SLAC–PUB–5738
February, 1992
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Physics Opportunities for a B Factory*

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ABSTRACT

In the short time alloted for this talk it is not possible to review all the physics opportunities offered by a B Factory. I focus on the physics of CP Violation and the resulting tests of the Standard Model.

INTRODUCTION

In this talk a "B Factory" in will be taken to mean an asymmetric e^+e^- collider running at the $\Upsilon(4S)$ with a luminosity of 3×10^{33} or greater. The decay of the $\Upsilon(4S)$ is essentially 50% to B^+B^- and 50% to $B^0\overline{B}^0$, so such a facility provides a copious and clean source of B mesons. The purpose of the asymmetric configuration is to produce the B's with high enough laboratory momenta that the two decays are typically well separated in space. The aim is to be able to reconstruct the two B-decay vertices independently and to measure their separation. This then allows the measurement of time-dependent correlated decay probabilities, which we shall see are essential for the extraction of CP violation physics. In the past couple of years groups at SLAC[1)] and Cornell[2)] as well as here at KEK and in Europe have refined and advanced the accelerator physics questions associated with such a machine and now have formulated detailed designs. I am not competent to judge the feasability of these designs but I am told that it is no longer just a theorists dream that such a machine could be built, provided that somewhere the funding is sufficient for the job. I fervently hope this will occur, because I think the physics opportunities for such a machine are extremely rich.

There is no time here for me to present anything like a complete survey of all the physics opportunities that would be provided by such a facility. Many physicists have been working hard in the past couple of years on this very subject, and fat reports have been produced detailing many topics.[3,4,5)] I will choose to focus on a few topics which are the core of any program for a B factory, primarily because they offer the opportunity to measure the parameters of the Standard Model that are as yet unknown and to test its predictions in a way that could be sensitive to new physics. I will briefly discuss the measurement of the CKM parameters V_{cb} and V_{ub}. I will devote most of my talk to the studies of CP violation which not only measure the phase in the CKM matrix but also test relationships predicted by the Standard Model. Some of the areas that I will not discuss will be covered in the later talk by Nobu Katayama.

Invited Lecture presented at the 2nd KEK Topical Conference
on e^+e^- Collision Physics, Tsukuba, Japan, November 26-29, 1991

* Work supported by the Department of Energy, contract DE-AC03-76SF00515.

MEASURING V_{cb} AND V_{ub}

The parameters V_{cb} and V_{ub} are important simply because they are as much fundamental parameters of the Standard Model as the masses and gauge coupling constants. Furthermore, as we shall see, these values are related to the lengths of sides of the unitarity triangle. Hence, together with measurements of the angles from CP violating decays, a good measurement of V_{ub}/V_{cb} can help over constrain that triangle and thus provide a test of the validity of the Standard Model, or perhaps, if we are lucky, a window to physics beyond it.

The parameter V_{cb} is best measured in the decay $B \to D^* l\nu$. The talk by Reidenbach on results from DORIS summarized the method and gave their latest value. The theoretical prediction for this decay is very clean, at least at the kinematic limit point where the D^* is at rest in the B rest frame. The Isgur Wise heavy-quark symmetry shows that the form factor is normalized to unity at this point.[6] Furthermore the leading corrections to the heavy quark limit, of order Λ_{QCD}/M_c, vanish for this process at this kinematic point.[7,8] Corrections from QCD loops have been calculated at order α_s. (One needs to include these corrections fully, not just in leading log. approximation.[9]) The accuracy of V_{ub} then depends on how close to the kinematic limit one can measure, since some model dependence creeps in to the extrapolation to the limit point from the data. A high luminosity source of B's should thus allow improved accuracy in the extraction of V_{cb}.

Unfortunately, for V_{ub} the theoretical situation is not as clean. In principle the heavy-quark symmetry relates the form factors for $B \to (\pi \mathrm{or} \rho)e\nu$ to those for similar D decays. Here there are certain kinematic $1/M_c$ dependence in the coefficients of the form factors that can be eliminated by using angular analysis to isolate the vector or axial form factors in $B(D) \to \rho e\nu$ decays. There remain some model dependent $1/M_c$ corrections to the universality of the form factors themselves that cannot be controlled experimentally. Hence the challenge here is to the theorists to calculate these corrections accurately. Naive estimates say these can be as large as 20% effects and they are quite model dependent. Lattice methods may be able to reduce the uncertainties compared to those in traditional model building approaches. At the Hiroshima meeting two weeks ago Martinelli claimed that these calculations could be done to about 5% accuracy within a couple of years. Since V_{ub} effectively gives the length of one side of the unitarity triangle it is important to push the accuracy of these estimates.

WHEN DOES CP VIOLATION OCCUR?

Before I get to the main topic of this talk, the physics of CP violation in B decays, I want to begin by reminding you of the conditions under which a theory is CP violating, and what that means for the Standard Model. A general Lagrangian represents a CP conserving theory whenever all phases in the coefficients are zero *or can be made so by any arbitrary set of field redefinitions*. Let us examine this statement more closely.

