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New physics with beauty

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Abstract. We review the effects of new physics on CP asymmetries and decays of B mesons. Possible sources and corresponding signals for new physics are studied briefly. We discuss how the decay mode $b \to s\ell\ell$ (and $B \to K^*\ell\ell$) will enable us to understand the nature of new physics. We also examine the possibility of truly clean signature of new physics – a signature based on observables alone and without hadronic uncertainties.

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The universe is asymmetric and I am persuaded that life as it is known to us, is a direct result of the asymmetry of the universe or of its indirect consequences. The universe is asymmetric.

— Louis Pasteur (1874) [1]

1. CP violation and the lure for new physics

Theoreticians can be very proud of themselves; they have the experimentalists work hard to verify the picture of the universe they believe in. However, in what I am going to talk about today, the story is different altogether. It is the story of CP violation – where neither the experimentalists nor the theoreticians clearly lead the race. CP violation [2] was discovered as a tiny effect (of the order 2×10^{-3}) in neutral K decays to two pions, almost 35 years ago. In fact, neutral K mesons is the only system where CP violation has been observed so far. The question is: *What is the origin of CP violation?* To answer this question is one of the important remaining goals of particle physics. It is hoped that the study of B mesons will help us in answering this question. Several experiments dedicated to studying the B system or capable of producing an unprecedented large numbers of B mesons, have started/will start operating during the coming years.

Why should one be worried about such a tiny effect that is observed only in a single system? There are two significant reasons for this:

1. CP violation constitutes one of the three essential ingredients in any attempt to understand the observed baryon–antibaryon asymmetry in the universe.
2. The quark mass eigenstates are not the same as the weak eigenstates, the fundamental reason for which is unknown.

The Kobayashi–Maskawa matrix [3] not only relates the 'mass' and the 'weak' bases but accommodates CP violation beautifully with an additional phase present for a minimum of three generations. The seeds for CP violating phases of the KM type are in the Yukawa couplings and thus strictly speaking driven by the Higgs dynamics. Inspite of its central role, the Higgs sector is the least known part of the Standard Model (SM). CP violation studies thus provide a tool for high sensitivity probe of the Higgs dynamics. Manifestation of Higgs driven CP violation would not answer questions about the fundamental origin of CP violation. However, analysing dynamical structures of CP violation will provide us with more missing pieces of the overall puzzle.

One of the most compelling features of CP violation in the B system is that all three interior angles of the unitarity triangle, $\phi_1(\equiv \beta)$– $\phi_2(\equiv \alpha)$–$\phi_3(\equiv \gamma)$ [4] can in principle all be measured cleanly, i.e. without theoretical hadronic uncertainties. The B system is thereby expected to provide a test of CP violation in the SM. Any inconsistency with the predictions of the SM will reveal the much sought after signal of new physics (NP).

Though the origin of CP violation is not yet understood (it is merely parameterized in the SM), the picture of CP violation in the SM is rather unique and highly predictive. Inspite of such exact predictions CP violation is one of the least tested aspect of the SM. To elucidate on this point let us first list [5] a few features of CP violation in the SM:

1. CP violation is broken explicitly.
2. All CP violation arises from a single phase δ in the KM matrix.
3. Measured values of ϵ requires $\delta \approx \mathcal{O}(1)$, implying that CP violation is not an approximate symmetry of the SM.
4. Values of all CP violating observables can be predicted in principle in terms of δ, (if hadronic effects can be calculated reliably).

This may be compared with CP violation in (certain) viable models of NP, e.g. certain SUSY models, which can have the following features:

1. CP violation is broken spontaneously.
2. There are many CP violating phases.
3. CP is an approximate symmetry, meaning that the CP violating phases $\phi_{\rm CP}$ in the Lagrangian are $10^{-3} \le \phi_{\rm CP} \le 10^{-2}$.
4. Values of CP violating observables could be very different from SM.

