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CP VIOLATION IN B_s DECAYS [a]

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CP-violating effects in non-leptonic B_s-meson decays are reviewed. Special emphasis is given to implications arising from the width difference $\Delta\Gamma_s$ between the B_s mass eigenstates. If $\Delta\Gamma_s$ is found to be sizable, certain untagged B_s-meson decays may allow interesting probes of CP violation, extractions of the CKM angle γ and the Wolfenstein parameter η, and may indicate physics beyond the Standard Model.

1 Introduction

A characteristic feature of the neutral B_q-meson systems ($q \in \{d, s\}$) is B_q^0–$\overline{B_q^0}$ mixing. The corresponding time-evolutions are governed by the B_q mass eigenstates $B_q^{\rm Heavy}$ and $B_q^{\rm Light}$ which are characterized by their mass eigenvalues $M_H^{(q)}$, $M_L^{(q)}$ and decay widths $\Gamma_H^{(q)}$, $\Gamma_L^{(q)}$. Because of these mixing effects, oscillatory $\Delta M_q t$ terms with $\Delta M_q \equiv M_H^{(q)} - M_L^{(q)}$ show up in the time-dependent transition rates $\Gamma(B_q^0(t) \to f)$ and $\Gamma(\overline{B_q^0}(t) \to f)$ describing decays of initially present B_q^0 and $\overline{B_q^0}$ mesons into a final state f, respectively. Essentially all the information that is needed to evaluate these decay rates is contained in the convention-independent observable [1]

$$\xi_f^{(q)} = \exp\left[-i\,\Theta_{M_{12}}^{(q)}\right] \frac{A(\overline{B_q^0} \to f)}{A(B_q^0 \to f)}\,, \tag{1}$$

where $\Theta_{M_{12}}^{(q)}$ is the weak B_q^0–$\overline{B_q^0}$ mixing phase that is related to $2\arg(V_{tq}^* V_{tb})$ and the A's denote the decay amplitudes corresponding to $\overline{B_q^0} \to f$ and $B_q^0 \to f$.

It is a well-known feature that $\xi_f^{(q)}$ can be calculated in a clean way if $B_q \to f$ is dominated by a single CKM amplitude (see e.g. Ref. [1] for a recent discussion). The "gold-plated" mode in this respect is $B_d \to J/\psi\, K_{\rm S}$ measuring $\sin(2\beta)$ with excellent accuracy through mixing-induced CP violation.[2] The B_s system plays an important role to determine γ – another angle of the usual "non-squashed" unitarity triangle of the CKM matrix.

A decay that was proposed frequently in the previous literature to accomplish this task is $B_s \to \rho^0 K_{\rm S}$. However, this mode is unfortunately not dominated by a single CKM amplitude. Here penguin contributions lead to

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serious problems so that

$$\xi^{(s)}_{\rho^0 K_S} \approx \exp(-i\,2\,\gamma) \tag{2}$$

is a very bad approximation.[1] Consequently $B_s \to \rho^0 K_S$ should be the "wrong" way to extract γ. Needless to note, the branching ratio of that decay is expected to be of $\mathcal{O}(10^{-7})$ which makes its experimental investigation very difficult. Before focussing on other B_s modes that do allow meaningful determinations of γ, let us turn to an experimental problem of B_s decays that is related to time-dependent measurements.

2 The B_s System in Light of $\Delta\Gamma_s$

The "strength" of the $B^0_q-\overline{B^0_q}$ oscillations is measured by the mixing parameter $x_q \equiv \Delta M_q/\Gamma_q$, where $\Gamma_q \equiv (\Gamma^{(q)}_H + \Gamma^{(q)}_L)/2$. While we have $x_d = 0.72 \pm 0.03$ in the B_d system, a large B_s mixing parameter $x_s = \mathcal{O}(20)$ is expected within the Standard Model implying very rapid $B^0_s - \overline{B^0_s}$ oscillations (see e.g. Ref. [3]). In order to keep track of the corresponding $\Delta M_s t$ terms in the time-dependent B_s decay rates, an excellent vertex resolution system is required which is a formidable experimental task.