One question you might ask is why are phases in the Lagrangian so important? After all, physical amplitudes are in general complex even when the Lagrangian is real. What is the difference between the phases which arise because there are coupled channels and hence the possibility of rescattering between these channels, and the phases which come directly from the Lagrangian? The answer lies in the relationship between a process and its CP conjugate. Any phases that arise from rescattering are generically called strong phases here because these final-state interactions are of course dominated by strong interactions. The strong phases are the same for both the original amplitude and for its CP conjugate. On the other hand the Lagrangian phases, which are referred to as weak phases because they occur in the weak interaction parts of the Lagrangian, appear with opposite sign in contributions to an amplitude and to the amplitude for the CP conjugate process.

Even this is not enough to produce CP violating effects. If the amplitude for a process has only a single term then the value of its phase has no physical consequence; the fact that the CP conjugate amplitude has a different phase produces no CP Violation. If however the amplitude has two or more terms representing different mechanisms, different paths from initial to final state, then interference between the terms is sensitive to their relative phases. Consider then some process for which

$$A = A_1 e^{i(\phi_1+\delta_1)} + A_2 e^{i(\phi_2+\delta_2)}$$

where the A_i are real, the ϕ_i are the strong or rescattering phases and the δ_i are the weak or Lagrangian phases. Then the amplitude for the CP conjugate process is given by

$$\overline{A} = A_1 e^{i(\phi_1-\delta_1)} + A_2 e^{i(\phi_2-\delta_2)}$$

The CP-violating difference between the two rates can readily be seen to be proportional

$$a = \frac{|A|^2 - |\overline{A}|^2}{|A|^2 + |\overline{A}|^2} \propto \sin(\phi_1 - \phi_2)\sin(\delta_1 - \delta_2) \tag{1}$$

which vanishes unless both the strong and the weak phases are different for the two contributions.

This requirement of two paths from initial to final state is realized in a special way in the neutral mesons K^0 and B^0. The meson can decay to a particular final state directly, or it can mix to its CP conjugate particle and then decay to the same final state. Here the final state rescattering phases will be the same for both contributions, the phase from the weak mixing term plays the role of the strong phase difference in Eq. (1). The two contributions will have opposite weak phases for the decay and CP violations occur. For the K system this is the familiar CP violation parameterized by ϵ.

In addition to this CP violation coming from mixing in the neutral sector, direct CP violation, that is CP violation due to the existence of two different classes of *decay* processes, occurs for many channels in the Standard Model. These two classes are (1) tree diagram processes and (2) penguin diagram processes. Figure 1 shows these two classes of diagram at the quark level. Note that the non-spectator annihilation and exchange diagrams are not distinguished from the spectator quark diagram, all are grouped together as tree diagrams. In any process where two of these diagrams contribute they do so with the same weak phase and hence can be treated as a single contribution for this analysis. In general the penguin contributions have a different weak phase from the tree contributions and hence interference between the two can lead to CP violating effects. For many charged B-decay channels this interference provides the only Standard Model source of CP violation. The fact that the resulting asymmetry is also proportional to the strong phase shift difference means that it cannot be calculated without some further assumptions. I will later discuss these processes further. Here I only note that these are direct CP violations, comparable to those parameterized by ϵ' in K-decays.

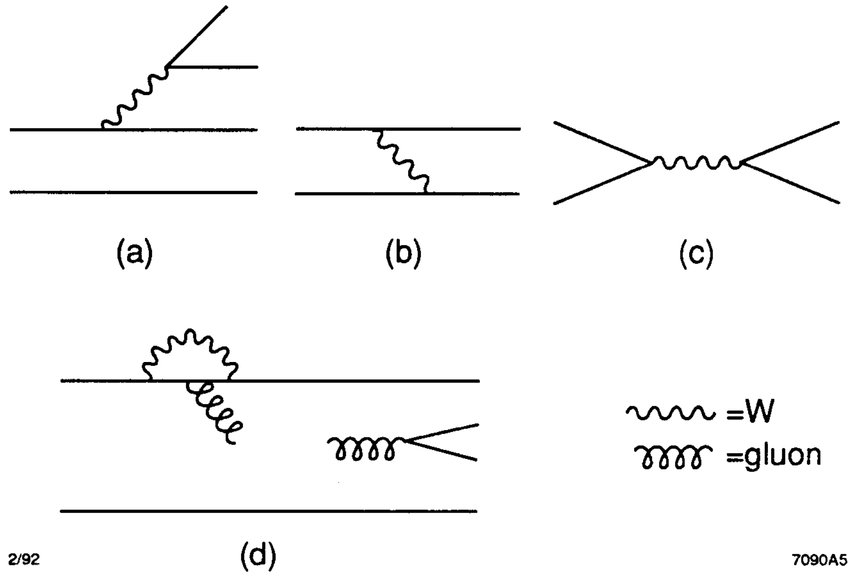

Figure 1. Tree and Penguin Diagrams. Digrams (a) spectator, (b) W-exchange and (c) annihilation are all tree contributions. Diagram (d) is the penguin contribution. Gloun lines responsible for binding are not shown.

