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CP Violation Beyond the Standard Model

Robert Fleischer
Theory Division, CERN, CH-1211 Geneva 23, Switzerland

Abstract

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CP VIOLATION BEYOND THE STANDARD MODEL

ROBERT FLEISCHER
Theory Division, CERN
CH-1211 Geneva 23, Switzerland

Recent developments concerning CP violation beyond the Standard Model are reviewed. The central target of this presentation is the B system, as it plays an outstanding role in the extraction of CKM phases. Besides a general discussion of the appearance of new physics in the corresponding CP-violating asymmetries through B_q^0–$\overline{B_q^0}$ mixing ($q \in \{d, s\}$), it is emphasized that CP violation in non-leptonic penguin modes, e.g. in $B_d \to \phi\, K_S$, offers a powerful tool to probe physics beyond the Standard Model. In this respect $B \to \pi K$ modes, which have been observed recently by the CLEO collaboration, may also turn out to be very useful. Their combined branching ratios allow us to constrain the CKM angle γ and may indicate the presence of physics beyond the Standard Model.

1 Introduction

CP violation is one of the least well understood and least experimentally tested phenomena in present particle physics. There are several reasons to expect physics beyond the Standard Model to show up in CP-violating effects. First, the Standard Model description of CP violation, i.e. the phase structure of the Cabibbo-Kobayashi-Maskawa matrix (CKM matrix) [1], has not yet been tested experimentally. Second, many extensions of the Standard Model have additional sources of CP violation or may affect Standard Model relations among CP-violating observables [2]. Third, CP violation is one of the three necessary conditions for the large imbalance between matter and antimatter that is observed in the Universe [3]. Calculations within the framework of the Standard Model show, however, that CP violation seems to be too small to generate this imbalance. This feature could be a hint for the need of sources for CP violation beyond the Standard Model.

At present the observed "indirect" CP violation in the neutral K-meson system [4] can successfully be described by the Standard Model. Since so far only a single CP-violating observable, ε, has to be fitted, it is, however, not surprising that many different "non-standard" model descriptions of CP violation are imaginable [2]. While a measurement of $\mathrm{Re}(\varepsilon'/\varepsilon) \neq 0$ describing "direct" CP violation in the neutral kaon system would exclude "superweak" scenarios of CP violation [5] in an unambiguous way, this observable will not allow a stringent test of the Standard Model description of CP violation, unless the presently large theoretical uncertainties related to poorly known hadronic matrix elements can be controlled in a reliable way [6]. More promising with respect to testing the CP-violating sector of the Standard Model are the rare decays $K_{\rm L} \to \pi^0 \overline{\nu} \nu$ and $K^+ \to \pi^+ \overline{\nu} \nu$, as has been stressed by Andrzej Buras at this symposium [7].

It is obvious from the brief discussion given above that the K-meson system by itself cannot provide the whole picture of CP violation. Therefore it is essential to study CP violation outside this system. In this respect, the B system appears to be most promising, which is also reflected by the tremendous experimental efforts at future B factory facilities [8]. Let me note that there are also other interesting systems to explore CP violation and to search for physics beyond the Standard Model, e.g. the D-meson system [9], where sizeable mixing or CP-violating effects would signal new physics because of the tiny Standard Model "background". In this presentation I unfortunately cannot discuss these systems in more detail and shall focus on B decays.

2 The Central Target: CP Violation in the B System

2.1 General Remarks

It is by now well-known that large CP-violating effects are expected to show up in non-leptonic B-meson decays [10,11]. In several cases the corresponding CP-violating observables are closely related to the angles α, β and γ of the usual "non-squashed" unitarity triangle [12] of the CKM matrix. Probably the most prominent example is the "gold-plated" mode $B_d \to J/\psi\, K_{\rm S}$, measuring $\sin(2\beta)$ in a clean way through "mixing-induced" CP violation [13]. Another "benchmark" mode is $B_d \to \pi^+\pi^-$, which at first sight seems to measure $\sin(2\alpha)$. A closer look shows, however, that in contrast to $B_d \to J/\psi\, K_{\rm S}$ penguin contributions may lead to serious hadronic uncertainties in the former decay requiring more involved strategies to extract a reliable value of α [10,11]. Although theoretical clean techniques to determine the third angle γ of the unitarity triangle are on the market, using for instance the "tree" decays $B^\pm \to DK^\pm$ or $B_s \to D_s K$ (see e.g. Ref. [11] for a recent review), these methods are in general very challenging from an experimental point of view. It should also be kept in mind that a generic problem of the determination of the angles of the unitarity triangle from CP-violating observables is that one has to deal with discrete ambiguities [14].

