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PROSPECTS FOR MEASURING GAMMA AT BABAR

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The prospects for measuring the angle γ with present day B factories are examined. A number of approaches are discussed with reference to recent preliminary measurements based on a data sample of approximately 88 million BB pairs collected by the BaBar detector at the PEP-II asymmetric B Factory at SLAC.

1 Introduction

Until recently it was thought that the measurement of the angle γ of the Cabibbo-Kobayashi-Maskawa (CKM) matrix was beyond the reach of present day B factories such as BaBar and Belle. A number of experimental and theoretical developments have resulted in a change in attitude. The speed at which the angles β and α_{eff} have been measured has confirmed that the current experiments can extract the maximum information from the data. At the same time, both Belle and BaBar are aiming to exceed their design luminosities by considerable amounts; BaBar expects to take 500 fb^{-1} by 2006 and 1 at^{-1} by the time LHC turns on. On the theoretical side, advances have been made in factorisation and flavour–symmetry models. Branching fraction (BF) measurements at B factories have added extra constraints to theses models. At the same time, our understanding of electro-weak penguins and rescattering have given us greater confidence in our ability to directly confront the predictions of the Standard Model [1].

BaBar has reported measurements of $\sin(2\beta)$ and $\sin(2\alpha_{eff})$ where $\mid \alpha - \alpha_{eff} \mid$ is expected to be less than 51° using the conservative Grossman-Quinn bound [2,3]. From these constraints, the range $50^\circ < \gamma < 70^\circ$ would appear to be favoured. But to really understand this angle, we must make a number of direct measurements.

In the following sections, a number of possible methods are discussed. Although only preliminary results from BaBar are reported, Belle has a similar physics reach.

2 Preliminary Measurements at BaBar

A description of the BaBar detector is given here [4]. All the following measurements contain some or more of the following elements. Beam constraints are used to define a signal region. Background from continuum events are suppressed by using a series of event shape variables often in the form of Fisher discriminants or neural nets. Particle Identification is performed using energy loss in the tracking detectors and the calorimeter and the Cherenkov angle in the DIRC. If required, the two B decay vertices are reconstructed and flavour tagging performed. Finally a global maximum likelihood technique is used to achieve the greatest sensitivity.

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2.1 $B^{\pm} \to D_{CP} K^{\pm}$

The CP eigenstates $\mid D^0_{\pm}\rangle$ of the neutral D meson system with CP eigenvalues ± 1 are given by:

$$\mid D^0_{\pm}\rangle = \frac{1}{\sqrt{2}}\left(\mid D^0\rangle \pm \mid \overline{D}^0\rangle\right) \tag{1}$$

so that the $B^{\pm} \to D^0_{+} K^{\pm}$ transition amplitudes can be expressed as:

$$\begin{aligned}\sqrt{2}A(B^+ \to D^0_+ K^+) &= A(B^+ \to D^0 K^+) + A(B^+ \to \overline{D}^0 K^+) \\ \sqrt{2}A(B^- \to D^0_+ K^-) &= A(B^- \to D^0 K^-) + A(B^- \to \overline{D}^0 K^-)\end{aligned} \tag{2}$$

These relations are exact, originate from pure tree decays and receive no contributions from penguins. They can be represented by 2 triangles in the complex plane. Since the transition amplitude A$(B^+ \to \overline{D}^0 K^+)$ = A$(B^- \to D^0 K^-)$ and the difference in CP-violating weak phase between the $B^+ \to D^0 K^+$ and the $B^- \to \overline{D}^0 K^-$ amplitudes is proportional to $e^{2i\gamma}$, these triangles allow a determination of γ by measuring the six amplitudes. A complementary method uses $B^0 \to D^0_+ K^{*0}$, $B^0 \to \overline{D}^0 K^{*0}$ and $B^0 \to D^0 K^{*0}$.

BaBar has measured the ratio of the branching fractions $B^- \to D^0 K^-$ and $B^- \to D^0 \pi^-$ to be $8.31 \pm 0.35 \pm 0.2\%$ with the individual ratios for the sub–decays $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^+\pi^-$ and $D^0 \to K^-\pi^+\pi^0$ to be $8.4 \pm 0.5 \pm 0.2\%$, $8.7 \pm 0.7 \pm 0.3\%$ and $7.7 \pm 0.7 \pm 0.2\%$ respectively. The ratio of the branching fractions for the decay $B^{\pm} \to D^0_+ K^{\pm}$ to $B^{\pm} \to D^0_+ \pi^{\pm}$ is $7.42 \pm 1.7 \pm 0.6\%$ for $D^0_+ \to K^-K^+$ and $12.9 \pm 4.0^{+1.1}_{-1.5}\%$ for $D^0_+ \to \pi^-\pi^+$. The weighted average is $8.8 \pm 1.6 \pm 0.5\%$. The CP asymmetry is measured to be [5]:

$$A_{CP} = \frac{BF(B^- \to D^0_+ K^-) - BF(B^+ \to D^0_+ K^+)}{BF(B^- \to D^0_+ K^-) + BF(B^+ \to D^0_+ K^+)} = 0.07 \pm 0.17 \pm 0.06 \tag{3}$$