The Minimal Standard Model

In the minimal (three generation, single Higgs doublet) Standard Model the most general Lagrangian has many coupling constant parameters with a priori independent phases. However only a single phase survives after the freedom to redefine the phase of every particle field in the Lagrangian has been used to eliminate as many of possible of the coupling constant phases. The one remaining phase occurs in the matrix which relates the weak eigenstates to the mass eigenstates, generally known as the Cabbibo Kobayashi Maskawa or CKM matrix. Since there is only one such phase there are automatically relationships between different CP-violating processes, since they must all depend in some way on this phase. The beauty of the neutral B system is that there are many different processes for which asymmetries can be measured and also can be calculated in terms of CKM parameters without strong interaction uncertainties. Thus the predictions of the model can be tested by comparison of these results. Perhaps this can lead us to clues to physics beyond the Standard Model.

The unitarity triangle is a simple geometrical representation of a relation which results from the unitarity of the three generation CKM matrix V:

$$\mathcal{U}_{db} = V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0, \tag{2}$$

The three complex quantities $V_{id}V_{ib}^*$ form a triangle in the complex plane, which is referred

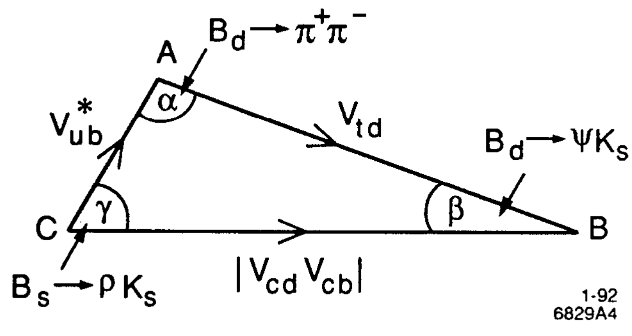

Figure 2. The Unitarity Triangle.

to as the unitarity triangle. The three angles of this triangle are labelled

$$\alpha \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right), \quad \beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right), \quad \gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right). \tag{3}$$

The aim is to make enough independent measurements of the sides and angles that this triangle is overdetermined and thus check the validity of the Standard Model. Figure 2 shows a representation of the unitarity triangle in a phase convention where the side proportional to $V_{cd}V_{cb}^*$ is real. The angles α, β and γ are labelled and an example of a decay for which the asymmetry can be related to this angle is given. I will discuss these examples in more detail later.

Beyond the Standard Model

The predictions for CP asymmetries in B decays in the standard model include three major components:

1. the mechanism for B^0 mixing,
2. the mechanism for B decay, and
3. the mechanism for K mixing, if there is a K^0 in the final state.

Models for physics beyond the Standard Model may in principle introduce new features in any of these three stages, however the third one is already well measured in K decays and so any new contribution there must be so small that it cannot significantly alter the predictions for B decays. Thus the possible new physics must be looked for in the first two.

A survey of models of new physics was made by Dib, London and Nir.[10] Their results can be summarized as follows. They looked for whether models predict violation of the unitarity constraints $\mathcal{U}_{db} = 0$; or the similar relation $\mathcal{U}_{sb} = 0$, and, more important, for contributions to $B_q - \overline{B}_q$ mixing which are different in phase and at least comparable in magnitude to the Standard Model contribution.

A summary of the conclusions of Dib, London and Nir is given in Table I, which I reproduce here from their work. The discussion which follows is also principally taken from their analysis. In the table, the second column describes, for each model, whether unitarity of the three generation CKM matrix is maintained (a triangle) or violated (some other shape). The third column gives examples of new contributions to $B_q - \overline{B}_q$ mixing. Unless otherwise mentioned, the contribution could be large and carry new phases.

1. Four quark generations[11–14]**:**

Although we know that there are only three light neutrinos there is still the possibility that there are further sequential generations with heavy neutrinos, or that there are further heavy quarks that do not fit the Standard Model generation pattern. In such models the unitarity of the three generation CKM matrix is no longer necessary and large violations could occur.[15] There could also be new box-graph contributions to mixing involving the additional heavy quarks. Such models therefore could give many violations of the three generation Standard Model predictions.

2. Z-mediated flavor changing neutral currents (FCNC)[16–17]**:**

In such theories there are tree-level Z-mediated contributions to b decays. However current experimental constraints require that they are below 5% of the tree-level W-mediated diagram. There are new contributions from Z mediated diagrams to Γ_{12} but they are not expected to be large. The direct decays are still dominated by the W-mediated tree diagrams. Unitarity of the CKM matrix is violated by contributions proportional to the non-diagonal Z-coupling. and there could also be significant new contributions to $B_q - \overline{B}_q$ mixing from tree-level Z-exchange diagrams. These give new independent phases in the neutral current mixing matrix.

3. Multi-Higgs doublets with natural flavor conservation (NFC): In these models there are tree-level charged-Higgs contributions to b decays. Experimental limits on the mass of the charged Higgs make these contributions negligible. There is no significant effect on Γ_{12} or direct decays and unitarity of the CKM matrix is maintained. There could be significant new contributions to $B_q - \overline{B}_q$ mixing from box-diagrams with charged Higgs. It can be shown however that in a general multi-Higgs model these contributions have the same phase as the Standard Model W-exchange contribution. Consequently, the phase $\arg(M_{12})$ remains unmodified.

