ state, however, another process becomes kinematically available: dissociation (by the usual strong interactions) into two hadrons, one containing the $b$ quark and the other the $\bar{b}$. Indeed, the dominant decay mode of the $\Upsilon(4 S)$ is

$$
\Upsilon(4 S) \rightarrow B \bar{B}
$$

where the $B$ mesons which are produced each have a mass of $\sim 5.28 \mathrm{GeV}$ and can be a $B_{d}=\bar{b} d$ or $B_{u}=\bar{b} u$ bound state of a $b$ quark with a light $d$ or $u$ quark. The extra constraint of knowing the energy of the $B$ or $\bar{B}$ when one tunes an electron-positron colliding beam machine to operate on the $\Upsilon(4 S)$ has proven to
be an invaluable tool up to now in reconstructing $B$ mesons in exclusive modes. At something like 100 to 120 MeV higher in mass we expect to find the state $B_{s}=\bar{b} s$.

## WEAK DECAYS OF $B$ MESONS

The lightest particles containing one $b$ or $\bar{b}$ quark will be stable with respect to the strong and electromagnetic interactions. They can decay weakly, since emission of a $W^{-}$takes one from the lower to the upper components of the weak isospin doublets:

$$
\binom{u}{d^{\prime}}_{L} \quad\binom{c}{s^{\prime}}_{L} \quad\binom{t}{b^{\prime}}_{L}
$$

where the upper components are chosen to be the mass eigenstates $u, c$, and $t$, and the essential complication that the weak and mass eigenstates are not the same is entirely represented in terms of a matrix transformation ${ }^{[2]}$ operating on the lower components. It takes us from the mass cigenstatcs $(d, s$, and $b)$ to the weak eigenstates ( $d^{\prime}, s^{\prime}$, and $b^{\prime}$ ), and is represented by the unitary ( $\mathrm{K}-\mathrm{M}$ ) matrix:

$$
\left(\begin{array}{c}
d^{\prime}  \tag{1}\\
s^{\prime} \\
b^{\prime}
\end{array}\right)=\left(\begin{array}{lll}
V_{u d} & V_{u s} & V_{u b} \\
V_{c d} & V_{c s} & V_{c b} \\
V_{t d} & V_{t s} & V_{t b}
\end{array}\right)\left(\begin{array}{c}
d \\
s \\
b
\end{array}\right)
$$

As $V$ is a $3 \times 3$ unitary matrix, it is specified by nine parameters. When we take into account that cach of the six quark fields can be changed by a phase with no change in the physics, but that a common phase change of all quark fields would not change the matrix $V$, we are left with $9-(6-1)=4$ parameters. These can be considered as three mixing angles and one phase, with a non-zero value of this phase inducing CP violation. More on this later.

At the present time the three angles and one phase of the three generation $\mathrm{K}-\mathrm{M}$ matrix are limited by direct measurements of the magnitudes of the $\mathrm{K}-\mathrm{M}$ matrix elements $V_{u d}, V_{u s}, V_{c d}, V_{c s}, V_{c b}$, and bounds on the magnitude of $V_{u b}$. This determines two of the angles (or combinations of the angles) fairly well, and bounds
a third one. The key experimental restrictions can be stated as ${ }^{[3]}$

$$
\begin{equation*}
\left|V_{u s}\right|=0.221 \pm 0.002 \tag{2}
\end{equation*}
$$

from strange particle decays, and ${ }^{[4]}$

$$
\begin{equation*}
\left|V_{c b}\right|=0.046 \pm 0.010 \tag{3}
\end{equation*}
$$

from the $b$ lifetime (see below), and

$$
\begin{equation*}
0.07 \leq\left|V_{u b} / V_{c b}\right| \leq 0.20 \tag{4}
\end{equation*}
$$

where the upper bound comes from the absence of a signal for $b \rightarrow u+\ell \bar{\nu}_{\ell}$ in semileptonic $B$ decay and the lower bound from the ARGUS observation ${ }^{[5]}$ of charmless final decay products that include baryons. Specifically, they find $B\left(B^{-} \rightarrow p \bar{p} \pi^{-}\right)=5.2 \pm 1.4 \pm 1.9 \times 10^{-4}$ and $B\left(B^{0} \rightarrow p \bar{p} \pi^{+} \pi^{-}\right)=6.0 \pm 2.0 \pm$ $2.2 \times 10^{-4}$ and have performed numerous checks to eliminate the possibility of a systematic error in the analysis or to have another interpretation of the origin of these final states.
'The CLEO collaboration, however, on the basis of an enlarged data sample sces no evidence for these modes; they only quote upper limits. ${ }^{[6]}$ They do scc other decay modes, like $B \rightarrow D \pi \rightarrow K \pi \pi$, whose product branching ratios are at or below the ARGUS numbers, so there is no lack of sensitivity at the desired level. The conflict between the two experiments is several standard deviations.

