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Yet another way to measure γ

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Abstract

We show that the CKM phase $2\beta+\gamma$ can be extracted from measurement of the time dependent rates in the decays $\bar{B}^0 \to D^{(*)\pm} M^{\mp}$ and $B^0 \to D^{(*)\pm} M^{\mp}$, where $M = a_0$, $\pi(1300)$, b_1, a_2, π_2, ρ_3. These channels have a large asymmetry between decays of $\bar{B}^0$ and B^0 into the same final state. Even though the branching ratios are small, their sensitivity to γ can be competitive with decays into $D^{(*)}$ and (π, ρ, a_1).

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Introduction. In the Standard Model of electroweak and strong interactions, *CP* violation arises naturally from mixing among three generations of quarks, encoded in the CKM matrix. Successful to date, this highly predictive prescription is being tested at the B-factories Belle, BaBar, CLEO. Further information will come from ongoing and future hadron collider experiments like Run II at the Tevatron, BTeV and LHC-B.

Among the three angles of the unitarity triangle parameterization of the CKM matrix, only β has been measured so far. The present world average is $\sin 2\beta = 0.48 \pm 0.16$ [1]. In the future this uncertainty will be greatly reduced, to $\mathcal{O}(10\%)$ at B-factories [2], and to a few percent at BTeV and LHC-B [3]. From Standard Model fits, the angle γ is expected to be large, $\gamma = 63^{+8}_{-11}$ degrees [1], in agreement with other analyses [4].

We have recently explored hadronic B decays into an isospin 1 meson with small or zero coupling to the weak vertex, either due to a small decay constant or because it has spin greater than one [5]. We found that specific decay modes involving the candidates

$$M = a_0(980), a_0(1450), \pi(1300), b_1, a_2, \pi_2, \rho_3 \tag{1}$$

are very sensitive to strong interaction dynamics, and allow one to quantitatively test the factorization approach. In this note we point out that the channels $\bar{B}^0 \to D^{(*)\pm} M^{\mp}$ and $B^0 \to D^{(*)\pm} M^{\mp}$ are well suited to probe *CP* violation in the B_d system. Namely, we show that the measurement of time dependent rates in these decays can provide theoretically clean information on $2\beta + \gamma$.

Time dependent rates. Aleksan et al. [6] have proposed to obtain CKM information from the time dependent rates of B-decays into non *CP* eigenstates f. Each final state f, $\bar{f}$ can be reached in B and $\bar{B}$ decays, both directly and via meson mixing, which leads to interference among terms with different CKM matrix elements. From measurement of all four decay rates

$$\begin{aligned}
\Gamma(B(t) \to f) &\sim e^{-\Gamma|t|}\left[\cos^2\left(\frac{\Delta m\, t}{2}\right) + \rho^2 \sin^2\left(\frac{\Delta m\, t}{2}\right) - \rho \sin(\phi + \Delta)\, \sin(\Delta m\, t)\right], \\
\Gamma(\bar{B}(t) \to \bar{f}) &\sim e^{-\Gamma|t|}\left[\cos^2\left(\frac{\Delta m\, t}{2}\right) + \rho^2 \sin^2\left(\frac{\Delta m\, t}{2}\right) + \rho \sin(\phi - \Delta)\, \sin(\Delta m\, t)\right], \\
\Gamma(B(t) \to \bar{f}) &\sim e^{-\Gamma|t|}\left[\rho^2 \cos^2\left(\frac{\Delta m\, t}{2}\right) + \sin^2\left(\frac{\Delta m\, t}{2}\right) - \rho \sin(\phi - \Delta)\, \sin(\Delta m\, t)\right], \\
\Gamma(\bar{B}(t) \to f) &\sim e^{-\Gamma|t|}\left[\rho^2 \cos^2\left(\frac{\Delta m\, t}{2}\right) + \sin^2\left(\frac{\Delta m\, t}{2}\right) + \rho \sin(\phi + \Delta)\, \sin(\Delta m\, t)\right],
\end{aligned} \tag{2}$$

one can then cleanly extract the ratio of matrix elements, the strong and the weak phase

