ABSTRACT

The role of penguin amplitudes in CP violating $B$ decays is reviewed, emphasizing recent progress in the analysis of electroweak penguin contributions. It is shown how these terms are included in a model-independent manner when measuring the weak phase $\alpha$ in $B \rightarrow \pi\pi$ using isospin symmetry, and when determining the phase $\gamma$ from $B \rightarrow K\pi$ applying flavor SU(3). Uncertainties due to rescattering effects in $B \rightarrow K\pi$ are discussed.

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1 Introduction

The long awaited recent report [1] on a clear observation of direct CP violation in $K \to \pi\pi$ decays, $\text{Re}(\epsilon'/\epsilon) = (28.0 \pm 3.0 \pm 2.6 \pm 1.0) \times 10^{-4}$, is the first evidence for the important role played by penguin amplitudes in the phenomena of CP violation [2]. $B$ decays are expected to provide a variety of CP asymmetry measurements, as well as measurements of certain combinations of rates, some of which carry the promise of determining the angles of the unitarity triangle [3], $\alpha, \beta$ and $\gamma$. This can test the commonly accepted hypothesis that CP violation arises solely from phases in the Cabibbo-Kobayashi-Maskawa matrix [4]. Let us review [5] a few of the ideas involved in this study, paying particular attention to the role of penguin amplitudes.

- $\beta$: In the experimentally feasible [6] and theoretically pure example of $B^0(t) \to J/\psi K_S$ the decay amplitude is real to a very high precision. Theoretically [7], the time-dependent mixing-induced CP asymmetry measures the phase $\beta \equiv -\text{Arg}V_{td}$ controlling $B^0-\bar{B}^0$ mixing to an accuracy of 1% [8].

- $\alpha$: $B^0(t) \to \pi^+\pi^-$ involves direct CP violation from the interference between a dominant current-current amplitude carrying a weak phase $\gamma$ and a smaller penguin contribution, which “pollutes” the measured $\sin\Delta m_t$ term in the time-dependent asymmetry [8]. A ratio of penguin to tree amplitudes $|P/T|$ = $0.3 \pm 0.1$ in $B^0 \to \pi^+\pi^-$ is inferred [8] from the measured rates [10] of $B \to K\pi$ dominated by a penguin amplitude. Such a penguin contribution introduces a sizable uncertainty [11] in the determination of $\alpha = \pi - \beta - \gamma$ in $B^0 \to \pi^+\pi^-$. Isospin symmetry may be used [12] to remove this unknown correction to $\alpha$ by measuring also the time-integrated rates of $B^\pm \to \pi^\pm\pi^0$ and $B^0(\bar{B}^0) \to \pi^0\pi^0$. In the likely case that the decay rate into $\pi^0\pi^0$ cannot be measured with sufficient precision, one can at least use this measurement to set upper limits on the error in $\alpha$ [13]. Further out in the future, one may combine the time-dependence of $B^0(t) \to \pi^+\pi^-$ with the U-spin related $B_s(t) \to K^+K^-$ to determine separately $\beta$ and $\gamma$ [14]. This involves uncertainties due to SU(3) breaking.

- $\gamma$: The angle $\gamma$ is apparently the most difficult to measure. It was suggested some time ago [15] to obtain information about this angle from charged $B$ decays to $K\pi$ final states by measuring the relative phase between a dominant real penguin amplitude and a smaller current-current amplitude carrying the phase $\gamma$. This is achieved by relating the latter amplitude through flavor SU(3) [16] to the amplitude of $B^\pm \to \pi^\pm\pi^0$, introducing SU(3) breaking in terms of $f_K/f_\pi$.

In the above two examples of determining $\alpha$ and $\gamma$, QCD penguin amplitudes were taken into account in terms of their very general properties, whereas electroweak penguin (EWP) contributions were first neglected and later on analyzed in a model-dependent manner [17]. Such an approach relies on factorization and on form factor
assumptions \[18\], and involves theoretical uncertainties in hadronic matrix elements similar to those plaguing \(\epsilon'/\epsilon\) \[2\].