With more data and more data analysis coming soon, we wait for a resolution of the difference between experimental results. A quantitative result for $V_{u b}$ may have to await the observation of the semileptonic decays $B \rightarrow \pi e \nu$ and $B \rightarrow \rho e \nu$.

The small magnitude of $\left|V_{u b} / V_{c b}\right|$ reflects the dominance of decays of the $b$ quark of the form $b \rightarrow c+d \bar{u}$. Typically, each of the exclusive hadronic decay channels which correspond to this process at the quark level has a branching ratio
of a few times $10^{-3}$, rather than the few times $10^{-2}$ for charm. There exists some fair theoretical understanding of their rough magnitude. ${ }^{[7]}$ For processes which involve $b \rightarrow u$ at the quark level, the corresponding typical hadronic branching ratios or limits upon them are at the few times $10^{-4}$ level.

In addition to changing the strength of the usual four-fermion effective weak interaction, there are additional operators introduced by QCD, the "penguins". In bottom decay it is possible to have particular quark level processes which are suppressed by Kobayashi-Maskawa angles and are such that "penguin" diagrams give rise to contributions comparable to, or maybe even larger than, those of ordinary tree level graphs. ${ }^{[8]}$ Figure 2 shows a possible example. The "penguin" diagram contributes an effective Hamiltonian density:

$$
\begin{equation*}
\mathcal{H}=\frac{G_{F}}{\sqrt{2}} \frac{\alpha_{s}}{12 \pi} V_{t b} V_{t s}^{*} \ln \left(m_{t}^{2} / m_{c}^{2}\right) \bar{s} \gamma_{\mu}\left(1-\gamma_{5}\right) \lambda^{a} b \bar{u} \gamma^{\mu} \lambda^{a} u \tag{5}
\end{equation*}
$$

whereas the usual spectator diagram (aside from short-distance QCD correction factors, $c_{ \pm}$, which are close to unity) corresponds to

$$
\begin{equation*}
\mathcal{H}=\frac{G_{F}}{\sqrt{2}} V_{u b} V_{u s}^{*} \bar{u} \gamma_{\mu}\left(1-\gamma_{5}\right) b \bar{s} \gamma^{\mu}\left(1-\gamma_{5}\right) u \tag{6}
\end{equation*}
$$

The "penguin" loses to the spectator graph because of the $\frac{\alpha_{s}}{12 \pi} \ln \left(m_{t}^{2} / m_{c}^{2}\right)$ that arises from having one loop and the couplings due to the presence of the gluon, but it wins by at least a factor of 20 in amplitude because of the Kobayashi-Maskawa factor $V_{t b} V_{t s}^{*}$ (which involves a combination of zero and one generation jumps), as compared to $V_{u b} V_{u s}$, (which involves a combination of two and one generation jumps). Depending in part on the matrix elements in particular processes, it could well be that the spectator graph gives the lesser of the two contributions. Then, for example, in the decays $B_{d} \rightarrow K^{+} \pi^{-}$or $B_{s} \rightarrow \phi \rho$ the "penguin" contribution may be dominant. ${ }^{[9]}$

It is possible that the inclusive rate for $b \rightarrow s \bar{q} q$ is of order $1 \%$ and exclusive modes a few percent of that. The experimental limits on exclusive channels ${ }^{[10,11]}$
are beginning to reach the appropriate level. In particular, the CLEO limit ${ }^{[11]}$ on the branching ratio for $B^{0} \rightarrow K^{+} \pi^{-}$is $0.9 \times 10^{-4}$ and a number of the limits on other decay channels of this type from both ARGUS and CLEO are at the several times $10^{-4}$ level. The next few years could well see the observation of some of these decays.