$$\rho \equiv \left|\frac{\mathcal{M}(B \to \bar{f})}{\mathcal{M}(\bar{B} \to \bar{f})}\right|, \quad \Delta, \quad \phi, \tag{3}$$

respectively, the latter within a discrete ambiguity. This is true provided that there is only one weak phase involved in the process, as is the case for tree level dominated decays mediated by $b \to c\bar{u}d$ and $b \to u\bar{c}d$. For simplicity, we have neglected in (2) effects from the width difference of the two neutral B_d mass eigenstates. The mass difference Δm has been measured in the B_d system as $\Delta m_d/\Gamma_d = 0.730 \pm 0.029$ [7]. We note that Eq. (2) is only valid if at least one of

the final state mesons has spin zero. Otherwise, there are several helicity amplitudes, and the extraction of the weak phase requires angular analysis [8].

In decays $B \to \bar{f}$ with $\bar{f} = D^+ M^-$ and $M^- = d\bar{u}$ the weak phase ϕ equals $-(2\beta + \gamma)$. Here, the first term comes from B^0–$\bar{B}^0$ mixing and can be cleanly measured from the *CP* asymmetry in $\bar{B}^0 \to J/\Psi\, K^0$. From the measurement of ϕ we can then extract γ, modulo a discrete ambiguity. We stress that here one does not have to rely on factorization or any other assumption on the strong decay dynamics: all quantities in (3) can be extracted from a fit to the rates (2) in a model independent way.

Large asymmetries versus large statistics. The possibility to obtain information on γ from time dependent studies in the decays $(\bar{B}^0, B^0) \to D^\pm(\pi, \rho, a_1)^\mp$ has been investigated in [9]. Here and in the following, D stands for both D and D^* mesons. Because the branching ratios $\mathcal{B}(\bar{B}^0 \to D^+(\pi, \rho, a_1)^-) \sim 10^{-3}$ [7] are large compared to those for the *CP* conjugate parent, $\mathcal{B}(B^0 \to D^+(\pi, \rho, a_1)^-) \sim 10^{-6}$, these modes are essentially self-tagging. Since the amplitude ratio is roughly $\rho \simeq |V_{ub}^* V_{cd}|/|V_{cb} V_{ud}^*| \approx 2 \cdot 10^{-2}$ and the sensitivity to $\sin(\phi \pm \Delta)$ scales with ρ, large data samples are required.

The situation is different for our decays $(\bar{B}^0, B^0) \to D^\pm M^\mp$. Unlike the case just discussed, the hierarchy of decay amplitudes induced by the CKM factors is removed by the small coupling of the meson M to the weak current, yielding branching ratios for $\bar{B}^0 \to \bar{f}$ and $B^0 \to \bar{f}$ of the *same order of magnitude* [5]. In the case of the a_0 and $\pi(1300)$ this is achieved with a decay constant of only a few MeV, so that the ratio

$$\rho \simeq \frac{|V_{ub}^* V_{cd}|}{|V_{cb} V_{ud}^*|} \frac{f_D}{f_M} \tag{4}$$

is of order one! This advantage is partly compensated by the fact that the corresponding branching ratios are only $\sim 10^{-6}$ [5], so that fewer events will be available in the analysis than for $B \to D\pi$.

To compare the sensitivity to the weak phase in the two cases we investigate the statistical error on a suitable *CP* asymmetry A in the decays (2),

$$\frac{\Delta A}{A} = \sqrt{\frac{1 - A^2}{A^2 N}}\,. \tag{5}$$

As an illustration let us take a data sample of 10^8 fully reconstructed B's. For decays into π we then have $N = 3 \cdot 10^5$ events and an asymmetry $A \sim \rho \approx 2 \cdot 10^{-2}$, so that $\Delta A/A \simeq 0.1$. For decays into M we have instead $N = 10^2$ and $A \sim \rho \sim 1$, giving $\Delta A/A \simeq 0.1\sqrt{1 - A^2}$. We see that the relative statistical errors are of the same order of magnitude. This result is general, as long as $\rho \leq 1$. The rate N is then controlled by $\bar{B}^0 \to \bar{f}$, the asymmetry A by the amplitude ratio ρ, and hence the factor $A^2 N$ in (5) by $B^0 \to \bar{f}$. The latter modes, $B^0 \to D^+\pi^-$ and $B^0 \to D^+ M^-$, are those where in naive factorization the D is emitted from the weak current while π or M pick up the spectator. Here the differences between the mesons M and π are less pronounced, and we expect branching ratios of similar size for all mesons M and π, ρ, a_1 [5].