2.2 $B \to \pi\pi, \pi K$

An alternative method is to use SU(3) flavour symmetries to derive amplitude relationships between B decays into $\pi\pi$, πK and $K\overline{K}$. The amplitudes for the decays $B^+ \to \pi^+\pi^0$, $B^+ \to \pi^+ K^0$ and $B^+ \to K^+\pi^0$ can be expanded in terms of colour-allowed and colour-suppressed tree diagrams and QCD penguin diagrams for both strangeness–preserving and strangeness–changing reactions. Neglecting electroweak penguins, this can be written in terms two triangles again:

$$\sqrt{2}A(B^+ \to \pi^0 K^+) + A(B^+ \to \pi^+ K^0) = r_u \sqrt{2}A(B^+ \to \pi^0\pi^+) \tag{4}$$
$$\sqrt{2}A(B^- \to \pi^0 K^-) + A(B^- \to \pi^- K^0) = r_u \sqrt{2}A(B^- \to \pi^0\pi^-) \tag{5}$$

where r_u is approximately the ratio of strangeness-changing to strangeness–preserving tree diagrams. Since no tagging or time–dependent analyses are required this is a promising experimental measurement.

The six sides of the two triangles have been measured by BaBar. Table 1 shows the 90% confidence upper limits, branching fractions and CP asymmetries for a number of πK modes [6]. Constraints on the angle γ can be derived from the ratio of the branching fractions of a number of these modes [7].

2.3 $\sin(2\beta + \gamma)$ *from* $B^0 \to D^{(*)-}\pi^+$

If the value of $\sin(2\beta)$ is taken from other measurements then γ can be extracted from measurements of $\sin(2\beta + \gamma)$ in the decays of $B^0 \to D^{(*)\pm}\pi^{\mp}$. The CP asymmetries are expected to be

Mode	Branching Fraction ($\times 10^{-6}$)	A_{CP}
$B^0 \to K^+\pi^-$	$17.9 \pm 0.9 \pm 0.7$	$-0.102 \pm 0.050 \pm 0.016$
$B^+ \to \pi^+\pi^0$	$5.5^{+1.0}_{-0.9} \pm 0.6$	$-0.03^{+0.18}_{-0.17} \pm 0.02$
$B^+ \to K^+\pi^0$	$12.8^{+1.2}_{-1.1} \pm 1.0$	$-0.09 \pm 0.09 \pm 0.01$
$B^+ \to K^0\pi^+$	$17.5 \pm 1.8 \pm 1.3$	$-0.17 \pm 0.10 \pm 0.02$
$B^0 \to K^0\pi^0$	$10.4 \pm 1.5 \pm 0.8$	$0.03 \pm 0.36 \pm 0.09$
$B^0 \to \pi^+\pi^-$	$4.6 \pm 0.6 \pm 0.2$	
$B^0 \to \pi^0\pi^0$	< 3.6	
$B^0 \to K^+K^-$	< 0.6	
$B^0 \to K^+K^0$	< 1.3	

Table 1: Branching Fractions, CP asymmetries and 90% confidence upper limits for $B \to K\pi$, $\pi\pi$ and KK decays.

small but the decay rates are large. Both $D^{(*)+}\pi^-$ and $D^{(*)-}\pi^+$ are accessible from B^0 and $\overline{B}^0$ decays. The angle γ enters through the Cabibbo–suppressed amplitude V_{ub}. The branching fraction $B^0 \to D^{(*)+}\pi^-$ has not been measured but it can be estimated from the measurement of $B^0 \to D_s^{(*)+}\pi^-$ and the SU(3) symmetry relation [8]:

$$BF(B^0 \to D_s^{(*)+}\pi^-) \equiv \frac{BF(B^0 \to D^{(*)-}\pi^+)}{\tan^2\theta_c} \frac{f^2_{D_s^{(*)}}}{f^2_{D^{(*)}}} \lambda^2_{D^{(*)}\pi} \tag{6}$$

where θ_c is the Cabibbo angle, f are calculated form factors [9] and $\lambda_{D^{(*)}\pi}$ is given by:

$$\lambda_{D^{(*)}\pi} = \frac{A(\overline{B}^0 \to D^{(*)+}\pi^-)}{A(B^0 \to D^{(*)+}\pi^-)} e^{-2\beta} = \mid \lambda_{D^{(*)}\pi} \mid e^{-i(2\beta+\gamma)} \tag{7}$$