There are also processes in the $B$ system induced by "electromagnetic penguin" diagrams. The benchmark process of this type is $B \rightarrow K \mu \bar{\mu}$. In the standard model the decay $b \rightarrow s e^{+} e^{-}$should occur with a branching ratio ${ }^{[12,13]}$ of several times $10^{-6}$; the associated exclusive modes should be roughly an order of magnitude smaller. The presence of a fourth generation ${ }^{[14]}$ could increase the branching ratio by perhaps an order of magnitude. The measurement of such small branching ratios still seems a way off.

The same basic one-loop diagram can lead to a real photon and result in the decay $b \rightarrow s+\gamma$ at the quark level, or $B \rightarrow K^{*}+\gamma, B \rightarrow K^{* *}+\gamma$, ctc. 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, $\left(m_{t}^{2}-m_{c}^{2}\right) / M_{W}^{2}$, to the softer form of a logarithm, $\ln \left(m_{t}^{2} / m_{c}^{2}\right)$. This corresponds to an enhancement, depending on $m_{t}$, of one order of magnitude or more ${ }^{[15-17]}$ over the rate expected from the simplest one-loop electroweak graph. ${ }^{[18]}$ The inclusive process at the quark level, $b \rightarrow s \gamma$, should then occur with a branching ratio of roughly ${ }^{[15,16,17]}$ several times $10^{-4}$; exclusive modes like $B \rightarrow K^{*} \gamma$ and $B \rightarrow K^{* *} \gamma$ are estimated at $5 \%$ to $10 \%$ of this. ${ }^{[15]}$ Again, a fourth generation could enhance this rate by an order of magnitude or so. ${ }^{[19]}$ 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 ${ }^{[20]}$ 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 an inclusive branching ratio that could be of order $10^{-3}$.

Here again, experiment is beginning to probe to the level of sensitivity needed to test theory. The ARGUS limit ${ }^{[10]}$ on the branching ratio for $B \rightarrow K^{*} \gamma$ is now $2.4 \times 10^{-4}$ and the limits on several other exclusive radiative $B$ decay channels are close to this level. One can already say that these processes cannot be enhanced far beyond the standard model predictions.

## DOING $B$ PHYSICS

A large part of the chance of doing interesting $B$ physics is due to two "surprises." First is the $b$ lifetime. The dominant semileptonic decay of the $b$ quark involves the $c$ quark, as noted above. The decay rate $\Gamma\left(b \rightarrow c e \bar{\nu}_{e}\right)$ can be easily related to that for muon decay, $G_{F}^{2} m_{\mu}^{5} / 192 \pi^{3}$ :

$$
\begin{equation*}
\Gamma\left(b \rightarrow c e \bar{\nu}_{e}\right)=\left|V_{c b}\right|^{2} \frac{G_{F}^{2} m_{b}^{5}}{192 \pi^{3}} F\left(\frac{m_{c}}{m_{b}}\right) \tag{7}
\end{equation*}
$$

where

$$
\begin{equation*}
F(\Delta)=1-8 \Delta^{2}+8 \Delta^{6}-\Delta^{8}-24 \Delta^{4} \ln \Delta \tag{8}
\end{equation*}
$$

The phase space factor, $F(\Delta)$, which is unity for a massless final quark (i.e., $F(0)=1$ ) drops off rather quickly, so that $F(0.30)=0.52$ - a value relevant approximately to the $b \rightarrow c$ transition. Given an inclusive semileptonic branching ratio of $\sim 12 \%$, the whole question of the $b$ lifetime boils down to the value of $\left|V_{c b}\right|$. Before the first measurement, there was a large range of possibilities but the theoretical guestimates hovered in the neighborhood of several times $10^{-14}$ seconds for $\tau_{b}$. An "upper limit" was about $10^{-12}$ seconds. Sure enough, the $b$ lifetime has turned out to be around $10^{-12}$ seconds. For the theorists this fact turned out to be not so difficult to accommodate after all; the value of $\left|V_{c b}\right|$ was adjusted accordingly (see Eq. (3)). For experimentalists it has meant that the gaps or tracks between production and decay of hadrons containing a $b$ quark are long enough to be susceptible to present vertex detector technology.