It may, however, not be necessary to trace these rapid $\Delta M_s t$ oscillations in order to obtain insights into the mechanism of CP violation.[4] This remarkable feature is due to the expected sizable width difference $\Delta\Gamma_s \equiv \Gamma^{(s)}_H - \Gamma^{(s)}_L$ originating mainly from CKM favored $\bar{b} \to \bar{c}c\bar{s}$ transitions into final states that are common both to B^0_s and $\overline{B^0_s}$. The width difference $\Delta\Gamma_s$ may be as large as $\mathcal{O}(20\%)$ of the average decay width Γ_s as is indicated by box diagram calculations [5], a second complementary approach [6] where one sums over many exclusive $\bar{b} \to \bar{c}c\bar{s}$ modes, and by an approach using the "Heavy Quark Expansion" leading to the most recent result [7] $|\Delta\Gamma_s|/\Gamma_s = 0.16^{+0.11}_{-0.09}$. This width difference can be determined experimentally e.g. from angular correlations in $B_s \to J/\psi\,\phi$ decays.[8] One expects $10^3 - 10^4$ reconstructed $B_s \to J/\psi\,\phi$ events both at Tevatron Run II and at HERA-B which may allow a precise measurement of $\Delta\Gamma_s$.

Because of this width difference already untagged B_s rates, which are defined by

$$\Gamma[f(t)] \equiv \Gamma(B^0_s(t) \to f) + \Gamma(\overline{B^0_s}(t) \to f)\,, \tag{3}$$

may provide valuable information about the phase structure of the observable $\xi^{(s)}_f$ defined by Eq. (1). This can be seen nicely by writing Eq. (3) in a more explicit way as follows:

$$\Gamma[f(t)] \propto \left[\left(1+\left|\xi_f^{(s)}\right|^2\right)\left(e^{-\Gamma_L^{(s)}t}+e^{-\Gamma_H^{(s)}t}\right)-2\,\mathrm{Re}\,\xi_f^{(s)}\left(e^{-\Gamma_L^{(s)}t}-e^{-\Gamma_H^{(s)}t}\right)\right]. \tag{4}$$

In this expression the rapid oscillatory $\Delta M_s t$ terms, which show up in the tagged rates, cancel. Therefore it depends only on the two exponents $e^{-\Gamma_L^{(s)}t}$ and $e^{-\Gamma_H^{(s)}t}$. From an experimental point of view such untagged analyses are clearly much more promising than tagged ones in respect of efficiency, acceptance and purity.

In order to illustrate these untagged strategies in more detail, let me discuss an estimate of γ from $B_s \to K^+K^-$ and $B_s \to K^0\overline{K^0}$ decays.[9] Using the $SU(2)$ isospin symmetry of strong interactions to relate the QCD penguin contributions to these decays (electroweak penguins are color-suppressed in these modes and thus play a minor role [1]) yields

$$\Gamma[K^+K^-(t)] \propto |P|^2\Big[\big(1-2\,|r|\cos\rho\,\cos\gamma+|r|^2\cos^2\gamma\big)e^{-\Gamma_L^{(s)}t}+|r|^2\sin^2\gamma\, e^{-\Gamma_H^{(s)}t}\Big] \tag{5}$$

and

$$\Gamma[K^0\overline{K^0}(t)] \propto |P|^2\, e^{-\Gamma_L^{(s)}t}\,, \tag{6}$$

where

$$r \equiv |r|e^{i\rho} = \frac{|T|}{|P|}e^{i(\delta_T-\delta_P)}\,. \tag{7}$$

Here P denotes the $\bar b \to \bar s$ QCD penguin amplitude, T is the color-allowed $\bar b \to \bar u u \bar s$ tree amplitude, and δ_P and δ_T are the corresponding CP-conserving strong phases. In order to determine γ from the untagged rates Eqs. (5) and (6), an additional input is needed. Using the $SU(3)$ flavor symmetry of strong interactions to this end and neglecting color-suppressed current-current contributions to $B^+ \to \pi^+\pi^0$ gives

$$|T| \approx \lambda\,\frac{f_K}{f_\pi}\,\sqrt{2}\,|A(B^+ \to \pi^+\pi^0)|\,, \tag{8}$$

where $\lambda = 0.22$ is the Wolfenstein parameter [10], f_K and f_π are the K and π meson decay constants, respectively, and $A(B^+ \to \pi^+\pi^0)$ denotes the appropriately normalized $B^+ \to \pi^+\pi^0$ decay amplitude. Since $|P|$ is known from $B_s \to K^0\,\overline{K^0}$, the quantity $|r| = |T|/|P|$ can be estimated with the help of Eq. (8) and allows an estimate of γ from the part of Eq. (5) evolving with exponent $e^{-\Gamma_H^{(s)}t}$. If more reliable ways to fix $|T|$ should become available in the future, this "estimate" of γ may well turn into a solid determination.