The presence of new physics could manifest itself in several ways, e.g. through a violation of the unitarity relation

$$\alpha + \beta + \gamma = 180^\circ. \tag{1}$$

Another possibility is to find that Eq. (1) is satisfied, but that the directly measured angles disagree with the Standard Model expectation, in particular with measurements of the sides of the unitarity triangle through semileptonic $b \to c\, l\, \overline{\nu}_l$, $b \to u\, l\, \overline{\nu}_l$ decays and B_d^0–$\overline{B_d^0}$ mixing [6].

The goal of future B physics experiments [8] is therefore to perform as many independent CP-violating measurements as possible to overconstrain the unitarity triangle as much as possible. Either these measurements will lead to results that are consistent with each other and with the Standard Model expectations, leading eventually to the full determination of the CKM matrix, or discrepancies may show up that could shed light on new physics. Needless to note, the latter option would be much more exciting.

2.2 Theoretical Ingredients

In order to analyse the impact of physics beyond the Standard Model, we have to briefly recapitulate the theoretical ingredients that are at the basis of direct measurements of CKM phases through CP-violating asymmetries, as sketched above. The central role is played by non-leptonic B decays into final CP eigenstates $|f\rangle$. In that case the corresponding time-dependent CP asymmetries can be expressed as

$$a_{\rm CP}(t) \equiv \frac{\Gamma(B_q^0(t) \to f) - \Gamma(\overline{B_q^0}(t) \to f)}{\Gamma(B_q^0(t) \to f) + \Gamma(\overline{B_q^0}(t) \to f)} = \mathcal{A}_{\rm CP}^{\rm dir}(B_q \to f)\cos(\Delta M_q\, t) + \mathcal{A}_{\rm CP}^{\rm mix-ind}(B_q \to f)\sin(\Delta M_q\, t)\,. \qquad (2)$$

Here direct CP violation has been separated from mixing-induced CP violation by introducing

$$\mathcal{A}_{\rm CP}^{\rm dir}(B_q \to f) \equiv \frac{1 - |\xi_f^{(q)}|^2}{1 + |\xi_f^{(q)}|^2}\,, \quad \mathcal{A}_{\rm CP}^{\rm mix-ind}(B_q \to f) \equiv \frac{2\,{\rm Im}\,\xi_f^{(q)}}{1 + |\xi_f^{(q)}|^2}\,. \qquad (3)$$

The observable $\xi_f^{(q)}$ contains essentially all the information that is needed to evaluate these asymmetries and will be discussed in more detail below.

In most decays $B_q \to f$ of interest for extracting CKM phases, only mixing-induced CP violation shows up. There are two conditions for a clean relation of $\mathcal{A}_{\rm CP}^{\rm mix-ind}(B_q \to f)$ to angles of the unitarity triangle:

- The ratio $|\Gamma_{12}^{(q)}|/|M_{12}^{(q)}|$ of the off-diagonal elements of the decay and mass matrices describing B_q^0–$\overline{B_q^0}$ mixing has to be much smaller than 1.
- The decay amplitude $A(B_q \to f)$ has to be dominated by a single weak amplitude implying vanishing direct CP violation, i.e. $\mathcal{A}_{\rm CP}^{\rm dir}(B_q \to f) = 0$.