The second "surprise" concerns mixing. The $B^{\circ}-\bar{B}^{\circ}$ mass matrix is $2 \times 2$, with the on-diagonal elements equal and the off-diagonal elements supplied (in the standard model) by the box diagram shown in Fig. 3. Assuming CP conservation for the moment, the eigenstates are

$$
B_{1,2}^{\circ}=\left(B^{\circ} \pm \bar{B}^{\circ}\right) / \sqrt{2},
$$

with masses $m_{1,2}=\bar{m} \pm\left|m_{12}\right|$. Therefore the time dependence of a state which starts at $t=0$ as a $B^{\circ}$ is

$$
\begin{equation*}
B^{\circ}(t)=e^{-i\left(m_{1}+m_{2}\right) t / 2} e^{-\Gamma t / 2}\left[\cos \left(\frac{\Delta m}{2} t\right) B^{\circ}+i \sin \left(\frac{\Delta m}{2} t\right) \bar{B}^{\circ}\right] \tag{9}
\end{equation*}
$$

whére we have assumed $\Gamma_{1} \approx \Gamma_{2}=\Gamma$ and set $\Delta m=m_{1}-m_{2}$. The initial $B^{\circ}$ oscillates to a $\bar{B}^{\circ}$ and then back again to a $B^{\circ}$ in a time $2 \pi / \Delta m$ (or $2 \pi \Gamma / \Delta m$ in lifetime units). The question then is: What is $\Delta m / \Gamma$ ? Before the fact, a theoretical guestimate on the high end for $(\Delta m / \Gamma)_{B_{d}}=x_{d}$ was $\sim 0.2$. In 1987 the ARGUS collaboration found ${ }^{[21]} x_{d}=0.73 \pm 0.18$ (corresponding to $r=0.21 \pm 0.08$ ); the mixing time is not so different from the lifetime. This has now been confirmed by the CLEO collaboration, which finds a value of $r=0.182 \pm 0.055 \pm 0.056$, which is compatible within the statistical or systematic errors. ${ }^{[6]}$ For theorists this has meant an upward adjustment in the combination of a hadronic matrix element, a $\mathrm{K}-\mathrm{M}$ matrix element, and, most importantly, in the value of $m_{t}$. For experimentalists, this together with the $b$ lifetime means that in some situations not only will $B_{d}$ mesons live long enough to leave a measurable gap, but that in this time there is a non-negligible chance that they will oscillate into the corresponding antiparticle state. The $B_{s}$ meson must have large mixing in the three generation standard model, which has important consequences for observing CP violation for the $B_{s}$ system as we will shortly see.

## CP VIOLATION IN $B$ DECAY

When we form a CP violating asymmetry we divide a difference between the rate for a given process and the rate for its CP conjugate by their sum:

$$
\begin{equation*}
\text { Asymmetry }=\frac{\Gamma-\bar{\Gamma}}{\Gamma+\bar{\Gamma}} \tag{10}
\end{equation*}
$$

If we do this for K decays, 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 $\mathrm{K}-\mathrm{M}$ factors:

Asymmetry $_{K ~ D e c a y} \propto s_{2} s_{3} s_{\delta}$.

The right-hand-side is of order $10^{-3}$. 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 the origin of CP violation 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 $\left(s_{1}^{2}\right)$ in K decay. But more importantly, we can look at decays which have rates that are K-M suppressed by factors of $\left(s_{1} s_{2}\right)^{2}$ or $\left(s_{1} s_{3}\right)^{2}$, just to choose two examples. By choosing particular decay modes, it is
even possible to have asymmetries which behave like

$$
\begin{equation*}
\text { Asymmetry }_{B \quad \text { Decay }} \propto s_{\delta} . \tag{12}
\end{equation*}
$$

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. (10). 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. A good example of this is provided by $B-\bar{B}$ mixing, which can be big because of a combination of the values of a hadronic matrix element and $m_{t}$, as well as a particular combination of Kobayashi-Maskawa matrix elements.

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.

