WEAK COUPLING PHASES

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Abstract
Recent results obtained from B decays on the phases of weak couplings described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix are discussed, with particular emphasis on α and $\gamma = \pi - \beta - \alpha$.

1 INTRODUCTION

The phases of Cabibbo-Kobayashi-Maskawa (CKM) matrix elements describing charge-changing weak couplings of quarks are fundamental quantities. They are sometimes described in terms of angles $\alpha = \phi_2$, $\beta = \phi_1$, and $\gamma = \phi_3$ in the unitarity triangle. Now that BaBar and Belle are converging on a value of $\sin(2\beta)$, attention has turned to ways of learning α and $\gamma = \pi - \beta - \alpha$. This summary describes some recent work on the subject.

In Sec. 2 we discuss $B^0 \to \pi^+\pi^-$ in the light of recent measurements at BaBar [1] and Belle [2] of time-dependent asymmetries. This work was performed in part in collaboration with M. Gronau [3, 4, 5] and in part with Z. Luo [6]. We then mention how to learn γ from various $B \to K\pi$ decays (Sec. 3, collaboration with M. Gronau [3] and M. Neubert [7, 8]), $2\beta + \gamma$ from $B \to D^{(*)}\pi$ (Sec. 4, collaboration with D. Suprun and C.-W. Chiang [9]), and α and γ from tree-penguin interference in $B \to PP,\ PV$ decays, where P is a light pseudoscalar and V a light vector meson (Sec. 5, collaboration with C.-W. Chiang [10]). Sec. 6 is a short guide to other recent work, while we summarize in Sec. 7.

2 α FROM $B^0 \to \pi^+\pi^-$

We regard α, γ as uncertain to about $\pi/4$: $126^\circ \ge \alpha \ge 83^\circ$, $32^\circ \le \gamma \le 75^\circ$ [3], in accord with $122^\circ \ge \alpha \ge 75^\circ$, $37^\circ \le \gamma \le 80^\circ$ [11]. If $B^0 \to \pi^+\pi^-$ were dominated by the "tree" amplitude T with phase $\gamma = \mathrm{Arg}(V^*_{ub}V_{ud})$, the parameter $\lambda_{\pi\pi} \equiv e^{-2i\beta}A(\overline{B}^0 \to \pi^+\pi^-)/A(B^0 \to \pi^+\pi^-)$ would be just $e^{2i\alpha}$ and the indirect CP-violating asymmetry $S_{\pi\pi} = 2\mathrm{Im}\lambda_{\pi\pi}/(1 + |\lambda_{\pi\pi}|^2)$ would be $\sin 2\alpha$. Here

$$\frac{d\Gamma}{dt}\left\{ \begin{array}{c} B^0|_{t=0} \to f \\ \overline{B}^0|_{t=0} \to f \end{array} \right\} \propto e^{-\Gamma t}[1 \mp S_{\pi\pi}\sin\Delta m t \pm C_{\pi\pi}\cos\Delta m t] \quad , \tag{1}$$

$C_{\pi\pi} = (1-|\lambda_{\pi\pi}|^2)/(1+|\lambda_{\pi\pi}|^2)$, and $\Delta\Gamma \simeq \Delta m/200$ has been neglected. In the presence of non-zero $\Delta\Gamma$ one can also measure $A_{\pi\pi} = 2\mathrm{Re}\lambda_{\pi\pi}/(1+|\lambda_{\pi\pi}|^2)$. Since $|S_{\pi\pi}|^2 + |C_{\pi\pi}|^2 + |A_{\pi\pi}|^2 = 1$ one has $|S_{\pi\pi}|^2 + |C_{\pi\pi}|^2 \le 1$. However, one also has a penguin amplitude P involving a $\bar{b} \to \bar{d}$ loop transition involving contributions $\sim V^*_{ud}V_{ub}$, $V^*_{cd}V_{cb}$, and $V^*_{td}V_{tb} = -V^*_{ud}V_{ub} - V^*_{cd}V_{cb}$. The decay amplitudes are then

$$A(B^0 \to \pi^+\pi^-) = -(|T|e^{i\delta_T}e^{i\gamma} + |P|e^{i\delta_P}),\ A(\overline{B}^0 \to \pi^+\pi^-) = -(|T|e^{i\delta_T}e^{-i\gamma} + |P|e^{i\delta_P}), \tag{2}$$

where the strong phase difference $\delta \equiv \delta_P - \delta_T$. It will be convenient to define $R_{\pi\pi} \equiv \overline{\mathcal{B}}(B^0 \to \pi^+\pi^-)/\overline{\mathcal{B}}(B^0 \to \pi^+\pi^-)_{\rm tree}$, where $\overline{\mathcal{B}}$ refers to a branching ratio averaged over B^0 and $\overline{B}^0$. One may use $S_{\pi\pi}$ and $C_{\pi\pi}$ to learn α, δ, resolving a discrete ambiguity with the help of $R_{\pi\pi}$ [4]. Alternatively, one may directly use $S_{\pi\pi}$, $C_{\pi\pi}$, and $R_{\pi\pi}$ to learn α, δ, and $|P/T|$ [5, 13].

