New Physics and the Unitarity Triangle

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Abstract. After reviewing the present experimental constraints on the unitarity triangle, I discuss the various ways in which new physics can manifest itself in measurements of the parameters of the unitarity triangle. Apart from one exception, which I describe, new physics enters principally through new contributions to $B^0$-$\bar{B}^0$ mixing. Different models of new physics can be partially distinguished by looking at their effects on rare, flavour-changing $B$ penguin decays.

At this conference, we have heard a number of talks discussing the prospects of various experiments for measuring CP asymmetries in $B$ decays, i.e. the angles of the unitarity triangle. Ultimately, the hope is that we will find an inconsistency with the standard model (SM), which will give us some clue regarding the new physics which most of us believe must lie beyond the SM. In discussing new physics and the unitarity triangle (UT), there are basically two questions which have to be addressed:

1. What are the signals of new physics?
2. If such signals are seen, how can we identify the new physics?

The first step in answering these questions is to review our current knowledge of the UT. There are a number of measurements which constrain the UT: $|V_{cb}|$, $|V_{ub}/V_{cb}|$, $B_d$ and $B_s$ mixing, and $|\epsilon|$ in the kaon system. However, the problem is that there are important theoretical uncertainties in translating the experimental numbers into information about the UT. Combining all theoretical and experimental errors in quadrature, our present knowledge of the UT can be summed up in Fig. 1 [1]. As is evident from this figure, we

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1) Invited talk given at the Symposium Twenty Beautiful Years of Bottom Physics, Chicago, IL, USA, June 29 – July 2, 1997.
really know rather little about the UT at present, due mainly to theoretical uncertainties.

On the other hand, the angles $\alpha$, $\beta$ and $\gamma$ can be extracted with essentially no theoretical uncertainty from CP-violating asymmetries in $B$ decays [2]. Due to $B^0$-$\bar{B}^0$ mixing, any neutral $B$ decay to a final state $f$ to which both $B^0$ and $\bar{B}^0$ can decay can exhibit CP violation, due to the interference between the amplitudes $B^0 \to f$ and $\bar{B}^0 \to f$. There are 4 distinct classes of CP asymmetries, involving the decays of $B^0_d$ or $B^0_s$ mesons, and the quark-level processes $b \to c$ or $b \to u$. For example, the asymmetries in $B^0_d(t) \to \pi^+\pi^-$ and $B^0_s(t) \to \Psi K_S$ probe $\sin 2\alpha$ and $\sin 2\beta$, respectively, while $\sin^2 \gamma$ can be extracted from $B^0_d(t) \to D^\pm K^\mp$. (The decay $B^\pm \to DK^\mp$ can also be used to obtain $\sin^2 \gamma$.) The fourth CP asymmetry (e.g. $B^0_d(t) \to \Psi \phi$) is expected to be zero, to a good approximation, within the SM. This is therefore a good place to look for new physics. The measurements of the three nonzero CP angles would allow us to reconstruct the UT with little theoretical error. Our present experimental knowledge constrains the angles to lie within the ranges $-1.0 \leq \sin 2\alpha \leq 1.0$, $0.26 \leq \sin 2\beta \leq 0.88$, and $0.22 \leq \sin^2 \gamma \leq 1.0$.

There are thus three distinct ways in which new physics can manifest itself in measurements of these CP asymmetries [3]:

1. $\alpha + \beta + \gamma \neq \pi$.

2. $\alpha + \beta + \gamma = \pi$, but the values of $\alpha$, $\beta$ and $\gamma$ found disagree with the SM predictions.