Inspite of the fact that predictions of the SM can be dramatically violated by NP, we are as yet unable to distinguish between the two scenarios. The above was only an example of NP whose predictions are clearly different from SM. How are SM predictions modified by NP in general? New physics modifies the low energy effective Hamiltonian, which can have the following effect:

- Cause new contributions to the SM operators.
- Generate new operators.
- Lead to new CP violating phases.

NP on the other hand cannot show up everywhere, as is demonstrated by the well known relation between the CP violating asymmetry for the modes $J/\psi K_S$ vs $J/\psi K_L$, i.e. $a_{\rm CP}(J/\psi K_S) = -a_{\rm CP}(J/\psi K_L)$, which is always true and is not modified by NP. NP is also unlikely to compete with large SM contributions e.g. $b \to c\bar{u}d$, which are dominated by W-exchange, and essentially unaffected by NP. One can therefore expect NP to affect loop-level processes, such as $B^0 - \overline{B^0}$ mixing [6], penguin decays [7] or SM suppressed observables. Where should one, then, look for NP? The obvious rules are to look for observables that are:

- Easy to measure, so that there is no large systematics or backgrounds to deal with.
- Have a small SM (theory) uncertainty, i.e. preferably no long distance effects. One certainly does not want the uncertainty of the type in ϵ'/ϵ.
- Sensitive to NP, so that NP signals are seen with the least numbers of B mesons.

The CP asymmetries *can* be affected if there are new contributions to B^0–$\bar{B}^0$ mixing [6]. Such NP contributions will affect the extraction of V_{td} and V_{ts}, as well as possible measurements of ϕ_1, ϕ_2 and ϕ_3. The angles ϕ_1, ϕ_2 and ϕ_3 are to be measured principally through the modes $B_d^0(t) \to \Psi K_s$, $B_d^0(t) \to \pi\pi$ (or $\rho\pi$) [8], and $B^\pm \to DK^\pm$ (or $D^* K^{*\pm}$) [9], respectively. NP in $B_d^0 - \overline{B_d^0}$ mixing will then affect the measurements of ϕ_1 and ϕ_2, but in opposite directions [10]. That is, in the presence of a NP phase $\phi_{\rm NP}$, the CP angles are changed as follows: $\phi_1 \to \phi_1 - \phi_{\rm NP}$ and $\phi_2 \to \phi_2 + \phi_{\rm NP}$. Hence the sum $\phi_1 + \phi_2 + \phi_3$ is *insensitive* to the NP [11].

A well known method for detecting NP is to compare the unitary triangle as constructed from measurements of the angles ϕ_1, ϕ_2 and ϕ_3, with that constructed from independent measurements of the sides. Any inconsistency will be evidence for NP. However, since at present the allowed region of the unitarity triangle is rather large, the triangle as constructed from the angles could still lie within the allowed region even if NP is present. Furthermore, even if the $\phi_1 - \phi_2 - \phi_3$ triangle lies outside the allowed region, one might still be skeptical about the presence of NP: perhaps the theoretical uncertainties which go into the constraints on the unitarity triangle have been underestimated.

In light of this, a more promising technique for searching for NP is to consider two distinct decay modes which, in the SM, probe the same CP angle. If there is a discrepancy between the two values, this would be unequivocal, clean evidence for NP. We discuss such a technique and look at the question of truly clean signals of NP in detail in §4. Before that, in the next section, §2, we summarize the effects of various models of NP on the equally large number of modes that have been studied. In §3, we study the possibility of identifying the kind of NP using the decay modes $b \to s\ell\ell$ and $B \to K^*\ell\ell$.

2. The Pundits judgment

The effect of new physics in B decays and $B^0 - \overline{B^0}$ mixing has been extensively studied in various models [12]. I do not wish to discuss one model after another, and their effect on the various modes. Fortunately, I just do not have enough time to discuss each of the decay modes and models in detail. Hence, I summarize the conclusions in table 1 that has been adopted from table 13.6 of the BaBar Physics Book [13].

Table 1. Model dependent effects of NP in various processes.

