On determing CKM angles α and β

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ABSTRACT: Because the $B_d \to J/\psi K_S$ asymmetry determines only $\sin 2\beta$, a discrete ambiguity in the true value of β remains. This note reviews how the ambiguity can be removed. Extractions of the CKM angle α are discussed next. Some of the methods require very large data samples and will not be feasible in the near future. Still, in the near future, semi-inclusive CP-violating searches could be undertaken, which are reviewed last.

KEYWORDS: Heavy Quark Physics, CKM Parameters, CP Violation.

1. CKM angle β

The primary goal of the various B-factories is to test most incisively the standard CKM (Cabibbo-Kobayashi-Maskawa) [1] description of CP violation.

For that purpose, the CKM angle β extraction via the "golden" $B_d \to J/\psi K_S$ asymmetry [2] can be contrasted to those via the $B \to \phi K_S, \eta' K_S, D\overline{D}, D^0_{CP}\rho^0$, etc. asymmetries. Any significant discrepancy in the measured β values indicates physics beyond the standard model [3].

The CKM predictions can be tested more incisively by removing discrete CKM ambiguities. The CP-violating asymmetry of $B_d \to J/\psi K_S$ allows the determination of $\sin 2\beta$ [2, 4]. A discrete ambiguity in determining $\beta \in [0, 2\pi)$ remains. Measuring $\cos 2\beta$ removes the ambiguity partially and can be accomplished, either by

(a) correlating $B_s(t) \to J/\psi\phi$ with $B_d(t) \to J/\psi(\pi^0 K_S)_{K^*}$ $[B_d(t) \to J/\psi\rho^0]$ decays [5].

(b) studying the decay-time (t_K) of the produced neutral kaon [6, 7] in the process

$$B_d(t) \to J/\psi \overset{(-)}{K^0} (t_K), \quad \overset{(-)}{K^0} (t_K) \to \pi\ell\nu, \pi\pi.$$

(c) analyzing Dalitz plots [8] of

$$B_d(t) \to D\overline{D}K_S, D^0_{CP}\pi^+\pi^-, \ldots$$

(d) using the $B_d - \overline{B}_d$ width difference[1]

$$(\Delta\Gamma/\Gamma)_{B_d} \lesssim 1\%. \quad [9]$$

Further methods to remove ambiguities can be found in Ref. [10].

1.1 Physics of Ambiguity Removal

The underlying reason on how $\cos 2\beta$ enters is in each case trivial. For instance, consider the above method (d). The interference term λ is defined by

$$\lambda \equiv \frac{q}{p}\frac{< f|\overline{B^0} >}{< f|B^0 >} = -e^{-i2\beta} \quad \text{for } f = J/\psi K_S. \tag{1.1}$$

The coefficients q and p describe the mass-eigenstates in terms of B^0 and $\overline{B^0}$ states, respectively [4, 11, 12]. Note that λ is an observable, i.e., a rephase-invariant quantity [12, 13]. Thus, both $Im\lambda$ and $Re\lambda$ are measurable, in principle.

The conventional CP-asymmetry measures $Im\lambda$, and is given by (ignoring $\Delta\Gamma$):

$$\text{Asym}(B_d(t) \to J/\psi K_S) = -Im\lambda \;\; \sin \Delta mt. \tag{1.2}$$

[1]If a non-zero width difference $(\Delta\Gamma)_{B_d}$ has been measured, then $\cos 2\beta$ can be obtained from the time-dependence of the untagged $J/\psi K_S$ sample.

However, $Re\lambda$ enters in the untagged time-dependence [11],[2]

$$\begin{aligned}\Gamma[J/\psi K_S(t)] \equiv\ & \Gamma(B_d(t) \to J/\psi K_S) + \\ & \Gamma(\overline{B_d}(t) \to J/\psi K_S) \\ \sim\ & e^{-\Gamma_L t} + e^{-\Gamma_H t} + \\ & Re\lambda(e^{-\Gamma_L t} - e^{-\Gamma_H t}). \quad (1.3)\end{aligned}$$

Because the expected $\Delta\Gamma/\Gamma$ is tiny, an excess of 10^5 untagged $J/\psi K_S$ events is required. Then studies of effects dependent on the $B_d - \overline{B_d}$ width difference become feasible.

While the above discussion may become relevant only in the far future of B_d physics, it is of more immediate importance for B_s physics.

The $B_s - \overline{B_s}$ width difference is predicted to be sizable (around 10%) [9], and once observed will permit the unambiguous [11] extraction of CKM phases in $B_s(t) \to f$ processes. For example, a time dependent study of $B_s(t) \to D_s^\pm K^\mp$ [15] will determine the CKM angle γ unambiguously. Experiments where B_s mesons are copiously produced, may be able to make extensive use of this opportunity.

2. CKM angle α

The CKM matrix can be completely specified by four independent quantities. The three angles of the CKM unitarity triangle satisfy

$$\alpha = \pi - \beta - \gamma,$$

and thus are not independent.

Since we were asked to discuss the extraction of the angle α, we should have reviewed the determination of the CKM angle γ. The angle γ can be determined from

(a) a $B \to K\pi$ analysis [16],

(b) $B_s(t) \to D_s^\pm K^\mp$ studies [15],

(c) a $B^- \to D^0 K^-, \overline{D^0} K^-$ analysis [17],

(d) Dalitz plot analyses [18],

(e) $B_d(t) \to \pi^+\pi^-$ and $B_s(t) \to K^+K^-$ correlations [19, 20],

(f) $B_d(t) \to J/\psi K_S$ and $B_s(t) \to J/\psi K_S$ correlations [19, 20].