If, in addition to natural flavor conservation, it is assumed that all CP violation arises spontaneously (denoted SCPV in the Table), then the predicted unitarity triangle becomes a line, and CP asymmetries in classes $i = 1,2,3$ all vanish. However, it seems that the limits on scalar masses from LEP, and current values for the allowed range of $\sin(2\beta)$ this class of models is now excluded.

4. Left-Right Symmetry (LRS)[18–19]**:**

In such models there are tree-level W_R-mediated contributions to b decays, but, given the experimental limits on the mass of the W_R, they are negligible. Thus, there is no significant effect on Γ_{12} or on the direct decays. Unitarity of the CKM matrix is maintained. The experimental limits on $M(W_R)$ from $K - \overline{K}$ mixing and the relations between the

TABLE I

Effects of new physics on CP asymmetries

Model	CKM Unitarity	B - $\bar{B}$ Mixing	SM Predictions for A^{CP}
SM		t W W t	
Four Quark Generations	$V_{t'd}V^*_{t'b}$	t'	Modified
Multi-Scalar with NFC (General)		ϕ^+	Unmodified
(+ SCPV)		No New Phases	All Asymmetries Vanish
Z-Mediated FCNC	U^*_{db}	Z	Modified
LRS		W_R Small	Unmodified
SUSY (General)		$\tilde{g}$ $\tilde{q}_L,\tilde{q}_R$ $\tilde{q}_L,\tilde{q}_R$ $\tilde{g}$	Modified
(Minimal)		$\tilde{g}$ $\tilde{q}_L$ $\tilde{q}_L$ $\tilde{g}$ No New Phases	Unmodified
"Real Superweak"		Real	Modified for B_d Unmodified for B_s

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mixing matrices for W_L and W_R interactions imply that there could be no significant new contributions to $B_q - \overline{B}_q$ mixing. A model of $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ gauge symmetry with no discrete $L \leftrightarrow R$ symmetry can evade these limits, but only by fine-tuning the quark sector parameters.

5. Supersymmetry (SUSY)[20]:

There are no new tree-level contributions to b decays. Thus, Γ_{12} remains unmodified and the direct tree-level decays are still dominated by the W-mediated diagrams. Unitarity of the CKM matrix is maintained.

There could be significant new contributions to $B_q - \overline{B}_q$ mixing from box-diagrams with intermediate gluinos and squarks. Whether these box diagrams carry phases that are different from those of the Standard Model box diagrams depends on the specific SUSY model. In the *minimal* SUSY extension of the Standard Model the new contributions come from the squarks that are superpartners of lefthanded quarks and contribute with the same phases as the partner quark contributions. Thus no new phases are introduced and CP asymmetries are not modified in minimal SUSY models.

In more general SUSY models, there can be contributions to box-diagrams from right-handed quark superpartners as well. Their mixing matrices are independent of the CKM matrix and thus, in general, introduce new phases.[21]

6. "Real Superweak" models[22]:

I want to begin here by emphasizing that the original idea of "superweak" CP violations is an old suggestion made prior to emergence of the three-generation Standard Model. The idea was that all CP violating effects would be due to mixing and there would be no direct CP violations of the type given in the Standard Model by interference between tree and penguin diagrams. I know of no modification of the Standard Model for which this is true. Thus superweak in this extreme form is a framework that provides a "straw man" against which to test the Standard Model but does not propose a viable alternative or extended theory if the tests should be failed.

A more modern version of the superweak idea is the hypothesis of 'real superweak' additions to the Standard Model. 'Real superweak' is also a generic framework rather than a specific Lagrangian model. It is assumed that decay processes are dominated by the Standard Model amplitudes, but mixing processes may have significant new contributions. These new contributions are assumed to be real. This means that the phases from the direct decays ($\overline{A}/A$) remain the same as in the Standard Model. As for the mixing, with this ansatz the phase in B_s mixing $(q/p)_{B_s}$ remains the same (real), but the phase in B_d mixing $(q/p)_{B_d}$ is reduced. Consequently, this model predicts no modification of the Standard Model prediction for asymmetries in B_s decays, a reduction in the asymmetry in $B_d \to \psi K_S$, and a modification (in either direction) of the asymmetry in $B_d \to \pi^+\pi^-$. This model demonstrates a general feature noted in Ref. 15: Even though the measurements of $B \to \psi K_S$ and $B \to \pi^+\pi^-$ do not measure β and α as defined in Eq. (3) anymore, the angles deduced from these measurements will sum with γ (deduced correctly from $B_s \to \rho K_S$) to 180^o. This occurs because the B_s mixing amplitude is real.