Theoretical uncertainties in the branching ratios of $\bar{B}^0 \to D^+ M^-$ decays are not small. This does not affect the extraction of γ, but it prevents us from making accurate predictions of event rates and asymmetries. One source of uncertainty are the poorly known decay constants

of the charged a_0, b_1, $\pi(1300)$. We note that their measurement in τ decays should be within reach of the B- and τ-charm factories. Their size is controlled by the light quark masses, $f_{a_0,b_1} \sim m_d - m_u$ and $f_{\pi(1300)} \sim m_d + m_u$, and various models find values in the MeV range for the a_0 and $\pi(1300)$. The branching ratios obtained in naive factorization are then so small that factorization breaking effects are important. We have calculated hard gluon corrections for the corresponding decays within QCD factorization [10] and found them comparable in size to the factorizing pieces [5]. The same will hold for the b_1, provided that its decay constant (on which we have not found any information in the literature) is not larger than a few MeV. With hard gluon exchange we can also have decays whose branching ratio is zero in naive factorization, namely $\bar{B}^0 \to D^+ M^-$ where M has spin greater than 1. Our calculation has given branching fractions $\sim 10^{-6}$ for b_1, a_2, whereas for π_2, ρ_3 we only found values $\sim 10^{-9}$. For all mesons M it is however quite possible that other contributions such as soft interactions or annihilation are larger than the hard ones we could calculate, so that the corresponding decays could have branching ratios above 10^{-6}. The *CP* asymmetries would then decrease while the event rate would go up, with a roughly constant statistical error on the weak phase as shown above. On the other hand, non-factorizable contributions cannot be arbitrarily large, given the success of factorization in the decays $\bar{B}^0 \to D^+(\pi, \rho, a_1)^-$ [10]. We also recall that annihilation graphs in our decays have the same weak phase ϕ as the tree level contributions.

Since hard and soft interactions are enhanced in the decays $\bar{B}^0 \to D^+ M^-$, strong phases can be sizeable there. We have found that the phases induced by the α_s corrections in QCD factorization are indeed large, in contrast to decays into π, ρ, a_1. As discussed in [6] nonzero phases Δ lead to an ambiguity in extracting ϕ. We expect however Δ to differ among our mesons M, so that a combination of channels should be able to resolve this ambiguity. Furthermore, the strong phases Δ carry themselves important information on the QCD dynamics in such decays.

Time integrated measurements. To the extent that our decays are statistics limited one will probably not be able to use the method of time integrated observables proposed in [11], where modes with hadronic decays of both B mesons from the $\Upsilon(4S)$ decay are required. We notice however that one can extract the interference terms from (2) while integrating over the time t if each event is weighted with $\mathrm{sgn}(t)$. Instead of tracing the complete time dependence one then only needs to know whether the corresponding decay took place *before* or *after* the one that tags the flavor of the B meson. While this will in general increase the statistical error, such an analysis may improve the systematics. One may also use more refined weighting factors like $\mathrm{artanh}(\kappa t)$ with a suitable constant κ. This avoids the abrupt change of the weight at $t = 0$, but does not actually lose relevant information since the "signal" terms in (2) vanish as $\sin(\Delta m\, t)$ for $t \to 0$.

Conclusions. We conclude that, even though the decays into mesons M are rare with branching ratios $\sim 10^{-6}$, their statistical errors in the determination of γ are competitive with the decays into π, ρ, a_1. Systematic uncertainties in the two types of channels will however be very different, so that they are indeed complementary. We stress that there are many final states (see (1)) where this method can be applied. Decays involving the mesons M thus open new perspectives for the B factories to perform clean and independent tests of the CKM picture of *CP* violation.

Note added in proof: *CP* violation can also be studied in charmless B decays involving the mesons M discussed here. This has been explored independently in a recent work by Laplace and Shelkov [12].

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