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# PHYSICS PROSPECTS FOR THE SLAC B-FACTORY *

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Abstract

A very brief presentation of the physics prospects for the SLAC B-Factory, now under construction, is presented.

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# PHYSICS PROSPECTS FOR THE SLAC B-FACTORY

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A very brief presentation of the physics prospects for the SLAC B-Factory, now under construction, is presented.

## 1 Introduction

CP violation has been an enigma since its discovery in the decays of neutral kaons in 1964.[1] The present version of the Standard Model can accommodate CP violation by means of a non-zero phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix. However, CP violation in the kaon system occurs at the part per mille level and the Standard Model's predictions for CP violation have not been conclusively tested. In contrast to the kaon system, $B$-mesons decay into a variety of final states, many of which could exhibit CP violation and therefore offer multiple tests of the Standard Model. Several large efforts currently are in progress to create dedicated experiments or factories which will produce large quanties of $B$-mesons which, in turn, should give large numbers of CP-violating decays. The large number of produced $B$-mesons will also give a copious supply of other "less-interesting" decays which may mask the desired CP-violating decays.

The time-dependent CP asymmetry $a_{f_{CP}}(t)$ for $B^0$- or $\overline{B}^0$-mesons to decay into a CP eigenstate $f_{CP}$, is given by:[2,3]

$$a_{f_{CP}}(t) = \frac{\Gamma(B^0(t) \to f_{CP}) - \Gamma(\overline{B}^0(t) \to f_{CP})}{\Gamma(B^0(t) \to f_{CP}) + \Gamma(\overline{B}^0(t) \to f_{CP})} .$$

If the mixing is governed by a single mixing phase $\phi_M$ and a single amplitude with weak decay phase $\phi_D$ dominates the decay, then:

$$|a_{f_{CP}}(t)| = \sin 2(\phi_M - \phi_D) \sin(\Delta M t) ,$$

where $\Delta M = M_{B^0_H} - M_{B^0_L}$ is the mass difference between the high-mass and low-mass neutral $B$-mesons.

Unitarity of the CKM matrix requires, for example, that

$$V_{tb}V^*_{td} + V_{cb}V^*_{cd} + V_{ub}V^*_{ud} = 0 .$$

This expression can be represented by a triangle in the complex plane, where the angles are:

$$\alpha \equiv \arg\left(-\frac{V_{td}V^*_{tb}}{V_{ud}V^*_{ub}}\right) ;$$
$$\beta \equiv \arg\left(-\frac{V_{cd}V^*_{cb}}{V_{td}V^*_{tb}}\right) ;$$
$$\gamma \equiv \arg\left(-\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}}\right) .$$

In the Wolfenstein parametrization of the CKM matrix, the elements $V_{ub}$ and $V_{td}$ carry the phase contributions. Relationships between the leading CKM coefficients and several of the $B$-meson decay channels have been tabulated by Quinn[4] and are shown in Tables 1 and 2.

At the $e^+e^-$ B-Factory (PEP-II and its associated detector BaBar[5]) now under construction at SLAC, the $B^0$ and $\overline{B}^0$ will be produced in a coherent $B^0\overline{B}^0$ initial state at the center-of-mass energy of the $\Upsilon(4S)$. The decay, for example, of the $B^0$ into a flavor-identifying mode will "tag" the event. Decays from the recoil $\overline{B}^0$ may show CP violation through their time-dependent decay asymmetries. Because the $e^+$ and $e^-$ beams will have very different energies, the $B$- and $\overline{B}$-mesons will have spatially separated decay vertices which will be measured very accurately with a silicon-tracking detector located very close to the interaction point, thus allowing reconstruction of the time-separation of decays. Estimates have been made of the tagging performance in BaBar.[5] Overall, it is anticipated that 34% of the produced $B^0\overline{B}^0$ events at the $\Upsilon(4S)$ will be tagged, with 21% of the produced events having a kaon tag and 13% having a lepton tag. These tagging efficiencies include dilutions due to wrong-tag probabilities. Measurements of asymmetries in many decay channels will be made in BaBar, with the goal being to overconstrain the unitarity triangle.