3 B_s Decays into Admixtures of CP Eigenstates

One can even do better than in the previous section, i.e. without using $SU(3)$ flavor symmetry, by considering decays corresponding to $B_s \to K\overline{K}$ where two vector mesons or higher resonances are present in the final states.[9]

3.1 An Extraction of γ using $B_s \to K^{*+}K^{*-}$ and $B_s \to K^{*0}\overline{K^{*0}}$

The untagged angular distributions of these decays, which are given explicitly in Ref. [9], provide many more observables than the untagged modes $B_s \to K^+K^-$ and $B_s \to K^0\overline{K^0}$ discussed in the previous section. In the case of $B_s \to K^{*0}\overline{K^{*0}}$ the formulae simplify considerably since it is a penguin-induced $\bar{b} \to \bar{s}d\bar{d}$ mode and receives therefore no tree contributions. Using again the $SU(2)$ isospin symmetry of strong interactions, the QCD penguin contributions to $B_s \to K^{*+}K^{*-}$ and $B_s \to K^{*0}\overline{K^{*0}}$ can be related to each other. If one takes into account these relations and goes very carefully through the observables of the untagged angular distributions, one finds that they allow the extraction of the CKM angle γ without any additional theoretical input.[9] Needless to note, the angular distributions provide moreover information about the hadronization dynamics of these decays. Since the formalism [9] for $B_s \to K^{*+}K^{*-}$ applies also to $B_s \to \rho^0\phi$, it may allow insights into the physics of electroweak penguins as the latter mode is dominated by these operators.[1]

3.2 The "Gold-plated" Transitions to Extract η

This subsection is devoted to the decays $B_s \to D_s^{*+}D_s^{*-}$ and $B_s \to J/\psi\,\phi$, which is the counterpart of the "gold-plated" mode $B_d \to J/\psi\,K_S$ to measure the CKM angle β. Since these decays are dominated by a single CKM amplitude, the hadronic uncertainties cancel in $\xi_f^{(s)}$ which takes in that particular case the form [9]

$$\xi_f^{(s)} = \exp(i\,\phi_{\rm CKM})\,. \tag{9}$$

Consequently the observables of the angular distributions simplify considerably. A characteristic feature of these angular distributions is interference between CP-even and CP-odd final state configurations leading to observables that are proportional to

$$\left(e^{-\Gamma_L^{(s)}t} - e^{-\Gamma_H^{(s)}t}\right)\sin\phi_{\rm CKM}\,. \tag{10}$$

Here the CP-violating weak phase is given by $\phi_{\rm CKM} = 2\lambda^2\eta \approx \mathcal{O}(0.03)$, where λ and η are two of the Wolfenstein parameters.[10] The observables of the angular distributions for both the color-allowed channel $B_s \to D_s^{*+}D_s^{*-}$ and the color-suppressed transition $B_s \to J/\psi\,\phi$ each provide sufficient information to determine the CP-violating weak phase $\phi_{\rm CKM}$ from their untagged data samples thereby fixing the Wolfenstein parameter η.[9] Note that this extraction of $\phi_{\rm CKM}$ is not as clean as that of β from $B_d \to J/\psi\,K_{\rm S}$. This feature is due to the smallness of $\phi_{\rm CKM}$ with respect to β.

Within the Standard Model one expects a very small value of $\phi_{\rm CKM}$ and $\Gamma_H^{(s)} < \Gamma_L^{(s)}$. However, that need not to be the case in many scenarios for "New Physics".[11] An experimental study of the decays $B_s \to D_s^{*+} D_s^{*-}$ and $B_s \to J/\psi\,\phi$ may shed light on this issue, and an extracted value of $\phi_{\rm CKM}$ much larger than $\mathcal{O}(0.03)$ would indicate physics beyond the Standard Model.

4 B_s Decays caused by $\bar{b} \to \bar{u}c\bar{s}$ ($b \to c\bar{u}s$)

The B_s decays discussed in this section are pure tree decays, i.e. receive no penguin contributions, and probe the CKM angle γ in a clean way.[12] There are by now well-known strategies on the market using the time evolutions of such modes, e.g. $\overset{(-)}{B_s} \to \overset{(-)}{D^0}\,\phi$ [12,13] and $\overset{(-)}{B_s} \to D_s^{\pm} K^{\mp}$ [14], to extract γ. However, in these strategies tagging is essential and the rapid $\Delta M_s t$ oscillations have to be resolved which is an experimental challenge. The question what can be learned from untagged data samples of these decays, where the $\Delta M_s t$ terms cancel, was investigated by Dunietz.[4] In the untagged case the determination of γ requires additional inputs: a measurement of the untagged $B_s \to D^0_{\rm CP}\phi$ rate in the case of the color-suppressed modes $\overset{(-)}{B_s} \to \overset{(-)}{D^0}\,\phi$, and a theoretical input corresponding to the ratio of the unmixed rates $\Gamma(B_s^0 \to D_s^- K^+)/\Gamma(B_s^0 \to D_s^- \pi^+)$ in the case of the color-allowed decays $\overset{(-)}{B_s} \to D_s^{\pm} K^{\mp}$. This ratio can be estimated with the help of the "factorization" hypothesis which may work reasonably well for these color-allowed channels.[15]