If these two requirements are met simultaneously, the observable $\xi_f^{(q)}$ is given by a pure phase factor, i.e. $|\xi_f^{(q)}|=1$, and can be expressed as [15]

$$\xi_f^{(q)} = \eta_{\rm CP}^f \cdot \left(\frac{X_f}{X_f^*}\right)\cdot\left(\frac{Y_q}{Y_q^*}\right)\cdot\left(\frac{Z_f}{Z_f^*}\right), \tag{4}$$

where X_f/X_f^* is the weak decay phase, Y_q/Y_q^* denotes the weak B_q^0–$\overline{B_q^0}$ mixing phase, and the last factor Z_f/Z_f^* is only needed if the CP eigenstate $|f\rangle$ satisfying $(\mathcal{CP})|f\rangle = \eta_{\rm CP}^f|f\rangle$ contains a neutral K meson as is, for instance, the case in $B_d\to J/\psi\, K_{\rm S}$.

2.3 What about New Physics?

There are several excellent reviews [2] dealing with this question, where much more detailed discussions can be found. Here I have to be rather general.

Let me first note that it is very difficult to change $|\Gamma_{12}^{(q)}|/|M_{12}^{(q)}| \ll 1$ through new physics. To this end one would need a new dominant contribution to tree decays of B_q mesons, which is very unlikely, or a strong suppression of the mixing compared to the Standard Model, which is also unlikely but not impossible for the B_s system.

The Z_f/Z_f^* factor in Eq. (4) may be different from the Standard Model value if new physics shows up in K^0–$\overline{K^0}$ mixing. An interesting test is provided by the relations [15]

$$\mathcal{A}_{\rm CP}^{\rm mix-ind}(B_d\to D^+D^-) \;=\; -\,\mathcal{A}_{\rm CP}^{\rm mix-ind}(B_d\to J/\psi\, K_{\rm S}) \;=\; \sin(2\beta) \tag{5}$$

$$\mathcal{A}_{\rm CP}^{\rm mix-ind}(B_s\to D_s^+D_s^-) \;=\; -\,\mathcal{A}_{\rm CP}^{\rm mix-ind}(B_s\to J/\psi\, K_{\rm S}) \;\approx\; 0 \tag{6}$$

holding within the Standard Model. Although $|Z_f|$ may be affected by new physics, $\arg(Z_f)$ can only be changed in very contrived models. This feature is guaranteed by the small value of ε parametrizing indirect CP violation in the kaon system [15].

Typically new physics is expected to show up at a scale Λ in the TeV regime so that its effects in W-mediated, CKM-allowed tree-level processes are highly suppressed by $\mathcal{O}(M_W^2/\Lambda^2)$. However, owing to the loop-suppression of "rare" flavour-changing neutral current (FCNC) processes, it is plausible that new physics contributions could there be of similar magnitude as those of the Standard Model. Consequently one expects sizeable effects either in B_q^0–$\overline{B_q^0}$ mixing affecting the phase factor Y_q/Y_q^*, or in the amplitudes of penguin-dominated decays, e.g. $B_d\to\phi\, K_{\rm S}$, affecting the X_f/X_f^* phase factor in Eq. (4). Specific examples for new physics are models with four generations, extended

Higgs sectors, Z-mediated FCNCs, non-minimal supersymmetric models, and many others discussed extensively in several reviews about that topic [2]. Before turning to penguin modes, let me first discuss the appearance of new physics through B_q^0–$\overline{B_q^0}$ mixing in more detail.

3 The Manifestation of New Physics through B_q^0–$\overline{B_q^0}$ Mixing

Since B_q^0–$\overline{B_q^0}$ mixing originating from the well-known box diagrams is already a one-loop effect in the Standard Model, it is plausible that new physics may affect this phenomenon considerably [15]. The corresponding mixing-induced CP-violating asymmetries are affected in particular by a possible shift of the weak B_q^0–$\overline{B_q^0}$ mixing phases from their Standard Model values through new physics:

$$\phi_{\rm M}^{(d)} = 2\beta + 2\phi_{\rm new}^{(d)} \tag{7}$$

$$\phi_{\rm M}^{(s)} = 0 + 2\phi_{\rm new}^{(s)}\,. \tag{8}$$

As far as the "benchmark" modes $B_d \to J/\psi\, K_{\rm S}$ and $B_d \to \pi^+\pi^-$ are concerned, their mixing-induced CP asymmetries are modified as follows (note that penguin contributions are neglected in $B_d \to \pi^+\pi^-$):