Table 1: Leading CKM decay coefficients for decays $b \to q\overline{q}'s$

| Decay | CKM Factors (Order in $\lambda$) | | $B_d$ Modes (Angle Measured) | $B_s$ Modes (Angle Measured) |
|---|---|---|---|---|
| | Tree | Dominant Penguin | | |
| $b \to c\overline{c}s$ | $V_{cb}V_{cs}^*$ ($\lambda^2$) | $V_{cb}V_{cs}^*$ ($\lambda^2$) | $\psi K_S$ ($\beta$) | $\psi\phi$ (0) |
| $b \to s\overline{s}s$ | 0 | $V_{cb}V_{cs}^*$ ($\lambda^2$) | $\phi K_S$ ($\beta$) | $\phi\eta'$ (0) |
| $b \to u\overline{u}s$ | $V_{ub}V_{us}^*$ ($\lambda^4$) | $V_{cb}V_{cs}^*$ ($\lambda^2$) | $\pi^0 K^0$ (Direct CP Violation) | $K^+K^-$, $K^0\overline{K}^0$ (Direct CP Violation) |
| $b \to d\overline{d}s$ | 0 | | | |
| $b \to c\overline{u}s$ | $V_{cb}V_{us}^*$ ($\lambda^3$) | 0 | $D^0 K \to \pi^+\pi^- K$ | $D^0\pi^0 \to \pi^+\pi^-\pi^0$ |
| $b \to u\overline{c}s$ | $V_{ub}V_{cs}^*$ ($\lambda^3$) | 0 | $\overline{D}^0 K \to \pi^+\pi^- K$ ($\gamma$) | $\overline{D}^0\pi^0 \to \pi^+\pi^-\pi^0$ |

## 2 sin2$\beta$

The decay $B^0 \to J/\psi K_S^0$ is a well-understood decay both from a theoretical as well as an experimental point-of-view. This is because the dominant penguin diagrams have the same weak phase as the tree diagram (see Table 1). The estimated reconstruction efficiency for this decay is 59% for a $K_S^0 \to \pi^+\pi^-$ final state, and 35% for a $K_S^0 \to \pi^0\pi^0$ final state. The accuracy to which $\sin 2\beta$ will be measured from a 30 $fb^{-1}$ data sample (one year of realistic operation at the $\Upsilon(4S)$ at the PEP-II design peak luminosity of $3 \times 10^{33} cm^{-2}s^{-1}$) is given in Table 3. [5]

## 3 sin2$\alpha$

This angle can be determined by studying $B$-meson decays into two pions. Despite the apparent simplicity, the decay $B^0 \to \pi^+\pi^-$ is hard to detect. The major particle backgrounds come from continuum production at the $\Upsilon(4S)$ center-of-mass as well as from misidentification of kaons from the decay $B^0 \to K^+\pi^-$. As a result, the analysis has to deal with rejection factors at the $10^{-5}$ to $10^{-6}$ level and requires a precise knowledge of detector systematics. Similar problems exist in the analyses of the decays $B^0 \to \pi^0\pi^0$ and $B^+ \to \pi^+\pi^0$.

There are a number of theoretical questions as well. The $B^0 \to \pi^0\pi^0$ decay is expected to be color-suppressed. Both QCD and electromagnetic penguin diagrams will contribute, although calculations[6,7,8] indicate that electroweak penguin contributions will be small. QCD penguin diagrams give $I = 0$ $\pi\pi$ final states. This is in contrast to the decay $B^+ \to \pi^+\pi^0$ in which the final state of two pions has only $I = 2$. Therefore, the prescription for untangling these theoretical uncertainties is that BaBar measure the rates for $B^0 \to \pi^+\pi^-$ and $B^+ \to \pi^+\pi^0$, and the time asymmetry for $B^0 \to \pi^+\pi^-$. (The time asymmetry for $B^0 \to \pi^0\pi^0$ will not be measured.)