Model	$B^0-\overline{B^0}$ mixing	Decay amplitude	Rare decays	Comment
MSSM	$\mathcal{O}(20\%)$ SM, same phase	No effect	$B\to X_s\gamma$– Yes	Not true
SUSY-align	$\mathcal{O}(20\%)$ SM, new phase	$\mathcal{O}(1)$	Small effect	$D^0-\overline{D^0}$
SUSY approximate universality	$\mathcal{O}(20\%)$ SM, new phases	$\mathcal{O}(1)$	No effects	
MHDM	$\sim$ SM/new phases	Suppressed	$B\to X_s\gamma$, $B\to X_s\tau\tau$	$D^0-\overline{D^0}$
2HDM	$\sim$ SM/new phases	Suppressed	$B\to X_s\gamma$	no effect
Quark singlets	Yes/new phases	Yes	Saturate limits	$Q=\frac{2}{3}$
Fourth generation	$\sim$ SM/new phases	Yes	Saturate limits	$D^0-\overline{D^0}$, $B\to\phi\pi$
Left–right models				
$V_L=V_R$	No effect	No effect	$B\to X_s\gamma$, $B\to X_s\ell\ell$	
$-V_L=V_R$	Big/new phases	Yes	$B\to X_s\gamma$, $B\to X_s\ell\ell$	
Dynamical EWSB	Big/same phase	No effect	$B\to X_s\ell\ell$, $B\to X_s\nu\nu$	$D^0-\overline{D^0}$
R-parity violating	Can do every thing except make coffee. See ref. [14] for comments.			???
ADD–Extra dimensions	Activity is just starting. Stringent limits on M_c (compactification scale) from FCNC at tree [15]. Recently a model with successful naturally suppressed FCNC has also been presented [16].			

Before we move on, let us see what lessons can be learnt from table 1. A large number of modes that may provide signal of NP are in fact rare ones. It is well known that rare processes are an important tool for investigating new interactions. The smallness of the SM contributions implies that NP manifests itself clearly. An example that may be familiar to many in the audience is the important role rare decays have played in providing guidelines for SUSY model building [17]. Observations of flavor changing neutral currents (FCNC) or bounds on them yield stringent relations between the many parameters in soft SUSY breaking terms. Constraints on FCNC in K mesons has led to the shaping of viable SUSY flavor models. Severe FCNC constraints have no direct explanation in MSSM. This is the so-called 'SUSY flavor problem'. There exist several SUSY models (within MSSM) with specific solutions. Popular ones are the ones in which dynamics of flavor sets in above the SUSY breaking scale and flavor problem is solved by the mechanism of communicating SUSY breaking to experimentally accessible sector. Some of the popular models in this category are SUGRA – where supergravity mediates SUSY breaking to the visible sector, GMSB (gauge mediated SUSY breaking) and AMSB (anomaly mediated SUSY breaking). FCNC constraints coming from B system will provide valuable input to model builders in the future.

In addition to the modes mentioned in table 1, the 'zero'-prediction observables provide a good opportunity to study NP. These observables are zero or close to zero in the SM and unexpected large signals for these observables would provide a signal for NP. Some of these observables are the CP asymmetries $a_{\rm CP}(B_s \to J/\psi\phi)$ and $a_{\rm CP}(B_s \to D_s^+ D_s^-)$, the direct asymmetries $a_{\rm dir}(B^\pm \to J/\psi K^\pm)$, $a_{\rm dir}(b \to s\gamma)$, $a_{\rm dir}(b \to s\ell^+\ell^-)$ and $a_{\rm dir}(B \to K^*\ell^+\ell^-)$, and the semi-leptonic asymmetry $a_{\rm SL}$. The role of such 'zero'-prediction observables in discovering NP is also known in K and D mesons. Such observables are $D^0 - \overline{D^0}$ mixing and $K_L \to \pi^0\nu\bar{\nu}$, whose study is strongly advocated as well.