$$\mathcal{A}_{\rm CP}^{\rm mix-ind}(B_d \to J/\psi\, K_{\rm S}) = -\sin(2\beta + 2\phi_{\rm new}^{(d)}) \equiv -\sin(2\beta_{\rm exp}) \tag{9}$$

$$\mathcal{A}_{\rm CP}^{\rm mix-ind}(B_d \to \pi^+\pi^-) = -\sin(2\alpha - 2\phi_{\rm new}^{(d)}) \equiv -\sin(2\alpha_{\rm exp})\,, \tag{10}$$

so that these observables do not probe the angles α and β of the unitarity triangle but

$$\alpha_{\rm exp} \equiv \alpha - \phi_{\rm new}^{(d)}\,, \quad \beta_{\rm exp} \equiv \beta + \phi_{\rm new}^{(d)}\,. \tag{11}$$

In the sum of these experimentally determined angles the new physics phase $\phi_{\rm new}^{(d)}$ cancels, however, so that we have

$$\alpha_{\rm exp} + \beta_{\rm exp} = \alpha + \beta\,, \tag{12}$$

as was pointed out by Nir and Silverman [15]. Consequently, in order to test the unitarity relation Eq. (1) thereby searching for physics beyond the Standard Model, it is crucial to determine γ in a variety of ways. The "standard" strategies to extract this angle [11] can be divided into two categories that are unfortunately both difficult to perform in practice as I have already noted. The first one uses charged $B^\pm \to DK^\pm$ and related decays [16], which are pure tree modes where no FCNCs are involved. Therefore new physics should play a minor role in these channels and one expects to find

$$\alpha_{\rm exp} + \beta_{\rm exp} + \gamma_{\rm exp}^{(1)} = 180^\circ, \tag{13}$$

where $\gamma_{\rm exp}^{(1)}$ denotes the value of γ that is determined from these modes. In the second category [17], one employs decays such as $B_s \to D_s K$, which are also pure tree modes, and determines an experimental value $\gamma_{\rm exp}^{(2)}$ for γ with the help of B_s^0–$\overline{B_s^0}$ mixing. Since here a loop-induced FCNC process – the mixing – and the related CP-violating weak phase enter, it is well possible to find

$$\alpha_{\rm exp} + \beta_{\rm exp} + \gamma_{\rm exp}^{(2)} \neq 180^\circ \tag{14}$$

because of $\phi_{\rm new}^{(s)}$. The presence of this phase would also be signalled by sizeable CP-violating effects in $B_s \to J/\psi\, \phi$ or $B_s \to D_s^+ D_s^-$ exhibiting tiny CP violation within the Standard Model due to the small B_s^0–$\overline{B_s^0}$ mixing phase [15].

The lesson that we have learned from these considerations is that it does not suffice to measure only $\alpha_{\rm exp}$ and $\beta_{\rm exp}$. It is essential to determine the third angle γ in several ways, which is unfortunately an experimental challenge.

As we have just seen, new physics can affect CP violation in the "benchmark" modes to extract CKM phases mainly through contributions to B_q^0–$\overline{B_q^0}$ mixing. The same new physics is, however, expected to manifest itself also in other FCNC processes, e.g. in $b \to s$ penguin modes and other rare decays. This is in fact the case in specific model calculations (see e.g. Ref. [18]). Models of new physics can in principle be distinguished by their contributions to such processes [19], and in order to get "the whole picture", it is important to measure both CP asymmetries and rare decays. The effects of new physics in the "usual" rare B decays [20] have been reviewed by JoAnne Hewett at this symposium [21]. In the subsequent section I would like to turn to another class of rare decays, the penguin-induced non-leptonic B decays.