Snyder and Quinn[9] looked at final-state interference effects in $B^0$ decays to any one of three $\rho\pi$ final states. They have shown that, in principle, a multi-parameter maximum likelihood fit to the time-dependent Dalitz plot for $B^0$ or $\overline{B}^0$ decaying to $\pi^+\pi^-\pi^0$ can be used to extract both $\sin 2\alpha$ and $\cos 2\alpha$. It also may be possible that the two decays $B^+ \to \rho^0\pi^+$ and $B^+ \to \rho^+\pi^0$ could be included in the analysis. This would give an independent fit for the weak phase of the penguin contributions. However, detection of the $\rho^+\pi^0$ decay will be difficult because of the $2\pi^0$s in the final state.

Table 3 shows the accuracy to which $\sin 2\alpha$ will be measured, under the assumption that contributions from penguin diagrams can be neglected, from a $30 fb^{-1}$ data sample collected at the $\Upsilon(4S)$.

Buras, Lautenbacher, and Ostermaier[10] have made extensive next-to-leading order QCD calculations for $B$-meson decays and have produced envelopes of $\sin 2\beta$ versus $\sin 2\alpha$ as a function of

Table 2: Leading CKM decay coefficients for decays $b \to q\bar{q}'d$

| Decay | CKM Factors (Order in $\lambda$) | | $B_d$ Modes (Angle Measured) | $B_s$ Modes (Angle Measured) |
|---|---|---|---|---|
| | Tree | Dominant Penguin | | |
| $b \to c\bar{c}d$ | $V_{cb}V_{cd}^*$ ($\lambda^3$) | $V_{tb}V_{td}^*$ ($\lambda^3$) | $\psi\pi$, $D^+D^-$ ($\beta$)† | $\psi K_S$ (Direct CP Violation) |
| $b \to s\bar{s}d$ | 0 | $V_{tb}V_{td}^*$ ($\lambda^3$) | $\phi\pi^0$, $K_S\overline{K_S}$ (Direct CP Violation) | $\phi K_S$ ($\beta$)† |
| $b \to u\bar{u}d$ | $V_{ub}V_{ud}^*$ ($\lambda^3$) | $V_{tb}V_{td}^*$ ($\lambda^3$) | $\pi\pi$, $\rho\pi$, $a_1\pi$ ($\alpha$)† | $\rho K_S$, $\pi^0 K_S$ ($\gamma$)† |
| $b \to d\bar{d}d$ | 0 | | | |
| $b \to c\bar{u}d$ | $V_{cb}V_{ud}^*$ ($\lambda^2$) | 0 | $D^0\pi^0 \to \pi^+\pi^-\pi^0$ | $D^0K_S \to \pi^+\pi^-K_S$ |
| | | | $\overline{D}^0K_S \to \pi^+\pi^-K_S$ | $\overline{D}^0K_S \to \pi^+\pi^-K_S$ |
| $b \to u\bar{c}d$ | $V_{ub}V_{cd}^*$ ($\lambda^4$) | 0 | (-) | (-) |

† Neglecting small direct CP-violation effects.

other QCD parameters whose accuracy improves with time. These envelopes are plotted in Figure 1 along with the experimental errors that should be obtainable at BaBar for the projected data samples. It is clear from this figure that BaBar can make an important contribution to CP-violation tests of the Standard Model.

## 4 $|V_{ub}|$

As was noted earlier, one of the goals of the BaBar physics program is to rigorously test the Standard Model and try to overconstrain the unitarity triangle. As such, it is important to make measurements that test the closure of the triangle. Since the length of the leg of the triangle opposite the angle $\beta$ is proportional to $V_{ub}^*$, an accurate measurement of $|V_{ub}|$ is warranted.

One method uses data taken near the endpoint of the lepton momentum spectrum from inclusive semileptonic $B^0$ decays. The semileptonic decay rate $\Gamma(B^0 \to X_u\ell^+\nu)$ is proportional to $|V_{ub}|$, and the problem lies in converting the measured rate into a value of $|V_{ub}|$. There are uncertainties in the subtraction of "feeddown" leptons from the cascade quark decays of the type: $b \to c \to lepton$.