Explicit expressions for $R_{\pi\pi}$, $S_{\pi\pi}$ and $C_{\pi\pi}$ may be found in [4, 5]. In [4] we estimated $|P/T| = 0.276 \pm 0.064$ (see also [12]), obtaining $|P|$ from $B^+ \to K^0\pi^+$ via (broken) flavor SU(3) and $|T|$ from $B \to \pi\ell\nu$. Plotting $C_{\pi\pi}$ against $S_{\pi\pi}$ for various values of α in the likely range, one obtains curves parametrized by δ which establish a one-to-one correspondence between a pair $(S_{\pi\pi}, C_{\pi\pi})$ and a pair (α, δ) as long as $|\delta| \leq 90^\circ$. However, if $|\delta|$ is allowed to exceed about 90° these curves can intersect with one another, giving rise to a discrete ambiguity corresponding to as much as 30° uncertainty in α when $C_{\pi\pi} = 0$. In this case, when $\delta = 0$ or π, one has $|\lambda_{\pi\pi}| = 1$ and $S_{\pi\pi} = \sin 2(\alpha + \Delta\alpha)$, where $\tan(\Delta\alpha) = \pm(|P/T| \sin\gamma)/(1 \pm (|P/T| \cos\gamma)$ is typically $\pm 15^\circ$. One can resolve the ambiguity either by comparing the predicted $R_{\pi\pi}$ with experiment (see [4] for details) , or by comparing the allowed (ρ, η) region with that determined by other observables [11]. An example is shown in [3].

Once errors on $R_{\pi\pi}$ are reduced to ± 0.1 (they are now about three times as large [4]), a distinction between $\delta = 0$ and $\delta = \pi$ will be possible when $S_{\pi\pi} \simeq 0$, as appears to be the case for BaBar [1]. For the Belle data [2], which suggest $S_{\pi\pi} < 0$, the distinction becomes easier; it becomes harder for $S_{\pi\pi} > 0$. With 100 fb^{-1} at each of BaBar and Belle, it will be possible to reduce $\Delta|T|^2/|T|^2$ from its present error of 44% and $\overline{\mathcal{B}}(B^0 \to \pi^+\pi^-)$ from its present error of 21% each to about 10% [6], which will go a long way toward this goal. In an analysis independent of $|P/T|$ performed since the workshop, the somewhat discrepant BaBar and Belle values of $S_{\pi\pi}$ and $C_{\pi\pi}$, when averaged, favor α between about 90° and 120° (see Fig. 1 of [5]).

3 γ from $B \to K\pi$

3.1 γ from $B^0 \to K^+\pi^-$ and $B^+ \to K^0\pi^+$

We mention some results of [3] on information provided by $B^0 \to K^+\pi^-$ decays, which involve both a penguin P' and a tree T' amplitude. One can use the flavor-averaged branching ratio $\overline{\mathcal{B}}$ and the CP asymmetry in these decays, together with P' information from the $B^+ \to K^0\pi^+$ decay rate (assuming it is equal to the charge-conjugate rate, which must be checked) and T' information from $B \to \pi\ell\nu$ and flavor SU(3), to obtain constraints on γ. One considers the ratio $R \equiv [\overline{\mathcal{B}}(B^0 \to K^+\pi^-)/\overline{\mathcal{B}}(B^+ \to K^0\pi^+)][\tau_+/\tau_0]$, where the B^+/B^0 lifetime ratio τ_+/τ_0 is about 1.07. Once the error on this quantity is reduced to ± 0.05 from its value of ± 0.14 as of February 2002, which should be possible with 200 fb^{-1} at each of BaBar and Belle, one should begin to see useful constaints arising from the value of R, especially if errors on the ratio $r \equiv |T'/P'|$ can be reduced with the help of better information on $|T'|$.