4 CP Violation in Penguin Modes as a Probe of New Physics

Let me begin the discussion of these decays by focusing on the $b \to d$ penguin mode $B_d \to K^0\overline{K^0}$. An analysis of new-physics effects in this channel was performed, e.g. in Ref. [22]. If one assumes that penguins with internal top quarks play the dominant role in this transition, the weak B_d^0–$\overline{B_d^0}$ mixing and $B_d \to K^0\overline{K^0}$ decay phases cancel each other in the corresponding observable $\xi_{K^0\overline{K^0}}^{(d)}$, implying vanishing CP violation in that decay. Consequently one would conclude that a measurement of non-vanishing CP violation in $B_d \to K^0\overline{K^0}$ would signal physics beyond the Standard Model. However, long-distance effects related to penguins with internal charm and up quarks may easily spoil the assumption of top-quark dominance [11,23]. As was pointed out in Ref. [24], these contributions may lead to sizeable CP violation in $B_d \to K^0\overline{K^0}$ even within the Standard Model, so that a measurement of such CP asymmetries would not necessarily imply new physics, as claimed in several previous papers. Unfortunately a measurement of these effects will be very difficult since the Standard Model expectation for the corresponding branching ratio is $\mathcal{O}(10^{-6})$ which is still one order of magnitude below the recent CLEO bound [25] $\mathrm{BR}(B_d \to K^0\overline{K^0}) < 1.7 \cdot 10^{-5}$.

More promising in this respect and – more importantly – to search for physics beyond the Standard Model is the $b \to s$ penguin mode $B_d \to \phi\, K_{\mathrm{S}}$. The branching ratio for this decay is expected to be of $\mathcal{O}(10^{-5})$ and may be large enough to investigate this channel at future B factories. Interestingly there is, to a very good approximation, no non-trivial CKM phase present in the corresponding decay amplitude [11], so that direct CP violation vanishes and mixing-induced CP violation measures simply the weak B_d^0–$\overline{B_d^0}$ mixing phase. It should be stressed that this statement does *not* require the questionable assumption of top-quark dominance in penguin amplitudes. Consequently an important probe for new physics in $b \to s$ FCNC processes is provided by the relation

$$\mathcal{A}_{\mathrm{CP}}^{\mathrm{mix-ind}}(B_d \to J/\psi\, K_{\mathrm{S}}) = \mathcal{A}_{\mathrm{CP}}^{\mathrm{mix-ind}}(B_d \to \phi\, K_{\mathrm{S}}) \tag{15}$$

holding within the Standard Model framework. The theoretical accuracy of this relation is limited by certain neglected terms that are CKM-suppressed by $\mathcal{O}(\lambda^2)$ and may lead to tiny direct CP-violating asymmetries in $B_d \to \phi\, K_{\mathrm{S}}$ of at most $\mathcal{O}(1\%)$ [11]. Recently the importance of $B_d \to \phi\, K_{\mathrm{S}}$ and similar modes such as $B_d \to \eta' K_{\mathrm{S}}$ to search for new physics in $b \to s$ transitions has been emphasized by several authors [11,18,26]. It is possible that new physics affects both $b \to s$ penguin decays and B_s^0–$\overline{B_s^0}$ mixing. While B_s^0–$\overline{B_s^0}$ mixing is difficult to measure because of the large mixing parameter, the penguin modes appear to be more promising from an experimental point of view.

5 Searching for γ and New Physics with $B \to \pi K$ Modes

A simple approach to determine γ with the help of the branching ratios for $B^+ \to \pi^+ K^0$, $B_d^0 \to \pi^- K^+$ and their charge conjugates was proposed in Ref. [27] (see also Ref. [11]). It makes use of the fact that the general phase structure of the corresponding decay amplitudes is known reliably within the Standard Model. Moreover it employs the $SU(2)$ isospin symmetry of strong interactions to relate the QCD penguin contributions. If the magnitude of the current-current amplitude T' contributing to $B_d^0 \to \pi^- K^+$ is known – it can be fixed e.g. through $B^+ \to \pi^+\pi^0$, "factorization", or hopefully lattice gauge theory one day – two amplitude triangles can be constructed, allowing in particular the extraction of γ. This approach is promising for future B-physics experiments since it requires only time-independent measurements of branching ratios at the $\mathcal{O}(10^{-5})$ level. If one measures in addition the branching ratios for $B^+ \to$

$\pi^0 K^+$ and its charge-conjugate, also the $b \to s$ electroweak penguin amplitude can be determined, which is another interesting probe for new physics [28].