An anomalous value of two-body decay modes *may* provide a signal of NP. It may even provide a 'smoking-gun' signal for a particular model, e.g. $B(B_s^0 \to \phi\pi^0) \sim B(B^+ \to \phi\pi^+)$ would clearly imply Z mediated FCNC as the NP [12]. However, this will not always be the case. How does one find the nature of NP then? Some help in answering this question will surely come from the decays to multi-body final states, such as $b \to s\ell^+\ell^-$ and $B \to K^*\ell^+\ell^-$, which we study in the next section.

3. The gold mine mode

Rare decays $b \to s\ell^+\ell^-$ is described in terms of effective Hamiltonian [18] obtained by integrating the top quark and $W^\pm$ bosons,

$$\mathcal{H}_{\rm eff} \propto \frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} \mathcal{C}_i(\mu)\mathcal{O}_i(\mu),$$

where μ is the renormalization point. The operators relevant for SM are

$$\mathcal{O}_7 = m_b(\bar{s}\sigma^{\mu\nu}b_R)\mathcal{F}_{\mu\nu}, \;\; \mathcal{O}_9 = (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\ell), \;\; \mathcal{O}_{10} = (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5\ell). \tag{1}$$

Other operators $\mathcal{O}_{1,2,\cdots,6}$ and $\mathcal{O}_8$ contribute through QCD corrections. The Wilson coefficients $\mathcal{O}_i$ are calculated at the electroweak scale for a model of choice and evolved down to the renormalization scale $\mu = m_b$. If one could experimentally extract the coefficients (both real and imaginary parts) and compare with the values obtained for NP model of choice, one may get an indication of the kind of NP, if any is present. We emphasize that $|C_7|$ can be bound independently using $b \to s\gamma$, as it depends only on its magnitude.

The mode $b \to s\ell\ell$ and $B \to K^*\ell\ell$ has been studied extensively [19]. The decay distribution $b(p_b) \to s(p_s)\ell(p_+, s_+)\ell(p_-, s_-)$ is described by two kinematical variables s and u, where $s = (p_b - p_s)^2 = (p_+ + p_-)^2$ and $u = (p_s + p_+)^2 - (p_s + p_-)^2 \equiv \mathcal{U}(s)\cos\theta$, θ is the angle between b and ℓ^+ in the $\ell^+\ell^-$ center of mass frame, and $\mathcal{U}(s) = \sqrt{(s-(m_b+m_s)^2)(s-(m_b-m_s)^2)(1-\frac{4m_l^2}{s})}$. Even without measuring the polarization of leptons, one can study for example, the lepton pair invariant mass distribution [20]

$$\frac{1}{\Gamma(b \to ce\nu)} \frac{\mathrm{d}\Gamma(b \to s\ell^+\ell^-)}{\mathrm{d}s}\ , \tag{2}$$

and the forward–backward asymmetry $A_{\rm FB}$ [21] as a function of s,

$$A_{\rm FB}(s) = \frac{\int_{-1}^{1} {\rm d}\cos\theta \frac{{\rm d}^2\Gamma(b\to s\ell^+\ell^-)}{{\rm d}\cos\theta{\rm d}s}\sin(\cos\theta)}{\int_{-1}^{1} {\rm d}\cos\theta \frac{{\rm d}^2\Gamma(b\to s\ell^+\ell^-)}{{\rm d}\cos\theta{\rm d}s}}\ , \tag{3}$$

to test various models.