This review of models shows that different extensions of the theory change the Standard Model in different ways, so that, should we find that the Standard Model does not fit the data, the pattern of the breakdown will give us some clues as to the type of extension of the theory that is required to accommodate the deviations. Unfortunately it is much harder to argue in the opposite way, should the tests all give consistency with the Standard Model it will still be hard to rule out most of these theories, or even to improve the lower bounds on the masses of any new particles that they introduce. There is almost always a way to choose the *phases* of additional couplings so that the predictions of the model do not look any different from those of the Standard Modelindependent of the magnitude of such contributions. While these choices are artificial they cannot be excluded as possibilities, and hence no bounds can be obtained. The one exception to this argument is the real superweak class of models where the phases are fixed by the assumption that all new mixing contributions are real.

Formalism for B Decays

The two mass eigenstates of the neutral B meson system can be written

$$\begin{aligned} |B_L\rangle =& p\,|B_0\rangle + q\,|\bar{B}^0\rangle\,, \\ |B_H\rangle =& p\,|B_0\rangle - q\,|\bar{B}^0\rangle\,. \end{aligned} \tag{4}$$

Here H and L stand for Heavy and Light, respectively. Since $\Delta\Gamma \ll \Gamma$, because it is produced by channels with branching ratios of $\mathcal{O}(10^{-3})$ which contribute with alternating signs,[23] we can neglect the tiny difference in width between B_H and B_L and set

$$\Gamma_H = \Gamma_L \equiv \Gamma. \tag{5}$$

We define:

$$M \equiv (M_H + M_L)/2, \quad \Delta M \equiv M_H - M_L. \tag{6}$$

Because $\Gamma_{12} \ll M_{12}$, one finds

$$|q/p| = 1. \tag{7}$$

We are interested in the decays of neutral B's into a CP eigenstate which we denote by f_{CP}. We define the amplitudes for these processes as

$$A \equiv \langle f_{CP}|\mathcal{H}|B^0\rangle\,, \quad \bar{A} \equiv \langle f_{CP}|\mathcal{H}|\bar{B}^0\rangle\,. \tag{8}$$

We further define

$$\lambda \equiv \frac{q}{p}\,\frac{\bar{A}}{A}. \tag{9}$$

Then the time-dependent rates for initially pure B^0 or $\bar{B}^0$ states to decay into a final CP

eigenstate at time t is given by:

$$\begin{aligned}\Gamma(B^0_{\text{phys}}(t) \to f_{CP}) =&|A|^2 e^{-\Gamma t}\left[\frac{1+|\lambda|^2}{2} + \frac{1-|\lambda|^2}{2}\cos(\Delta M t) - \text{Im}\lambda \sin(\Delta M t)\right],\\ \Gamma(\overline{B}^0_{\text{phys}}(t) \to f_{CP}) =&|A|^2 e^{-\Gamma t}\left[\frac{1+|\lambda|^2}{2} - \frac{1-|\lambda|^2}{2}\cos(\Delta M t) + \text{Im}\lambda \sin(\Delta M t)\right].\end{aligned} \tag{10}$$

The time-dependent CP asymmetry is given by

$$a_{f_{CP}}(t) \equiv \frac{\Gamma(B^0_{\text{phys}}(t) \to f_{CP}) - \Gamma(\overline{B}^0_{\text{phys}}(t) \to f_{CP})}{\Gamma(B^0_{\text{phys}}(t) \to f_{CP}) + \Gamma(\overline{B}^0_{\text{phys}}(t) \to f_{CP})}. \tag{11}$$

Thus

$$a_{f_{CP}}(t) = \frac{(1-|\lambda|^2)\cos(\Delta M t) - 2\text{Im}\lambda \sin(\Delta M t)}{1+|\lambda|^2}. \tag{12}$$

The quantity $\text{Im}\lambda$ which can be extracted from $a_{f_{CP}}(t)$ is theoretically very interesting since it can be directly related to CKM matrix elements in the Standard Model.

In an e^+e^- B factory the initial B system is produced in a coherent state which remains $B^0\overline{B}^0$ until such time as one of the particles decays. The time evolution of the second particle is thus dependent on the time of the decay of the first. If one B decays to a flavor-tagging mode at time t_{tag} while the other decays to a CP-study mode at time $t_{f_{CP}}$ we have an event that can be used to reconstruct the time dependence of the asymmetry. The time that appears in the equations above is $t = t_{f_{CP}} - t_{tag}$. The tagging decay may be the later decay, in which case the correct procedure is to assign a negative time to that event. Note that this makes the measurement of time dependence essential at such a machine since the time-integrated CP asymmetry vanishes.