Another method involves making measurements of exclusive semileptonic decays of the form $B^0 \to X_u\ell^+\nu$, where $X_u$ is $\pi^-$, $\rho^-$, or $\omega^-$. There are theoretical uncertainties in the resonant rate calculations and questions of nonresonant contributions that may limit the ultimate accuracy of $|V_{ub}|$ by this method.

With its large data sample, BaBar will be able to make separate measurements of the inclusive and exclusive semileptonic branching ratios for both charged and neutral $B$-meson decays. Because the separation of the decay vertices of the $B$- and $\overline{B}$-mesons will reduce greatly the combinatorial problem of assigning a particular particle to one of the two decaying $B$-mesons, BaBar should be able to fully reconstruct one of the $B$-mesons in the event and have a cleaner reconstruction of the semileptonic decay of the other $B$-meson. The separation of the two $B$-mesons will also be very useful in the measurements of small branching ratios.

## 5 sin2$\gamma$

A measurement of $\sin 2\gamma$ will be very hard. One method would require that PEP-II be run at the center-of-mass energy of the $\Upsilon(5S)$ so that BaBar could detect $B_S^0 \to \rho^0 K_S$ decays. This method suffers from three effects: (1) the $\Upsilon(5S)$ is a smaller resonance than the $\Upsilon(4S)$; (2) $B_S^0\overline{B}_S^0$ final states are only a fraction of the decays of the $\Upsilon(5S)$; and (3) BaBar has been optimized for $\Upsilon(4S)$ decays and not for $\Upsilon(5S)$ decays. Of course, at the same time $B_S^0\overline{B}_S^0$ mixing also would be measured.

Table 3: Errors on the measurement of $\sin 2(\phi_M - \phi_D)$ for various channels for a $30 fb^{-1}$ data sample. The A-tag sample includes those events tagged with a lepton which has a high probability of being a primary lepton from a semileptonic $B^0$ decay, while the B-tag sample includes all other tagged events (mainly kaon tags).

| Final State | $BR$ | $\sin 2(\phi_M - \phi_D)$ | $\sigma$ A Tags | $\sigma$ B Tags | $\sigma$ All Tags |
|---|---|---|---|---|---|
| $J/\Psi\ K_S^0$ | $5 \times 10^{-4}$ | $\sin 2\beta$ | 0.15 | 0.13 | 0.098 |
| $J/\Psi\ K_L^0$ | $5 \times 10^{-4}$ | | 0.25 | 0.21 | 0.16 |
| $J/\Psi\ K^*$ | $16 \times 10^{-4}$ | | 0.29 | 0.25 | 0.19 |
| $D^+D^-$ | $6 \times 10^{-4}$ | $\sin 2\beta$ | 0.32 | 0.27 | 0.21 |
| $D^{*+}D^{*-}$ | $7 \times 10^{-4}$ | | 0.24 | 0.20 | 0.15 |
| $D^{*\pm}D^{\mp}$ | $8 \times 10^{-4}$ | | | | 0.15 |
| Combined | | $\sin 2\beta$ | | | 0.059 |
| $\pi^+\pi^-$ | $1.2 \times 10^{-5}$ | $\sin 2\alpha$ | 0.29 | 0.27 | 0.20 |
| $\rho\pi$ | $5.8 \times 10^{-5}$ | | 0.16 | 0.16 | 0.11 |
| $a_1\pi$ | $6 \times 10^{-5}$ | | | | 0.24 |
| Combined | | $\sin 2\alpha$ | | | 0.085 |