Recently the CLEO collaboration [25] has reported the first observation of the decays $B^+ \to \pi^+ K^0$ and $B_d^0 \to \pi^- K^+$. At present, however, only combined branching ratios, i.e. averaged ones over decays and their charge-conjugates, are available with large experimental uncertainties. Therefore it is not yet possible to extract γ from the triangle construction proposed in Ref. [27]. The recent CLEO measurements allow, however, to derive interesting *constraints* on γ, which are of the form

$$0^\circ \leq \gamma \leq \gamma_0 \quad \vee \quad 180^\circ - \gamma_0 \leq \gamma \leq 180^\circ \tag{16}$$

and are hence complementary to the presently allowed range of

$$42^\circ \lesssim \gamma \lesssim 135^\circ \tag{17}$$

for that angle arising from the usual fits of the unitarity triangle [6]. This remarkable feature has been pointed out recently by Mannel and myself in Ref. [29]. The quantity γ_0 in Eq. (16) depends both on the ratio

$$R \equiv \frac{\mathrm{BR}(B_d \to \pi^\mp K^\pm)}{\mathrm{BR}(B^\pm \to \pi^\pm K)} = \frac{\mathrm{BR}(B_d^0 \to \pi^- K^+) + \mathrm{BR}(\overline{B_d^0} \to \pi^+ K^-)}{\mathrm{BR}(B^+ \to \pi^+ K^0) + \mathrm{BR}(B^- \to \pi^- \overline{K^0})} \tag{18}$$

of the combined branching ratios and on the amplitude ratio $r \equiv |T'|/|P'|$ of the current-current and penguin operator contributions to $B_d \to \pi^\mp K^\pm$.

A very important special case is $R = 1$. For $R > 1$, the constraints on γ require some knowledge about r. On the other hand, if R is found experimentally to be smaller than 1, bounds on γ can always be obtained independently of r. The point is that γ_0 takes a maximal value

$$\gamma_0^{\max} = \arccos(\sqrt{1-R})\,, \tag{19}$$

depending only on the ratio R of combined $B \to \pi K$ branching ratios [29].

Let us take as an example the central value 0.65 of the recent CLEO measurements [25] yielding $R = 0.65 \pm 0.40$. This value corresponds to $\gamma_0^{\max} = 54^\circ$ and implies the range $0^\circ \leq \gamma \leq 54^\circ \vee 126^\circ \leq \gamma \leq 180^\circ$, which has only the small overlap $42^\circ \lesssim \gamma \leq 54^\circ \vee 126^\circ \leq \gamma \lesssim 135^\circ$ with the range (17). The two pieces of this range are distinguished by the sign of the quantity $\cos\delta$, where δ is the CP-conserving strong phase shift between the T' and P' amplitudes. Using arguments based on "factorization", one expects $\cos\delta > 0$ corresponding to the former interval of that range, i.e. $42^\circ \lesssim \gamma \leq 54^\circ$ in our example [29] (see Ref. [30] for a recent model calculation). Consequently, once more data come in confirming $R < 1$, the decays $B_d \to \pi^{\mp} K^{\pm}$ and $B^{\pm} \to \pi^{\pm} K$ may put the Standard Model to a decisive test and could open a window to new physics. Effects of physics beyond the Standard Model in $B \to \pi K$ modes have been analysed in a recent paper [31]. A detailed study of various implications of the bounds on γ discussed above has been performed very recently in Ref. [32], where the issue of new physics has also been addressed.

6 Summary and Outlook

In conclusion, we have seen that the kaon system – the only one where CP violation has been observed to date – cannot provide the whole picture of that phenomenon. In addition to other interesting systems, e.g. the D system, non-leptonic B-meson decays, where large CP asymmetries are expected within the Standard Model, are extremely promising to test the CKM picture of CP violation. Physics beyond the Standard Model may show up in CP-violating asymmetries of B decays through several mechanisms. Probably the most important ones are new-physics contributions to B_q^0–$\overline{B_q^0}$ mixing, and contributions to loop-suppressed, "rare" penguin-induced B decays. A sensitive probe of new physics is also provided by $B \to \pi K$ decays that have recently been observed by the CLEO collaboration and allow us to constrain the CKM angle γ. In the foreseeable future, dedicated B-physics experiments may bring unexpected results that could guide us to physics beyond the Standard Model. Certainly a very exciting era of particle physics is ahead of us!

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