The measurement of the CP asymmetry (11) will determine $\text{Im}\lambda$ through (12). If $|A/\overline{A}| = 1$ then $\text{Im}\lambda$ depends on electroweak parameters only, without hadronic uncertainties. The condition $|A| = |\overline{A}|$ holds if all amplitudes that contribute to the decay have the same CKM phase, which we will denote by ϕ_D.[24)] In such a case

$$\overline{A}/A = e^{-2i\phi_D}. \tag{13}$$

As mentioned above, for $\Gamma_{12} \ll M_{12}$

$$q/p = \sqrt{M^*_{12}/M_{12}} = e^{-2i\phi_M}, \tag{14}$$

where ϕ_M is the CKM phase in the $B-\overline{B}$ mixing. Thus

$$\lambda = e^{-2i(\phi_M+\phi_D)} \quad \Longrightarrow \quad \text{Im}\lambda = -\sin 2(\phi_M + \phi_D). \tag{15}$$

(Note that each of ϕ_M and ϕ_D is convention dependent, but the sum $\phi_M + \phi_D$ is not, $\text{Im}\lambda$ depends on convention independent combinations of CKM parameters only.) Note that sign($\text{Im}\lambda$) depends on the CP transformation properties of the final state. The analysis above corresponds to CP-even final states. For CP-odd states, $\text{Im}\lambda$ has the opposite sign.

I now turn to a review of some experiments which can, at least in principle, measure the three angles α, β and γ:

(i) $\sin(2\beta)$: the mode $B \to \psi K_S$.

The mixing phase in the B_d system is given by

$$(q/p)_{B_d} = (V_{tb}^* V_{td})/(V_{tb} V_{td}^*). \tag{16}$$

With a single final kaon, one has to take into account the mixing phase in the K system, $(q/p)_K = (V_{cs} V_{cd}^*)/(V_{cs}^* V_{cd})$. The decay phase in the quark subprocess $b \to c\bar{c}s$ is

$$\frac{\overline{A}}{A} = \frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}}. \tag{17}$$

Thus

$$\lambda(B \to \psi K_S) = \left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right) \left(\frac{V_{cs}^* V_{cb}}{V_{cs} V_{cb}^*}\right) \left(\frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*}\right) \Longrightarrow \mathrm{Im}\lambda = -\sin(2\beta). \tag{18}$$

(As ψK_S is a $CP = -1$ state, there is an extra minus sign in the asymmetry which I have not included here.)

This is the easiest CP violating B_d decay channel to tackle; both experimentally and theoretically it is very clean. The decay of the ψ to a pair of leptons, (e or μ), gives a readily recognized signature. There is a small penguin contribution to $b \to c\bar{c}s$, however it depends on the CKM combination $V_{tb} V_{ts}^*$ which has, to a very good approximation, the same phase (mod π) as the tree diagram which depends on $V_{cb} V_{cs}^*$. Since both tree and penguin amplitudes have the same weak phase, the extraction of the CKM phase from the experiment does not suffer from uncertainties due to the limitations of our ability to calculate hadronic processes. In particular the relative strength of tree and penguin contributions does not affect the answer. In addition, since this is one of the observed decay modes of B mesons, we know the branching ratio and are not dependent on models to estimate it. Hence we can quite reliably estimate the luminosity needed to measure the angle β. The result is that with $30 fb^{-1}$, (about one year of running at design luminosity), one can achieve a precision of about $\delta(\sin(2\beta)) = \pm 0.05$.[25] This estimate includes detector efficiencies for both this decay mode and for tagging modes that identify the flavor of the other B in the event. This means that in a couple of years of B factory running one can almost certainly achieve a reliable measurement of this angle, since current measurements of related quantities already restrict $-1 \leq \sin(2\beta) \leq -0.08$ within the Standard Model.

This asymmetry is possibly the only one that will be accessible to hadron machines such as the upgraded Tevatron, or the LHC or SSC. The leptons in the final state give a clean signature even in the presence of hadronic backgrounds. A preliminary estimate is that the accuracy obtainable with a year of running for example at the upgraded Tevatron is about $\delta(\sin(2\beta)) = \pm 0.15$.[26]

A further measurement of $\sin(2\beta)$ can be made using the channel ψK^*. In this channel angular analysis is necessary to select the contribution of a definite CP. The relative angular momentum between the two particles can be either even and odd which means that there are contributions of both even and odd CP.[27,28] The branching ratio to this channel is a factor of 3 to 6 times bigger than that for ψK^0_S. Furthermore preliminary indications from Argus[29] suggest that at least part of the kinematically-allowed region is dominated by a single CP. If this is so then the angular analysis should not dilute the statistical significance and this mode may provide a more accurate constraint on $\sin(2\beta)$ than the simpler mode ψK^0_S.

(ii) $\sin(2\alpha)$: the mode $B \to \pi^+\pi^-$.

The mixing phase in the B_d system is given in Eq. (16). The decay phase for the quark subprocess $b \to u\bar{u}d$ is

$$\frac{\overline{A}}{A} = \frac{V_{ub}V^*_{ud}}{V^*_{ub}V_{ud}}. \tag{19}$$

We get

$$\lambda(B \to \pi^+\pi^-) = \left(\frac{V^*_{tb}V_{td}}{V_{tb}V^*_{td}}\right)\left(\frac{V^*_{ud}V_{ub}}{V_{ud}V^*_{ub}}\right) \Longrightarrow \mathrm{Im}\lambda = \sin(2\alpha). \tag{20}$$

For this mode, the penguin contribution is expected to be small, but it depends on the CKM combination $V^*_{td}V_{tb}$ and thus has a different decay phase from that of the tree diagram. This introduces a small and uncertain correction into the relationship between the measured asymmetry and the CKM-parameter dependent quantity $\sin(2\alpha)$. Such uncertainties can be eliminated using isospin analysis.[30,31,32] This will require good data for the full set of isospin related channels, including the more difficult $\pi^0\pi^0$ mode. Only one asymmetry need be measured, that is time dependence needs to be reconstructed only in the $\pi^+\pi^-$ channel. This is fortunate because this would be very difficult to achieve a time-dependent measurement in the $\pi^0\pi^0$ channel. The most likely outcome of the isospin analysis is to verify that the penguin contribution is small enough that, within experimental errors the measured asymmetry is directly related to $\sin(2\alpha)$.