In the present report we will focus on recent developments in the study of EWP contributions, which partially avoid these uncertainties, thereby improving the potential accuracy of measuring \(\alpha\) and \(\gamma\).

2 Model-independent treatment of electroweak penguins

The weak Hamiltonian governing \(B\) decays is given by \[19\]
\[
\mathcal{H} = \frac{G_F}{\sqrt{2}} \sum_{q=d,s} \left( \sum_{q' = u,c} \lambda_{q'}^{(q)} [c_1 Q_1 + c_2 Q_2] - \lambda_t^{(q)} \sum_{i=3}^{10} c_i Q_i^{(q)} \right),
\]
where \(Q_1 = (\bar{b} q')_{V-A}(q' q)_{V-A}, Q_2 = (\bar{b} q')_{V-A}(q' q)_{V-A}, \lambda_{q'}^{(q)} = V_{qb}^{*} V_{q'q}, q = d, s, q' = u, c, t, \lambda_u^{(q)} + \lambda_c^{(q)} + \lambda_t^{(q)} = 0\). The dominant EWP operators \(Q_9, Q_{10}\) have a \((V-A)(V-A)\) chiral structure, similar to the current-current operators \(Q_1, Q_2\).

Thus, isospin alone relates the matrix elements of these operators in \(B^+ \to \pi^+ \pi^0\) \[20\]
\[
\sqrt{2} P^{EW}(B^+ \to \pi^+ \pi^0) = \frac{3}{2} \kappa (T + C), \quad \kappa = \frac{c_9 + c_{10}}{c_1 + c_2} = -0.0088 ,
\]
where \(T + C\) represents graphically \[16\] the current-current amplitudes dominating \(B^+ \to \pi^+ \pi^0\). Similarly, flavor \(SU(3)\) implies \[20\]
\[
P^{EW}(B^0 \to K^0 \pi^+) + \sqrt{2} P^{EW}(B^+ \to K^+ \pi^0) = \frac{3}{2} \kappa (T + C) ,
\]
\[
P^{EW}(B^0 \to K^+ \pi^-) + P^{EW}(B^+ \to K^0 \pi^+) = \frac{3}{2} \kappa (C - E) .
\]

In the next three sections we describe briefly applications of these three relations to the determination of \(\alpha\) and \(\gamma\) from \(B \to \pi\pi\) and \(B \to K\pi\), respectively.

3 Controlling EWP contributions in \(B \to \pi\pi\)

The time-dependent rate of \(B^0 \to \pi^+ \pi^-\) includes a term \(\sim \sin(2\alpha + \theta) \sin(\Delta mt)\), where the correction \(\theta\) is due to penguin amplitudes \[12\]. Using isospin \[2\], the EWP contribution to \(\theta\), denoted by \(\xi\), is found to be very small \[21, 22\]
\[
\tan \xi = \frac{x \sin \alpha}{1 + x \cos \alpha}, \quad x \equiv \frac{3}{2} \kappa |\frac{\lambda_t^{(d)}}{\lambda_u^{(d)}}| = -0.013 |\frac{\lambda_t^{(d)}}{\lambda_u^{(d)}}| ,
\]
and is nicely incorporated into the analysis of Ref. 12 which determines \(\alpha\).
4  \( \gamma \) from \( B^+ \to K\pi \)

Using (3), EWP terms are included in the triangle construction of Ref. 15 \[23\]

\[
\sqrt{2}A(B^+ \to K^+\pi^0) + A(B^+ \to K^0\pi^+) = \tilde{r}_u A(B^+ \to \pi^+\pi^0) \left(1 - \delta_{EW} e^{-i\gamma}\right),
\]