Measuring lepton polarizations of one of the leptons allows more possibilities. Three orthogonal unit vectors can be defined as

$$\hat{\epsilon}_L = \frac{\vec{p}_-}{|\vec{p}_-|},\ \ \hat{\epsilon}_N = \frac{\vec{p}_s\times\vec{p}_-}{|\vec{p}_s\times\vec{p}_-|},\ \ \hat{\epsilon}_T = \vec{p}_N\times\vec{p}_L\ . \tag{4}$$

With a unit vector along ℓ^- spin defined as $\hat{n}$, one can write [22]

$$\frac{{\rm d}\Gamma(\hat{n})}{{\rm d}s} = \frac{1}{2}\left(\frac{{\rm d}\Gamma}{{\rm d}s}\right)_{\rm unpol}(1+[P_L\hat{\epsilon}_L+P_T\hat{\epsilon}_T+P_N\hat{\epsilon}_N]\cdot\hat{n}). \tag{5}$$

The polarization asymmetries P_i in eq. (5), may then be defined as

$$P_i(s) = \frac{\frac{{\rm d}\Gamma(\hat{n}=\hat{\epsilon}_i)}{{\rm d}s} - \frac{{\rm d}\Gamma(\hat{n}=-\hat{\epsilon}_i)}{{\rm d}s}}{\frac{{\rm d}\Gamma(\hat{n}=\hat{\epsilon}_i)}{{\rm d}s} + \frac{{\rm d}\Gamma(\hat{n}=-\hat{\epsilon}_i)}{{\rm d}s}}\ . \tag{6}$$

Study of the polarizations of both the leptons is even more rewarding. The coefficients of triple cross products involving spins like $\vec{p}_b\cdot(\vec{s}_+\times\vec{s}_-)$ is proportional to ${\rm Im}(C_9C_{10}^*)$. By measuring such triple-cross-product correlations one may perhaps be able to study [24] the phases involved in C_9 as well.

New physics can generate new operators which should be included in the analysis. In principle a general set of operators in the NP Hamiltonian $\mathcal{H}_{\rm NP}$ should include [25]:

$$\begin{aligned}\mathcal{H}_{\rm NP} \propto\ & C_{RL}(\bar{s}_R\gamma^\mu b_R)(\bar{\ell}_L\gamma_\mu\ell_L) + C_{RR}(\bar{s}_R\gamma^\mu b_R)(\bar{\ell}_R\gamma_\mu\ell_R)\\ &+ C_{LRLR}\ \ (\bar{s}_L b_R)(\bar{\ell}_L\ell_R) + C_{RLLR}\ \ (\bar{s}_R b_L)(\bar{\ell}_L\ell_R)\\ &+ C_{LRRL}\ \ (\bar{s}_L b_R)(\bar{\ell}_R\ell_L) + C_{RLRL}\ \ (\bar{s}_R b_L)(\bar{\ell}_R\ell_L)\\ &+ C_T(\bar{s}\sigma_{\mu\nu}b)(\bar{\ell}\sigma^{\mu\nu}\ell) + C_{TE}(\bar{s}\sigma_{\mu\nu}b)(\bar{\ell}\sigma_{\alpha\beta}\ell)\epsilon^{\mu\nu\alpha\beta}\ .\end{aligned} \tag{7}$$

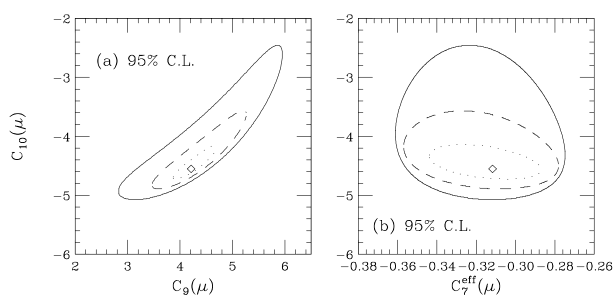

Figure 1. The 95% C.L. projections in the (a) $C_9 - C_{10}$ and (b) $C_7^{\rm eff} - C_{10}$ planes, where the allowed regions lie inside of the contours. The solid, dashed, and dotted contours correspond to $3\times10^7, 10^8$, and $5\times10^8 B\overline{B}$ pairs. SM is labelled by the diamond. This figure is reproduced from ref. [23].