A second problem for estimates of the accuracy that can be achieved with this channel is that it has yet to be observed as a B decay and hence we must rely on model-dependent estimates of the branching ratio. An assumed branching ratio of order 2×10^{-5} gives an estimate of about $\delta(\sin(2\alpha)) = \pm 0.18$ for $30 fb^{-1}$ of data. Other channels such as $\rho\pi$ and $a_1\pi$ can be added to improve this estimate to $\delta(\sin(2\alpha)) = \pm 0.08$.[25]

(iii) $\sin(2\gamma)$

The standard example is the mode $B_s \to \rho K_s$. The mixing phase in the B_s system is $(q/p)_{B_s} = (V^*_{tb}V_{ts})/(V_{tb}V^*_{ts})$. Due to the final K_S, the mixing phase for the K system has to be taken into account. The quark subprocess is the same as in $B \to \pi\pi$, namely $b \to u\bar{u}d$. Thus

$$\lambda(B_s \to \rho K_S) = \left(\frac{V^*_{tb}V_{ts}}{V_{tb}V^*_{ts}}\right)\left(\frac{V^*_{ud}V_{ub}}{V_{ud}V^*_{ub}}\right)\left(\frac{V^*_{cs}V_{cd}}{V_{cs}V^*_{cd}}\right) \Longrightarrow \mathrm{Im}\lambda = -\sin(2\gamma). \tag{21}$$

However production of the B_s requires that the accelerator be run at the $\Upsilon(5S)$ which has a smaller cross section than that for $\Upsilon(4S)$. Furthermore decays to $B_s\overline{B}_s$ are only a fraction of the decays of this resonance. The nett effect is that with present machine designs one cannot achieve a sufficient rate of $B_s\overline{B}_s$ production to measure the asymmetry of this mode and extract a value of γ in this way.

A second interesting possibility for studying γ has been suggested.[33,34] These authors suggest a study of B^+ (or B_d^0) decays to D^0K, or D^0K^*. Here CP violation can be observed in the case where the D^0 decays to a CP eigenstate mode such as $\pi^+\pi^-$. The interference is between the D^0 and $\overline{D}^0$ contributions, both of which can be produced from the B decays. This is a promising idea, but it requires accurate measurements of the branching ratios to the D^0 and $\overline{D}^0$. Measurements of flavor-tagging D decay modes can be used to extract these quantities as long as the D branching fractions to the tagging modes are well measured. Detailed modelling of all these measurements is needed to be able to estimate the accuracy that one could achieve with this method. I am told that a preliminary estimate by KEK researchers suggests it may indeed be feasible.[35]

These examples demonstrate that the three angles of the unitarity triangle can in principle be measured independently of each other. Perhaps most difficult will be the measurement of γ. Other methods of over constraining the unitarity triangle are needed. One possibility, mentioned earlier, is an accurate measurement of V_{ub}, if we can obtain reliable estimates of uncertainties from the theory side.

Charged B Decays

With the exception of the D^0K modes mentioned above, CP asymmetries in charged B decays occur only because of interference between tree and penguin contributions in the Standard Model. The observation of any CP asymmetries of this type would be proof that direct CP violation occurs, equivalent to that given by a non-zero measurement of ϵ' in K decays. The calculations of Standard Model predictions of CP violating asymmetries in charged B decays contain many uncertainties.[36,37,38] Most of the calculations give asymmetries for particular quark processes, calculated perturbatively. For the penguin contributions I have drawn the diagram in Figure 1. without identifying the gluon which is emitted from the W-quark loop with that which produces the additional quark-antiquark pair. I do this to stress the fact that the term "penguin" in principle includes all possible such contributions. Note that the many gluons involved in the binding are not drawn here, so the disconnected line simply means a gluon absorbed in, and another produced from, the general glue. When people evaluate the penguin contribution perturbatively they identify these two gluon lines for the leading contribution and then add additional gluon corrections for a higher order calculation. The justification for this perturbative treatment of the gluons is that the gluon emitted from the quark loop is quite hard because of the large mass difference between the b quark and the s or d quark that it becomes after the W-loop. I am doubtful that this approach is completely correct. For example a contribution in which the hard gluon is absorbed by the other quark of the original meson and then hadronization occurs non-perturbatively could be comparable to the one usually calculated, especially for an inclusive rate estimate.