Interestingly the untagged data samples may exhibit CP-violating effects that are described by observables of the form

$$\Gamma[f(t)] - \Gamma[\overline{f}(t)] \propto \left(e^{-\Gamma_L^{(s)} t} - e^{-\Gamma_H^{(s)} t}\right) \sin\varrho_f\, \sin\gamma\,. \tag{11}$$

Here ϱ_f is a CP-conserving strong phase shift and γ is the usual angle of the unitarity triangle. Because of the $\sin\varrho_f$ factor, a non-trivial strong phase shift is essential in that case. Consequently the CP-violating observables Eq. (11) vanish within the factorization approximation predicting $\varrho_f \in \{0, \pi\}$. Since factorization may be a reasonable working assumption for the color-allowed modes $\overset{(-)}{B_s} \to D_s^{\pm} K^{\mp}$, the CP-violating effects in their untagged data samples are expected to be very small. On the other hand, the factorization hypothesis is very questionable for the color-suppressed decays $\overset{(-)}{B_s}\to\overset{(-)}{D^0}\,\phi$ and sizable CP violation may show up in the corresponding untagged rates.[4]

Concerning such CP-violating effects and the extraction of γ from untagged B_s decays, the modes $\overset{(-)}{B_s}\to D_s^{*\pm}K^{*\mp}$ and $\overset{(-)}{B_s}\to\overset{(-)}{D^{*0}}\,\phi$ are expected to be more promising than the transitions discussed above. As was shown in Ref. [16], the time-dependences of their untagged angular distributions allow a clean extraction of γ without any additional input. The final state configurations of these decays are not admixtures of CP eigenstates as in Section 3. They can instead be classified by their parity eigenvalues. A characteristic feature of the angular distributions is interference between parity-even and parity-odd configurations that may lead to potentially large CP-violating effects in the untagged data samples even when all strong phase shifts vanish. Therefore one expects even within the factorization approximation, which may apply to the color-allowed modes $\overset{(-)}{B_s}\to D_s^{*\pm}K^{*\mp}$, potentially large CP-violating effects in the corresponding untagged data samples.[16] Since the soft photons in the decays $D_s^*\to D_s\gamma$, $D^{*0}\to D^0\gamma$ are difficult to detect, higher resonances exhibiting significant all-charged final states, e.g. $D_{s1}(2536)^+\to D^{*+}K^0$, $D_1(2420)^0\to D^{*+}\pi^-$ with $D^{*+}\to D^0\pi^+$, may be more promising for certain detector configurations. A similar comment applies also to the mode $B_s\to D_s^{*+}D_s^{*-}$ discussed in Subsection 3.2.

5 Conclusions

Whereas $B_s\to\rho^0K_S$ is expected to be the "wrong" way to extract γ because of hadronic uncertainties related to penguin contributions, there are other B_s decays which should allow meaningful determinations of this CKM angle. Some of these strategies are even theoretically clean and suffer from no hadronic uncertainties.

Within the Standard Model one expects very rapid $B_s^0-\overline{B_s^0}$ oscillations which may be too fast to be resolved with present vertex technology. However, the corresponding $\Delta M_s t$ terms cancel in untagged rates of B_s decays that depend therefore only on the two exponents $e^{-\Gamma_L^{(s)}t}$ and $e^{-\Gamma_H^{(s)}t}$. If the width difference $\Delta\Gamma_s$ is sizable – as is expected from theoretical analyses – untagged B_s decays may allow the determination both of the CKM angle γ and of the Wolfenstein parameter η. Following these lines one may furthermore obtain valuable insights into the mechanism of CP violation thereby getting indications for physics beyond the Standard Model.

Obviously the feasibility of such untagged B_s strategies to search for CP violation and to extract CKM phases depends crucially on a sizable width difference $\Delta\Gamma_s$. Moreover a lot of statistics is required so that hadron machines seem to be the natural place for such experiments. It is not yet clear whether the B_s width difference will turn out to be large enough to make these measurements possible. However, even if it should be too small, once $\Delta\Gamma_s \neq 0$ has been found experimentally, the formulae developed in Refs. [9,16] have also to be used to determine CKM phases correctly from tagged B_s decays. Certainly time will tell and hopefully an exciting future of CP violation in B_s decays is ahead of us.

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