The exclusive decay mode $B \to K^* \ell^+ \ell^-$ is described in terms of matrix elements of the quark operators over meson states. The advantage of studying K^* in the final state is the additional information in its polarization, if it can be measured. This is easily done by studying the decay of $K^* \to K\pi$ in the final state, i.e. by studying the four body mode $B \to (K\pi)\ell^+\ell^-$, where $(K\pi)$ indicates that the invariant mass of $K\pi$ is the mass of K^*.

The differential cross-section will have the form $\mathrm{d}\Gamma \propto I \mathrm{d}s_\ell \mathrm{d}\cos\theta_\ell \mathrm{d}\cos\theta_P \mathrm{d}\phi$, where

$$\begin{aligned} I = I_1 &+ I_2 \cos 2\theta_\ell + I_3 \sin^2\theta_\ell \cos 2\phi + I_4 \sin 2\theta_\ell \cos\phi + I_5 \sin\theta_\ell \cos\phi \\ &+ I_6 \cos\theta_\ell + I_7 \sin\theta_\ell \sin\phi + I_8 \sin 2\theta_\ell \sin\phi + I_9 \sin^2\theta_\ell \sin 2\phi \,, \end{aligned} \tag{8}$$

where θ_ℓ is the angle of the ℓ^- in the $\ell^+\ell^-$ CM frame, θ_P is the angle between K^- in the $K\pi$ CM frame, and ϕ is the angle between $\vec{p}_{K^-} \times \vec{p}_{\pi^+}$ and $\vec{p}_{\ell^-} \times \vec{p}_{\ell^+}$. The I_i depend on θ_P the tranversality amplitudes $A_0^{L,R}$, $A_{\|}^{L,R}$ which are S and D wave mixtures and $A_\perp^{L,R}$ is the P wave. The coefficients of each of the I_i is linearly independent. Hence, one can obtain each of the I_i by a transversality analysis of data. The wealth of information would be useful in detecting NP inspite of the presence of form factors in this decay mode involving hadrons.

An interesting observation is that in the 'large energy effective theory' [26] the forward–backward asymmetry $A_{\mathrm{FB}}(s)$ for the mode $B \to K^* \ell^+ \ell^-$ in the SM has a unique zero, at $s = s_0 = (p_+ + p_-)^2 = 2.9\ \mathrm{GeV}^2$, which is almost independent of the form factor. For the SM,

$$A_{\mathrm{FB}}(s) > 0 \ \text{ for } \ s < s_0 \quad \text{and} \quad A_{\mathrm{FB}}(s) < 0 \ \text{ for } \ s > s_0 \,.$$

Any NP always changes the shape and/or location of the zero i.e. s_0 for A_{FB}. See ref. [27] for details.

The final state with both CP even and CP odd partial waves has a great advantage for CP violating observables. Some CP violating asymmetries for the differential cross-section can be constructed by adding B and $\overline{B}$ decays. Such asymmetries [29] involve the interference terms of 'CP even' and 'CP odd' partial waves, i.e. terms involving I_7, I_8 and I_9, and can be expressed as

$$A_{2\phi} = \frac{\left(\int_0^\pi - \int_\pi^{2\pi}\right) \mathrm{d}\phi \int_D \mathrm{d}\cos\theta_\ell \int_D \mathrm{d}\cos\theta_P \ \dfrac{\Gamma(B \to f) + \Gamma(\overline{B} \to \bar{f})}{\mathrm{d}\Omega}}{\int_0^{2\pi} \mathrm{d}\phi \int_S \mathrm{d}\cos\theta_\ell \int_S \mathrm{d}\cos\theta_P \ \dfrac{\Gamma(B \to f) + \Gamma(\overline{B} \to \bar{f})}{\mathrm{d}\Omega}} \,,$$

where $\int_{D(S)} \equiv \int_{-1}^0 \mp \int_0^1$, $\mathrm{d}\Omega = \mathrm{d}\cos\theta_\ell \mathrm{d}\cos\theta_P \mathrm{d}\phi$, and