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. ${ }^{[22]}$

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 $\epsilon_{B}$. It is related to $p$ and $q$, the coefficients of the $B^{\circ}$ and $\bar{B}^{\circ}$, respectively, in the combination which is a mass matrix eigenstate by

$$
\frac{q}{p}=\frac{1-\epsilon_{B}}{1+\epsilon_{B}}
$$

The charge asymmetry in $B^{\circ} \bar{B}^{\circ} \rightarrow \ell^{ \pm} \ell^{ \pm}+X$ is given by ${ }^{[23]}$

$$
\begin{gather*}
\frac{\sigma\left(B^{\circ} \bar{B}^{\circ} \rightarrow \ell^{+} \ell^{+}+X\right)-\sigma\left(B^{\circ} \bar{B}^{\circ} \rightarrow \ell^{-} \ell^{-}+X\right)}{\sigma\left(B^{\circ} \bar{B}^{\circ} \rightarrow \ell^{+} \ell^{+}+X\right)+\sigma\left(B^{\circ} \bar{B}^{\circ} \rightarrow \ell^{-} \ell^{-}+X\right)}=\frac{\left|\frac{p}{q}\right|^{2}-\left|\frac{q}{p}\right|^{2}}{\left|\frac{p}{q}\right|^{2}+\left|\frac{q}{p}\right|^{2}}  \tag{13}\\
=\frac{\operatorname{Im}\left(\Gamma_{12} / M_{12}\right)}{1+\frac{1}{4}\left|\Gamma_{12} / M_{12}\right|^{2}}, \tag{14}
\end{gather*}
$$

where we define $<B^{\circ}|H| \bar{B}^{\circ}>=M_{12}-\frac{i}{2} \Gamma_{12}$. The quantity $\left|M_{12}\right|$ is measured in $B-\bar{B}$ mixing and we may estimate $\Gamma_{12}$ by noting that it gets contributions from $B^{\circ}$ decay channels which are common to both $B^{\circ}$ and $\bar{B}^{\circ}$, i.e., $\mathrm{K}-\mathrm{M}$ 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 $\psi K_{s}^{\circ}$. Since there is substantial $B^{\circ}-\bar{B}^{\circ}$ mixing, one can consider two decay chains of an initial $B^{\circ}$ meson:

where $f$ is a CP eigenstate. The second path differs in its phase because of the mixing of $B^{\circ} \rightarrow \bar{B}^{\circ}$, and because the decay of a $\bar{B}$ involves the complex conjugate of the $\mathrm{K}-\mathrm{M}$ 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 $\Gamma\left(B^{\circ}(t) \rightarrow f\right)$ and $\Gamma\left(\bar{B}^{\circ}(t) \rightarrow\right.$ f). Specifically,

$$
\begin{equation*}
\Gamma\left(\bar{B}^{\circ}(t) \rightarrow f\right) \sim e^{-\Gamma t}\left(1-\sin [\Delta m t] \operatorname{Im}\left(\frac{p}{q} \rho\right)\right) \tag{15a}
\end{equation*}
$$

and

$$
\begin{equation*}
\Gamma\left(B^{\circ}(t) \rightarrow f\right) \sim e^{-\Gamma t}\left(1+\sin [\Delta m t] \operatorname{Im}\left(\frac{p}{q} \rho\right)\right) \tag{15b}
\end{equation*}
$$

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 $\rho=A(B \rightarrow f) / A(\bar{B} \rightarrow f)$, the ratio of the amplitudes, and we have used the fact that $|\rho|=1$ when $f$ is a CP eigenstate in writing Eqs. (15). From this we can form the asymmetry:

$$
\begin{equation*}
A_{\mathrm{CP} \text { Violation }}=\frac{\Gamma(B)-\Gamma(\bar{B})}{\Gamma(B)+\Gamma(\bar{B})}=\sin [\Delta m t] \operatorname{Im}\left(\frac{p}{q} \rho\right) \tag{16}
\end{equation*}
$$