(6)

where \( \tilde{r}_u = (f_K/f_\pi)\tan \theta_c \simeq 0.28 \), \( \delta_{EW} = -(3/2) |\lambda^{(s)}_t/\lambda^{(u)}_u| \kappa \simeq 0.66 \pm 0.15 \). This relation and its charge-conjugate permit a determination of \( \gamma \) \[15, 23\] under the assumption that a rescattering amplitude with phase \( \gamma \) can be neglected in \( B^+ \to K^0\pi^+ \). This amplitude is bounded by the U-spin related rate of \( B^{\pm} \to K^{\pm}\bar{K}^0 \) \[24, 25, 26\]. Present limits are at the level of 20 – 30\% of the dominant penguin amplitude \[20, 27\], and are expected to be improved to the level of 10\%. In this case the rescattering effect, which depends strongly on the final state phase difference \( \phi \) between \( I = 3/2 \) current-current and penguin amplitudes, introduces an uncertainty at a level of 15\° in the determination of \( \gamma \) if \( \phi \) is near 90\° \[28\]. A considerably smaller theoretical error \[27\] would be implied if this measurable phase is found to be far from 90\°.

Other sources of errors in \( \gamma \), such as SU(3) breaking, are discussed elsewhere at this meeting \[27, 29\]. We note that in this determination of \( \gamma \) SU(3) breaking does not occur in the leading penguin amplitudes as it does in some other methods \[14\].

The phase \( \gamma \) can also be constrained by measuring only charge-averaged \( B^{\pm} \to K\pi \) rates. Defining

\[
R^{-1} = \frac{2[B(B^+ \to K^+\pi^0) + B(B^- \to K^-\pi^0)]}{B(B^+ \to K^0\pi^+) + B(B^- \to K^0\pi^-)},
\]

(7)

one finds using (3) \[20, 21\]

\[
R^{-1} = 1 - 2\epsilon \cos \phi (\cos \gamma - \delta_{EW}) + O(\epsilon^2, \epsilon_A^2, \epsilon_A),
\]

(8)

where \[15, 27\] \( \epsilon = \tilde{r}_u \sqrt{2} |A(B^{\pm} \to \pi^+\pi^0)/A(B^{\pm} \to K^0\pi^\pm)| \sim 0.24 \), while \( \epsilon_A \) is the suitably normalized rescattering amplitude. The resulting bound

\[
|\cos \gamma - \delta_{EW}| \geq \frac{|1 - R^{-1}|}{2\epsilon},
\]

(9)

which neglects second order corrections, can be used to exclude an interesting region around \( \cos \gamma = \delta_{EW} \) if \( R^{-1} \neq 1 \) is measured. Again, this would be very difficult if \( \phi \simeq 90\° \). The present value of the ratio of rates is \[10\] \( R^{-1} = 2.1 \pm 1.1 \).

5 \( \gamma \) from the ratio of \( B^0 \to K^{\pm}\pi^{\mp} \) to \( B^{\pm} \to K^0\pi^{\pm} \) rates

Denoting this ratio of charged-averaged rates by \( R \) \[30\], one finds using (4) a constraint very similar to (8) \[14, 24, 22\]

\[
|\cos \gamma - \delta'_{EW}| \geq \frac{|1 - R|}{2\epsilon'},
\]

(10)
where $\delta'_{EW} \sim 0.2\delta_{EW} \sim 0.13$ represents color-suppressed EWP contributions, and $\epsilon' \sim 0.2$ is the ratio of tree to penguin amplitudes in $B^0 \to K^+\pi^-$. In contrast to (9), this bound neglects first order rescattering effects, and the values of $\delta'_{EW}$ and $\epsilon'$ are less solid than those of $\delta_{EW}$ and $\epsilon$ in (9). Eq. (10) can exclude a region around $\gamma = 90^\circ$ if $R \neq 1$ is found. Presently $R = 1.07 \pm 0.45$.

6 Conclusion

- In $B \to \pi\pi$ strong and electroweak penguins are controlled by isospin.
- In $B \to K\pi$ strong penguins dominate and EWP are controlled by SU(3).
- Interesting bounds on $\gamma$, in one case susceptible to rescattering effects, are implied if the $B \to K\pi$ charge-averaged ratios of rates differ from 1.
- A precise determination of $\gamma$ from $B \to K\pi$ is challenging and requires a combined effort involving further theoretical and experimental studies.

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