Furthermore the perturbative calculation predicts only the sum of all states with a particular quark content. Inclusive measurement of such a quantity is a difficult experiment. The problem of strong rescatterings that change quark identities introduces further uncertainties for such an approach. For exclusive (few body) channels there remains the problem of how to convert the quark diagram calculations into reliable estimates for rates and asymmetries. Each configuration of final hadrons corresponds to some weighted integral over quark kinematics, but unfortunately we have no way to determine that integral. Since the calculated quark-level asymmetries depend on the momentum transfer to the $q\bar{q}$ pair and even change sign as a function of this variable in some cases, it is very difficult to convert the quark estimates into estimates for exclusive hadron processes.

Because of the dependence of the asymmetry on the difference of strong phases as well as that of the weak phases, calculations are sensitive to other aspects of hadronization. In the quark diagram calculation, the long-range final state hadron-hadron interaction phase shifts are ignored, except in the sense that final-state interactions which involve quark-antiquark annihilation processes are included in the absorptive part of the penguin processes. The assumption of small final-state phase effects from hadronization, known as the factorization assumption, is built into the calculations but has not yet been well tested. I will return shortly to summarize the theoretical arguments for and against factorization. Wolfenstein has argued[40] that hadronization can result in final-state phase shifts which could decrease the resulting asymmetries compared to the quark-diagram perturbative calculations. This question remains an open one.

Even without further suppression due to such effects, the predictions of Refs. 36 and 37 suggest that the CP violations in charged B decays predicted by the Standard Model will be extremely difficult to observe, requiring of order 10^{10} produced B's for exclusive $b \rightarrow s$ modes and of order 10^9 B's for exclusive $b \rightarrow d$ modes. In Ref. 36 it is suggested that this can be improved to perhaps as low as 10^7 B's if one can sum all two-body or quasi two-body $b \rightarrow ds\bar{s}$ modes, but the experimental difficulties of such a semi-inclusive measurement may defeat this theoretical improvement. Since these estimates include only branching fractions and required statistical accuracy but not the inefficiencies due to triggering and background rejection cuts they are anyway quite optimistic.

The Factorization Hypothesis.

Both the calculations for charged B decay asymmetries described above and the much-used model for B decay branching fractions of Bauer, Stech and Wirbel[39] depend on an assumption of factorization. This is the assumption that strong final state rescattering effects can be ignored in going from quark diagrams to estimates for few-body hadronic final states. There is a physical picture, perhaps most clearly annunciated by Bjorken,[41] which supports this assumption. The argument is that the quark and antiquark which hadronize as a high momentum meson are produced by the weak interaction in a region much smaller than the size of a typical hadron. Hence they travel far from the other quark anti-quark system before they separate sufficiently from one another to have the usual strong interaction cross-section with that system. By then the separation of the two systems is large compared to the range of strong interactions. The strong interactions of a tiny quark-antiquark color singlet system are suppressed compared to those of a hadron because their color-charges form a local color singlet without the need for an extended region of non-zero gluon field strength. This is closely related to the idea of color transparency suggested by Brodsky and Mueller.[42]

This justification for neglecting final state interactions is just a word-picture, but physical understanding often begins with such pictures. As a challenge to this picture Wolfenstein[43] asks whether the lack of interaction should be true channel by channel for all final states of this tiny $q\bar{q}$ system, or only for the complete linear superposition of states that is formed by the system. Put another way he asks is there any sense in which a particular emerging meson extrapolates back to only the tiny system? All this argument just illustrates how little can actually be calculated about the strong interactions. Until we have a well defined calculational scheme that clearly shows that factorization is or is not a property of the theory it is hard to reach a conclusion in such debates. Factorization has been rigorously demonstrated to be valid under certain conditions in the infinite quark-mass limit,[44] but the models apply it in a much more general way. The consequences of factorization include relationships between hadronic and semileptonic channels, and allow the extension of heavy-quark predictions to some hadronic channels. It would be interesting to have accurate experimental tests of these relationships. These studies have already begun at CESR and DORIS (see talks at this meeting) but can be made more precise at the higher luminosity of a B factory.

Conclusions

The observation of CP violation in B decays is crucial in testing the Standard Model. Particularly promising are CP asymmetries in neutral B decays into CP eigenstates, these processes are subject to clean theoretical interpretation and seem to be experimentally most accessible. The observation of CP asymmetries in charged B decays would demonstrate the existence of direct CP violation but predictions involve theoretical uncertainties. It will therefore be difficult to translate such measurements into information on the values of Standard Model parameters.

This physics is only part of the rich program of physics one could achieve at a B factory, but it is the part which shows the special nature of such a facility as a tool to probe some remaining untested features of the Standard Model and perhaps thereby to find clues to physics beyond the Standard Model. I for one hope very much that at least one such a facility will be built some place in the world, so these questions can be studied.

ACKNOWLEDGEMENT

I want to thank the organizers of this meeting for their hospitality and also to thank Hideaki Aoyama for making my trip to Japan so easy. I also acknowledge the input of many colleagues to my views on B physics, especially Isi Dunietz, Yosef Nir, and Art Snyder.

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