In the particular case of decay to a CP eigenstate, the quantity $\operatorname{Im}\left(\frac{p}{q} \rho\right)$ is given entirely by the Kobayashi-Maskawa matrix and is independent of hadronic amplitudes. However, to measure the asymmetry experimentally, one must know if one starts with an initial $B^{\circ}$ 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 $B_{d} \rightarrow D \pi$ compared to $\bar{B}_{d} \rightarrow \bar{D} \bar{\pi} ; B_{d} \rightarrow \bar{D} \pi$ compared to $\bar{B}_{d} \rightarrow D \bar{\pi}$; or $B_{s} \rightarrow D_{s}^{+} K^{-}$compared to $\bar{B}_{s} \rightarrow \bar{D}_{s}^{-} K^{+}$. These is a decided disadvantage here in theoretical interpretation, in that the quantity $\operatorname{Im}\left(\frac{p}{q} \rho\right)$ 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, ${ }^{[24]}$ as given in Eqs. (15a) and (15b). As a first example, Figs. 4, 5, and 6 show ${ }^{[25]}$ the
time dependence for the process $\bar{b} \rightarrow \bar{c} u \bar{d}$ (solid curve) in comparison to that for $b \rightarrow c \bar{u} d$ (dashed curve). At the hadron level this could be, for example, $B_{d} \rightarrow \bar{D}^{-} \pi^{+}$in comparison to $\bar{B}_{d} \rightarrow D^{+} \pi^{-}$. 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. Figures 4,5 , and 6 show ${ }^{[26]}$ the situation for $\Delta m / \Gamma=0.2$ (at the high end of theoretical prejudice before the ARGUS result, ${ }^{[21]}$ for $B_{d}$ mixing), $\Delta m / \Gamma=\pi / 4$ (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 finat state has a very small amplitude, and hence not much of an interference effect.

A much more interesting case is shown in Figs. 7, 8 and 9 for the time dependence at the quark level for the process $\bar{b} \rightarrow \bar{c} c \bar{s}$ (solid curve) in comparison to that for $b \rightarrow c \bar{c} s$ (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, $\psi K_{s}^{\circ}$. As discussed before, $|\rho|=1$ in this case. The advantages of having $\Delta m / \Gamma$ for the $B_{d}^{\circ}$ system as suggested by ARGUS (Fig. 8) rather than previous theoretical estimates (Fig. 7) are very apparent. When we go to mixing parameters expected for the $B_{s}^{\circ}$ system (Fig. 9), the effects are truly spectacular.

Figures 10, 11 and 12 illustrate the opposite situation to that in Figs. 4-6; mixing into a big amplitude from a small one. We are explicitly comparing the quark level process $\bar{b} \rightarrow \bar{u} c \bar{d}$ (solid curve) to $b \rightarrow u \bar{c} d$ (dashed curve). At the hadron level this could be, for example, $B_{d} \rightarrow D^{+} \pi^{-}$in comparison to $\bar{B}_{d} \rightarrow \bar{D}^{-} \pi^{+}$. 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 Figs. 10-12), 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 more likely example of the situation for $B_{s}$ mixing is shown ${ }^{[27]}$ in Fig. 13(c). The oscillations are so rapid that even with a very favorable difference in the time dependence for an initial $B_{s}$ versus an initial $\bar{B}_{s}$, the time-integrated asymmetry is quite small. Measurement of the time dependence becomes a necessity for CP violation studies.

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: $B_{u}^{-} \rightarrow D^{\circ} K^{-} \rightarrow K_{s}^{\circ} \pi^{\circ} K^{-}$and $B_{u}^{-} \rightarrow \bar{D}^{\circ} K^{-} \rightarrow K_{s}^{\circ} \pi^{\circ} K^{-}$. Another possibility is to have spectator and annihilation graphs contribute to the same process. ${ }^{[28]}$ Still another is to have spectator and "penguin" diagrams interfere. This latter possibility is the analogue of the origin of the parameter $\epsilon^{\prime}$ 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, $3 \sigma$ ), depending on the decay mode chosen. ${ }^{[22]}$ This is beyond the samples available today (of order a few times $10^{5}$ ) or in the near future $\left(\sim 10^{6}\right)$. The exciting prospect of being able to do this physics, but needing at least an order of magnitude more $B$ 's to have even a reasonable chance to see a statistically significant effect, has led to a series of studies (and
even proposals) of high luminosity electron-positron machines (" $B$ factorics"), of detectors for hadron colliders, and of the possibilities in fixed target experiments. ${ }^{[29]}$

I look at the next several years as being analogous to reconnaissance before a battle: We are looking for the right place and manner to attack CP violation in the $B$ meson system. We need:

- Information on branching ratios of "interesting" modes down to the $\sim 10^{-5}$ level in branching ratio. For example, we would like to know the branching ratios for $B_{d} \rightarrow \pi \pi, p \bar{p}, K \pi, \psi K, D \bar{D}+$ three body modes $+\ldots$ and for $B_{s} \rightarrow \psi \phi, K \bar{K}, D \pi, \rho K, \ldots$
- Accurate $B \bar{B}$ mixing data, first for $B_{d}$, but especially verification of the predicted large mixing of $B_{s}$.
- A look at the "benchmark" process of rare decays, $B \rightarrow K \mu \bar{\mu}$.
- Experience with triggering, secondary vertices, tertiary vertices, "tagging" $B$ versus $\bar{B}$, distinguishing $B_{u}$ from $B_{d}$, distinguishing $B_{d}$ from $B_{s}, \ldots$
- Various "engineering numbers" on cross sections, $x_{F}$ dependence, $B$ versus $\bar{B}$ production in hadronic collisions, . . . .