However, Neubert addressed the extraction of the CKM angle γ [21], and this note thus reviews the "traditional" CKM α determinations.

The angle α can be determined from

(1) the $B_d(t) \to \pi^+\pi^-$ asymmetry if penguin amplitudes were negligible,

(2) $B_d(t) \to \rho\pi$ Dalitz plot analyses [22],

(3) $B_d(t) \to D^{(*)\pm}\pi^\mp$ studies [23].

Penguin amplitudes in the $B \to \pi^+\pi^-$ process are likely to be sizable, as can be inferred from the recent CLEO measurement [24]

$$\frac{B(B \to K\pi)}{B(B \to \pi\pi)} \approx 4,$$

and the naive approach (1) will probably not work. The CKM angle α can be extracted by selecting the "penguin-free" $B \to (\pi\pi)_{I=2}$ process [25].[3] The selection requires studies of $B \to \pi^0\pi^0$, which is not feasible with first generation B-experiments.

However, recent theoretical advances indicate that it may be possible to determine the CKM angle α from the $B_d(t) \to \pi^+\pi^-$ asymmetry alone [27].

Approach (2) requires large statistics [28]. But once obtained, the CKM angle α can be extracted even if penguins are present. Electroweak penguin contributions may introduce sizable uncertainties, and must be studied further.[4]

The $D^{(*)\pm}\pi^\mp$ processes permit the clean determination of $\beta - \alpha$ or of $2\beta + \gamma$ because no penguins are involved [23]. Since β will be known α (or γ) can thus be determined.

[2] Eq. (1.3) is correct for $|q/p| = 1$, which holds to an excellent approximation within the CKM model. However, when the statistics gets sufficiently large to detect effects due to a non-vanishing width difference, then also the effects due to $|q/p| \neq 1$ [14] may have to be incorporated. Determining the sign of $\cos 2\beta$ from Eq. (1.3) requires independent knowledge of whether $\Delta\Gamma \equiv \Gamma_H - \Gamma_L$ is positive or negative. This independent knowledge may be very difficult to achieve. Thus, the argument can be reversed and Eq. (1.3) may be used to determine the observable sign($\Delta\Gamma$), because sign($\cos 2\beta$) will be known by other means.

[3] Electro-weak penguin amplitudes may have to be accounted for also [26].

[4] They were found to be small in particular models [29].

3. Near Future

For the near future, experiments will not be sensitive to CP violationg effects with tiny branching ratios, because of limited integrated luminosity. One may still be able to study (semi-) inclusive CP asymmetries.

For instance, mixing-induced CP violation can be searched for in double charm, single charm and charmless B^0 samples [30, 31, 9].

Table I lists the required number of tagged B^0 and $\overline{B^0}$ mesons to observe 3σ effects [31]. Such effects, once observed, can be related to CKM parameters [30, 31, 9].

Other promising mixing-induced CP asymmetries are

(1) $B^0(t) \to J/\psi X$ versus $\overline{B^0}(t) \to J/\psi X$,

(2) $B^0(t) \to (\text{primary } K_S)X$ versus $\overline{B^0}(t) \to (\text{primary } K_S)X$.

All the above effects in this Section require flavor-tagging, which is expensive. The flavor-tagging requirement reduces the statistical reach by an order of magnitude.

Thus, direct CP violation should be searched for also. It requires neither flavor-tagging nor mixing nor time-dependences. [At hadron colliders, the long b-lifetimes are a blessing and provide the primary distinction between b-hadrons and backgrounds. For hadron colliders, time-dependences are no hindrance.]

Browder et al. [32] suggested to search for semi-inclusive CP asymmetries in

$$B \to K^+X, K^*X \text{ versus } \overline{B} \to K^-X, \overline{K^*}X,$$

where the $K^{(*)}$ has a very high momentum. The $BR \sim 10^{-4}$ and the CP asymmetries are expected to be $\lesssim 10\%$. Additional semi-inclusive CP-violating effects were discussed in Ref. [33].

The semi-inclusive $b \to J/\psi + d$ processes also may exhibit direct CP asymmetries at the $\lesssim$ few % level [34, 19]. Their $BR \approx 5 \times 10^{-4}$ and the effect can be searched for in charged $B^\pm$ decays,

$$N(J/\psi X_d^+) \neq N(J/\psi X_d^-).$$

4. Conclusions

The CKM quantity $\sin 2\beta$ will soon be measured accurately from the $B \to J/\psi K_S$ asymmetry.

Measurements of the sign of $\cos 2\beta$ will test the CKM model more incisively (see Section 1). Section 1 emphasizes that time-dependent studies of B_s decays can determine CKM parameters without any discrete ambiguity! The relevant B_s modes thus probe the CKM model in detail.

Section 2 discusses several ways of determing the CKM angle α. Because CP effects with tiny $BR's$ are unreachable in the near future, Section 3 suggests several (semi-)inclusive CP asymmetries, some of which could even yield valuable CKM information.

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Final state of $B^0 (\equiv B_d^0$ or $B_s^0)$	Required number of flavor tagged B_s^0 & $\overline{B_s^0}$ (B_d^0 & $\overline{B_d^0}$) mesons
double charm	2×10^5 (2×10^6)
single charm	6×10^5 (8×10^6)
charmless	10^6 (2×10^7)

Table 1: Number of flavor-tagged B^0 plus $\overline{B^0}$ mesons necessary to observe a 3σ CP-violating effect (column 2) in the modes specified by column 1.

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