$$A_\phi = \frac{\int_Q \mathrm{d}\phi \int_S \mathrm{d}\cos\theta_\ell \int_S \mathrm{d}\cos\theta_P \ \dfrac{\Gamma(B \to f) + \Gamma(\overline{B} \to \bar{f})}{\mathrm{d}\Omega}}{\mathrm{d}\phi \int_S \mathrm{d}\cos\theta_\ell \int_S \mathrm{d}\cos\theta_P \ \dfrac{\Gamma(B \to f) + \Gamma(\overline{B} \to \bar{f})}{\mathrm{d}\Omega}} \,,$$

where, $\int_Q = (\int_0^{\pi/2} - \int_{\pi/2}^{\pi} + \int_\pi^{3\pi/2} - \int_{3\pi/2}^{2\pi})$. CP violating asymmetries corresponding to I_7, I_8, I_9 are very small [28] in the SM, $A_7^{\mathrm{CP}} \equiv 0$, $A_8^{\mathrm{CP}} = 0.6 \times 10^{-4}$ and $A_9^{CP} = -0.04 \times 10^{-4}$. These numbers are so small that they are almost unobservable. Hence, this is an excellent place to look for NP. It is a clean mode and the analysis does not require flavor or time tagging [29].

4. Are clean signals of new physics possible?

As seen in the previous sections, test of NP depend on hadronic parameters, which may not be calculated reliably or without model dependence. Ideally, we would like cleaner, more direct tests of the SM in order to probe for the presence of NP. In fact, such direct tests are possible. One can compare the rate asymmetries in $B^\pm \to DK^\pm$ and $B_s^0(t) \to D_s^\pm K^\mp$, both of which measure ϕ_3. A discrepancy between the extracted values would point to NP in $B_s^0 - \overline{B_s^0}$ mixing. Similarly, a discrepancy in ϕ_1, as measured via $B_d^0(t) \to \Psi K_S$ and $B_d^0(t) \to \phi K_S$, implies NP in the $b \to s$ penguin [7]. One can also measure the CP asymmetry in the decay $B_s^0(t) \to \Psi\phi$, which vanishes to a good approximation in the SM. Such an asymmetry would indicate the presence of NP in $B_s^0 - \overline{B_s^0}$ mixing. Note that all such tests probe NP in the $b \to s$ flavor-changing neutral current (FCNC).

One may then ask the question: are there any direct tests of NP in the $b \to d$ FCNC? For example, consider pure $b \to d$ penguin decays such as $B_d^0 \to K^0\overline{K^0}$ or $B_s^0 \to \phi K_S$, with the assumption that t-quark contribution dominates among up-type quarks in the loop. In such a case the SM would predict that (i) the CP asymmetry in $B_d^0(t) \to K^0\overline{K^0}$ vanishes, and (ii) the CP asymmetry in $B_s^0(t) \to \phi K_S$ measures $\sin 2\phi_1$ [30]. Any discrepancy between measurements of these CP asymmetries and their predictions would thus imply that there is NP in either $B_d^0 - \overline{B_d^0}$ mixing or the $b \to d$ penguin, i.e. in the $b \to d$ FCNC. However, it is well known that $b \to d$ penguins are *not* dominated by the internal t-quark. The contributions of the u- and c-quarks can be as large as 20–50% of that of the t-quark [31]. As a consequence, one cannot probe NP in $b \to d$ FCNC using such modes, and, unfortunately, the answer to the question asked is *no* [32].

The full $b \to d$ penguin amplitude is a sum of contributions from the three internal up-type quarks in the loop:

$$P = P_u\, V_{ub}^* V_{ud} + P_c\, V_{cb}^* V_{cd} + P_t\, V_{tb}^* V_{td}\ , \tag{9}$$

with $V_{ub} \sim \mathrm{e}^{-i\phi_3}$ and $V_{td} \sim \mathrm{e}^{-i\phi_1}$. Using the unitarity relation, $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$, the u-quark piece can be eliminated in eq. (9), allowing us to write

$$P = \mathcal{P}_{cu}\, \mathrm{e}^{i\delta_{cu}} + \mathcal{P}_{tu}\, \mathrm{e}^{i\delta_{tu}} \mathrm{e}^{-i\phi_1}\ , \tag{10}$$

where δ_{cu} and δ_{tu} are strong phases. Now imagine that there were a method in which a series of measurements allowed us to cleanly extract ϕ_1 using the above expression. In this case, we would be able to express $-\phi_1$ as a function of the observables.