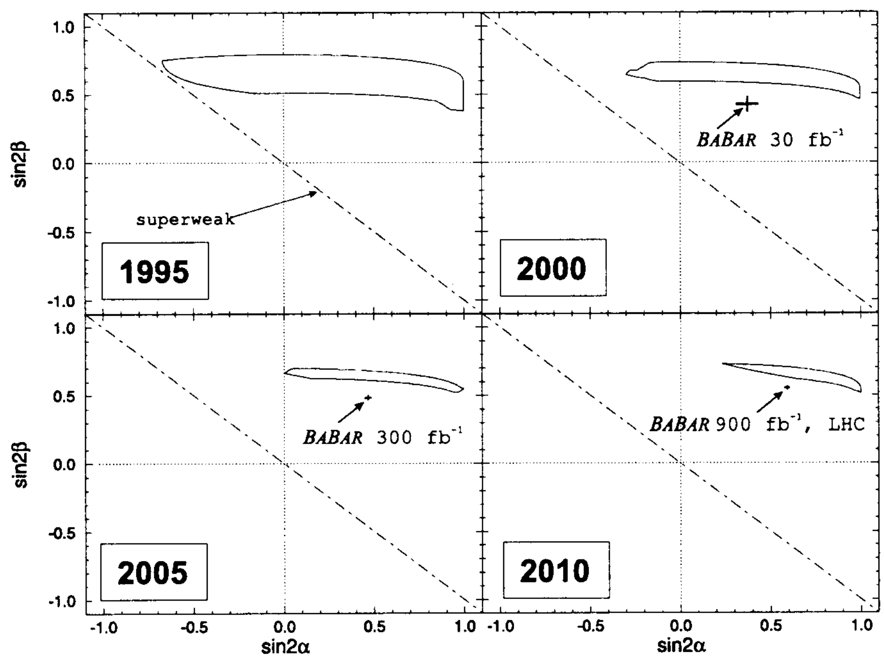


Figure 1: Plots of $\sin 2\beta$ vs $\sin 2\alpha$. The projections by Buras *et al.*,[10] based on increasingly more accurate experimental and theoretical knowledge of CKM matrix elements, quark mixing, and other QCD parameters, are given, for the years shown, by the regions inside the "banana-shaped" plots in the figures. Also shown are the projected errors in $\sin 2\alpha$ and $\sin 2\beta$ that should be achieved by BaBar from data samples of the sizes indicated.

An alternative method looks for the decays $B^+ \to \overline{D}^0 K^+$ ($B^- \to D^0 K^-$) or $B^0 \to \overline{D}^0 K^{*0}$ ($\overline{B}^0 \to D^0 K^{*0}$), where $K^{*0} \to K^+\pi^-$, and observes $D^0$ decays to CP eigenstates such as $\pi^+\pi^-$. Unfortunately these decays are Cabibbo-suppressed and thus expected to be small. The interference is between the $D^0$ and $\overline{D}^0$ contributions. For this method to be successful, it will be necessary to measure accurately a number of $B$- and $D$-meson branching fractions.

## 6 Conclusions

In conclusion, the field of $B$ physics at BaBar promises to be rich! Only now are all the options and opportunities being explored that will be available when the experimental physics program starts in two years. Our theoretical colleagues are having fun trying to understand how penguin diagrams and other higher-order QCD effects will contribute.

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## References

1. J.H. Christenson *et al.*, *Phys. Rev. Lett.* **13**, 138 (1964).
2. A.B. Carter and A.I. Sanda, *Phys. Rev. Lett.* **45**, 952 (1980); *Phys. Rev.* D **23**, 1567 (1981).
3. I.I. Bigi and A.I. Sanda, *Nucl. Phys.* B **193**, 85 (1981); *Nucl. Phys.* B **281**, 41 (1987).
4. Helen Quinn, *Nucl. Phys. Proc. Suppl.* **50**, 17 (1996)
5. BaBar Technical Design Report (D. Boutigny *et al.*), SLAC-R-95-457, 1995.
6. N.G. Deshpande and X.-G. He, *Phys. Rev. Lett.* **74**, 26 (1995).
7. M. Gronau *et al.*, *Phys. Rev.* D **52**, 6374 (1995).
8. G. Kramer and W.F. Palmer, *Phys. Rev.* D **52**, 6411 (1995).
9. A.E. Snyder and H.R. Quinn, *Phys. Rev.* D **48**, 2139 (1993).
10. A.J. Buras, M.E. Lautenbacher, and G. Ostermaier, *Phys. Rev.* D **50**, 3433 (1994).