Many of these things are worthy, lesser goals in their own right, and may reveal their own "surprises." But the major goal is to observe CP violation. With all the possibilities, plus our past history of getting some "lucky breaks," over the next few years we ought to be able to find some favorable modes and a workable trigger and detection strategy. While the actual observation of CP violation may well be five or more years away, this is a subject whose time has come.

## FIGURE CAPTIONS

1) The expected energy levels of the $b \bar{b}$ system. Checkmarks indicate those states which are experimentally observed.
2) "Penguin" diagram (left) and spectator diagram (right) contributing to $\mathrm{K}-\mathrm{M}$ suppressed decays of the $\bar{B}_{d}$ meson.
3) Box diagram contributing an off-diagonal element to the $B-\bar{B}$ mass matrix. The important (short-distance) contribution comes from a $t$ quark in the loop.
4) The time dependence for the quark level process $\bar{b} \rightarrow \bar{c} u \bar{d}$ (solid curve) in comparison to that for $b \rightarrow c \bar{u} d$ (dashed curve). At the hadron level this could be, for example, $B_{d} \rightarrow \bar{D}^{-} \pi^{+}$in comparison to $\bar{B}_{d} \rightarrow D^{+} \pi^{-} . \Delta m / \Gamma=0.2$.
5) Same as Fig. 11, but with $\Delta m / \Gamma=\pi / 1$.
6) Same as Fig. 11, but with $\Delta m / \Gamma=5$.
7) The time dependence for the quark level process $\bar{b} \rightarrow \bar{c} c \bar{s}$ (solid curve) in comparison to that for $b \rightarrow c \bar{c} s$ (dashed curve). At the hadron level this could be, for example, $B_{d} \rightarrow \psi K_{s}^{\circ}$ (dashed curve) in comparison to $\bar{B}_{d} \rightarrow \psi K_{s}^{\circ}$ (solid curve). (The curves are interchanged for the $\psi K_{s}^{\circ}$ final state because it is odd under CP.) $\Delta m / \Gamma=0.2$.
8) Same as Fig. 14, but with $\Delta m / \Gamma=\pi / 4$.
9) Same as Fig. 14, but with $\Delta m / \Gamma=5$.
10) The time dependence for the quark level process $\bar{b} \rightarrow \bar{u} c \bar{d}$ (solid curve) in comparison to that for $b \rightarrow u \bar{c} d$ (dashed curve). At the hadron level this could be, for example, $B_{d} \rightarrow D^{+} \pi^{-}$in comparison to $\bar{B}_{d} \rightarrow \bar{D}^{-} \pi^{+} . \Delta m / \Gamma=0.2$.
11) Same as Fig. 17, but with $\Delta m / \Gamma=\pi / 4$.
12) Same as Fig. 17, but with $\Delta m / \Gamma=5$.
13) The time dependence for the quark level process $\bar{b} \rightarrow \bar{u} u \bar{d}$ (dashed curve) in comparison to that for $b \rightarrow u \bar{u} d$ (solid curve). At the hadron level this could be, for example, $B_{s} \rightarrow \rho K_{s}^{\circ}$ (solid curve) in comparison to $\bar{B}_{s} \rightarrow \rho K_{s}^{\circ}$ (dashed curve) (the curves are interchanged for the $\rho K_{s}^{\circ}$ final state because it is odd under CP) for values of (a) $\Delta m / \Gamma=1$, (b) $\Delta m / \Gamma=5$, and (c) $\Delta m / \Gamma=15$, from Ref. (27).

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Fig. 1


Fig. 2


Fig. 3


Fig. 4


Fig. 5


Fig. 6


Fig. 7


Fig. 8


Fig. 9


Fig. 10


Fig. 11


Fig. 12


Fig. 13