$\lambda_{D\pi}$ is measured by BaBar to be $0.021^{+0.004}_{-0.005}$ and $\lambda_{D^*\pi} = 0.017^{+0.005}_{-0.007}$. An additional error of 30% is required for uncertainties in the SU(3) symmetry breaking. In addition the following branching fractions and 90% confidence upper limits have been measured [10]: $B^0 \to D_s^+\pi^- = 3.1 \pm 1.0 \pm 1.0 \times 10^{-5}$, $B^0 \to D_s^{*+}\pi^- < 4.1 \times 10^{-5}$, $B^0 \to D_s^- K^+ = 3.2 \pm 1.0 \pm 1.0 \times 10^{-5}$ and $B^0 \to D_s^{*-}K^+ < 2.5 \times 10^{-5}$.

2.4 $B^\pm \to \pi\pi\pi, \pi\pi K$

It has been proposed that Dalitz plots in charmless 3-body decays can be used to extract γ [11]. The Dalitz plot for $B^\pm \to \pi^+\pi^-\pi^\pm$ has a number of resonances with amplitudes proportional to $V_{ub}V_{ud} \sim e^{-i\gamma}$. Providing there are at least 2 weak and 2 strong phases, the angle γ can be extracted from interference between the resonances and non–resonance decays. There are some approximations concerning the relative contributions of tree and penguin diagrams; this can be compensated for by using the $B^\pm \to K^+\pi^-\pi^\pm$ Dalitz plot and SU(3) symmetry relations.

BaBar has measured the inclusive rates and CP asymmetries for $B^\pm \to h^+h^-h^\pm$ where h=π,K and exclusive rates for $B^\pm \to K^+\pi^-\pi^\pm$. These results are tabulated in Table 2 [12].

3 Conclusion

Progress has been made on a number of approaches to the measurement of the angle γ. The ultimate accuracy is hard to estimate as the error on γ depends on the value of γ but meaningful measurements of the angle γ should be possible by the end of the lifetime of the current experiments.

Mode	Branching Fraction ($\times 10^{-6}$)	A_{CP}
$B^+ \to \pi^+\pi^-\pi^+$	$10.9 \pm 3.3 \pm 1.6$	$-.039 \pm 0.33 \pm 0.12$
$B^+ \to K^+\pi^-\pi^+$	$59.2 \pm 3.8 \pm 3.2$	$0.01 \pm 0.07 \pm 0.03$
$B^+ \to K^+K^-K^+$	$29.6 \pm 2.1 \pm 1.6$	$0.02 \pm 0.07 \pm 0.03$
$B^+ \to K^+K^-K^+$	< 6.3	
$B^+ \to \pi^+K^-\pi^+$	< 1.8	
$B^+ \to K^+\pi^-K^+$	< 1.3	
$B^+ \to K^{*0}(892)\pi^+, K^{*0} \to K^-\pi^-$	$10.3 \pm 1.2^{+1.0}_{-2.7}$	
$B^+ \to f_0(980)K^+, f_0 \to \pi^+\pi^-$	$9.2 \pm 1.2^{+2.1}_{-2.0}$	
$B^+ \to \chi_{c0}K^+, \chi_{c0} \to \pi^+\pi^-$	$1.46 \pm 0.35 \pm 0.12$	
$B^+ \to D^0\pi^+, D^0 \to K^+\pi^-$	$184.6 \pm 3.2 \pm 9.7$	
$B^+ \to$ higher $K^{*0}\pi^+, K^{*0} \to K^+\pi^-$	$25.1 \pm 2.0^{+11.0}_{-5.7}$	
$B^+ \to \rho_0(770)K^+, \rho_0 \to \pi^+\pi^-$	< 6.2	
$B^+ \to K^+\pi^+\pi^-$ (non–resonant)	< 17	
$B^+ \to$ higher f $K^+, f \to \pi^+\pi^-$	< 12	

Table 2: Branching Fractions, CP asymmetries and 90% confidence upper limits for inclusive 3-body decays to $h^+h^-h^+$ ($h = \pi, K$) and exclusive decays to $K^+\pi^-\pi^+$.

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