3.2 γ from $B^+ \to K^+\pi^0$ and $B^+ \to K^0\pi^+$

One can use the ratio $R_c \equiv 2\overline{\mathcal{B}}(BB^+ \to K^+\pi^0)/\overline{\mathcal{B}}(B^+ \to K^0\pi^+)$ to determine γ [3, 7, 8]. Given the values as of February 2002, $R_c = 1.25 \pm 0.22$, $A_c \equiv [\mathcal{B}(B^- \to K^-\pi^0) - \mathcal{B}(B^+ \to K^+\pi^0)]/\overline{\mathcal{B}}(B^+ \to K^0\pi^+) = -0.13 \pm 0.17$, and $r_c \equiv |T' + C'|/|p'| = 0.230 \pm 0.035$ (here C' is a color-suppressed amplitude, while p' is a penguin amplitude including an electroweak contribution), and an estimate [7, 8] of the electroweak penguin contribution, one finds $\gamma \leq 90^\circ$ or $\gamma \geq 140^\circ$ at the 1σ level, updating an earlier bound [3] $\gamma \geq 50^\circ$. A useful determination would involve $\Delta R_c = \pm 0.1$, achievable with 150 fb^{-1} each at BaBar and Belle.

4 $2\beta+\gamma$ FROM $B \to D^{(*)}\pi$

The "right-sign" (RS) decay $B^0 \to D^{(*)-}\pi^+$, governed by the CKM factor $V^*_{cb}V_{ud}$, and the "wrong-sign" (WS) decay $\overline{B}^0 \to D^{(*)-}\pi^+$, governed by $V^*_{cd}V_{ub}$, can interfere through B^0–$\overline{B}^0$ mixing, leading to information on the weak phase $2\beta+\gamma$. One must separate out the dependence on a strong phase δ between the RS and WS amplitudes, measuring time-dependent observables

$$A_\pm(t) = (1+R^2) \pm (1-R^2)\cos\Delta m t~,~~B_\pm(t) = -2R\sin(2\beta+\gamma\pm\delta)\sin\Delta m t~, \quad (3)$$

where $R \equiv |\mathrm{WS}/\mathrm{RS}| = r|V^*_{cd}V_{ub}/V^*_{cb}V_{ud}| \simeq 0.02r$, with r a parameter of order 1 which needs to be known better. In Ref. [9] we use the fact that R can be measured in the decay $B^+ \to D^{*+}\pi^0$ to conclude that with 250 million $B\bar{B}$ pairs one can obtain an error of less than ± 0.05 on $\sin(2\beta+\gamma)$, which is expected to be greater than about 0.89 in the standard model. Thus, such a measurement is not likely to constrain CKM parameters, but has potential for an interesting non-standard outcome.

5 α and γ FROM $B \to PP,~PV$

Some other processes which have a near-term potential for providing information on tree-penguin interference (and hence on α and γ) are the following [10]: (1) the CP asymmetries in $B^+ \to \pi^+\eta$ and $\pi^+\eta'$; (2) rates in $B^+ \to \eta' K^+$ and $B^0 \to \eta' K^0$; (3) rates in $B^+ \to \eta K^{*+}$ and $B^0 \to \eta K^{*0}$; and (4) rates in $B^+ \to \omega K^+$ and $B^0 \to \omega K^0$. Other interesting branching ratios include those for $B^0 \to \pi^- K^{*+}$, $B^0 \to K^+\rho^-$, $B^+ \to \pi^+\rho^0$, $B^+ \to \pi^+\omega$, and $B^{(+,0)} \to \eta' K^{*(+,0)}$, with a story for each [10]. In order to see tree-penguin interference at the predicted level one needs to measure branching ratios at the level of $\Delta\overline{\mathcal{B}} = (1-2)\times 10^{-6}$.

6 OTHER WORK

For other recent suggestions on measuring α and γ, see the review of [14] and the contributions of [15] on the isospin triangle in $B \to \pi\pi$ (α), [16, 17] on $B^+ \to DK^+$ (γ), [18] on $B^0 \to DK_S$ ($2\beta+\gamma$), [19] on $B^0 \to K\pi$ (γ), [20] on $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K_-$ (γ), and [21] on $B^0 \to K^+\pi^-$ and $B_s \to K^-\pi^+$ (γ). These contain references to earlier work.

7 SUMMARY

CKM phases will be learned in many ways. While β is well-known now and will be better-known soon, present errors on α and γ are about 45°. To reduce them to 10° or less, several methods will help. (1) Time-dependent asymmetries in $B^0 \to \pi^+\pi^-$ already contain useful information. The next step will come when both BaBar and Belle accumulate samples of at least 100 fb^{-1}. (2) In $B^0 \to \pi^+\pi^-$ an ambiguity between a strong phase δ near zero and one near π (if the direct asymmetry parameter $C_{\pi\pi}$ is small) can be resolved experimentally, for example by better measurement of the $B^0 \to \pi^+\pi^-$ branching ratio and the $B \to \pi\ell\nu$ spectrum. (3) Several $B \to K\pi$ modes, when compared, can constrain γ through penguin-tree interference. This has been recognized, for example, in [11]. (4) The rates in several $B \to PP,~PV$ modes are sensitive to tree-penguin interference. One needs to measure branching ratios with errors less than 2×10^{-6} to see such effects reliably.

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