On the other hand, we can instead use the unitarity relation to eliminate the t-quark contribution in eq. (9), yielding

$$P = \mathcal{P}_{ct}\, \mathrm{e}^{i\delta_{ct}} + \mathcal{P}_{ut}\, \mathrm{e}^{i\delta_{ut}} \mathrm{e}^{i\phi_3}. \tag{11}$$

Comparing eqs (10) and (11), we see that they have the same form. Thus, the same method used to extract $-\phi_1$ from eq. (10) can be used on eq. (11) to obtain ϕ_3. That is, we would be able to write ϕ_3 as *the same function* of the observables as was used for $-\phi_1$ above! But this implies that $-\phi_1 = \phi_3$, which clearly does not hold in general.

Due to the ambiguity in the parameterization of the $b \to d$ penguin — which we refer to as the *CKM ambiguity* — we conclude that one cannot cleanly extract the weak phase of any penguin contribution. Indeed, it is *impossible* to cleanly test for the presence of NP in the $b \to d$ FCNC. Nevertheless, it is instructive to examine in detail a few candidate methods, to see exactly how they fail.

The measurement of the time-dependent rate for the decay $B_d^0(t) \to K^0\overline{K^0}$ can at best allow one to extract the magnitudes and relative phase of $\mathrm{e}^{i\phi_1}A$ and $\mathrm{e}^{-i\phi_1}\bar{A}$, where A is the amplitude for $B_d^0 \to K^0\overline{K^0}$. With an independent measurement of ϕ_1, there are a total of 4 measurements. Using the form of the $b \to d$ penguin given in eq. (10), we have $\mathrm{e}^{i\phi_1}A = \mathrm{e}^{i\phi_1}(\mathcal{P}_{cu}\,\mathrm{e}^{i\delta_{cu}} + \mathcal{P}_{tu}\,\mathrm{e}^{i\delta_{tu}}\mathrm{e}^{-i\phi_1'})$, where we have written the phase ϕ_1' to allow for the possibility of NP.

There are thus 5 theoretical (hadronic) parameters: $\mathcal{P}_{cu}$, $\mathcal{P}_{tu}$, $\delta_{cu} - \delta_{tu}$, ϕ_1, and $\theta_{\rm NP} \equiv \phi_1' - \phi_1$. We see that there are not enough measurements to determine all the theoretical parameters. In fact, there is just one more theoretical unknown than there are measurements. A similar examination [32] of the $B \to \pi\pi$ isospin analysis, Dalitz-plot analysis of $B \to 3\pi$, angular analysis of $B^0 \to VV$ (where V is a vector meson), and a combined isospin + angular analysis of $B \to \rho\rho$ leads to the same conclusion, that there is one more unknown than there are measurements.

5. Epilogue

In this talk I have touched only the tip of the iceberg – I have just presented a very small sample of the many prospects, for the discovery of NP with B mesons. It is for this reason that one very often hears the remark 'we are at the dawn of a golden era of flavor physics.' Flavor physics has been instrumental in guiding us to the SM. The well known $\tau - \theta$ puzzle led to the realization that parity is not conserved. Absence of FCNC incorporated through introduction of charm led to the completion of the second family. CP violation itself led to the postulation of the third family. $B_d^0 - \overline{B_d^0}$ oscillation led to the realization that top quark can be very heavy. These are just a few of the many examples one can cite where flavor physics led to what was NP then . . . . If history were to be a judge one must conclude that '*a golden era of flavor physics must mean a golden age for particle physics*'.

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