3. $\alpha + \beta + \gamma = \pi$, $\alpha$, $\beta$ and $\gamma$ are consistent with the SM, but measurements of the angles are inconsistent with measurements of the *sides* of the UT.
Now, how can new physics affect these CP asymmetries? There are basically only two ways, via either new contributions to $B$ decays ($b \to c, u$), or to $B$-$\bar{B}$ mixing. The first possibility can be virtually eliminated – apart from some very fine-tuned models, there are no models of physics beyond the SM in which the new contributions are competitive with the SM $W$-mediated decays. On the other hand, there are many models of new physics in which there are new contributions to $B$-$\bar{B}$ mixing, possibly with new phases [4]. Therefore the principal way in which new physics can affect the UT is via new contributions to $B$ mixing. (There is an exception to this, which I will discuss below.) These new contributions will affect the experimental determinations of $V_{td}$, $V_{ts}$, $\alpha$, $\beta$ and $\gamma$.

In light of this, let us reconsider the three ways in which new physics can be detected. The first is to measure the 3 CP angles, and find $\alpha + \beta + \gamma \neq \pi$. In order for this to happen, there must be new physics, with new phases, in $B_d$ or $B_s$ mixing. However, there is a interesting twist here. Suppose there is new physics in $B$ mixing. If $\beta$ is measured in $B_d(t) \to \Psi K_S$, then the phase extracted will be $\beta + \phi_{NP}^d$. And if $\alpha$ is obtained via $B_d(t) \to \pi^+\pi^-$, then one gets $\alpha - \phi_{NP}^d$. The key point here is that the sum $\alpha + \beta$ is insensitive to new physics [5]. Turning to the third angle, if $\gamma$ is measured in $B^\pm \to DK^\pm$, then it is extracted with no modification, since neutral $B$’s are not involved. However, if $\gamma$ is obtained from $B_s(t) \to D_s^\pm K^{\mp}$, then $\gamma + \phi_{NP}^s$ will be extracted. The upshot is: since $B$-factories such as BaBar and Belle do not measure CP asymmetries in $B^0_s$ decays, they will never find $\alpha + \beta + \gamma \neq 0$. (Once again, there is an exception, to be discussed below.) However, hadron colliders may find $\alpha + \beta + \gamma \neq 0$ if $\gamma$ is measured in $B^0_s$ decays. In fact, a discrepancy in the value of $\gamma$ as extracted in these two ways would be a clear signal for new physics in $B^0_s$-$\bar{B}^0_s$ mixing.

The second way to detect new physics is if $\alpha + \beta + \gamma = \pi$, but the values of $\alpha$, $\beta$ and $\gamma$ are in disagreement with the SM predictions. This can happen if there are new contributions, with new phases, to $B_d$ or $B_s$ mixing. Finally, the third way is if $\alpha + \beta + \gamma = \pi$ and $\alpha$, $\beta$ and $\gamma$ are consistent with the SM, but are inconsistent with measurements of the sides of the UT. In this case, we need new contributions to $B_d$ or $B_s$ mixing with the same phase as in the SM.

Before examining which types of physics can contribute to $B$-$\bar{B}$ mixing, let me first discuss the exception I mentioned above. Most CP asymmetries involve tree-level $B$ decays. However, there is another class of decays which can also be used: penguin decays [6,7]. Consider, for example, the decay $B^0_d \to \phi K_S$, which is dominated by the quark-level $\bar{b} \to \bar{s}s\bar{s}$ penguin decay. Since the final state is a CP eigenstate, both $B^0_d$ and $\bar{B}^0_d$ can decay to it, thus leading to a possible CP-violating asymmetry. What does this CP asymmetry measure? The $b \to s$ penguin is dominated by internal $t$-quarks, so that it is proportional to the product of CKM matrix elements $V_{tb}^*V_{ts}$. Within the
Wolfenstein approximation, this is real, just like $V_{cb}^* V_{cs}$, which describes the decay $B_0^0 \rightarrow \Psi K_S$. In other words, the CP asymmetry in $B_d(t) \rightarrow \phi K_S$ measures $\beta$, just like $B_d(t) \rightarrow \Psi K_S$. Therefore, within the SM, $\beta$ as extracted from the CP asymmetry in $\phi K_S$ equals that as found in $\Psi K_S$ [6]. In fact, this is true even if there are new-physics contributions to $B_0^0$-$\overline{B}_0^0$ mixing.

However, since the $b \rightarrow s$ penguin is a pure loop effect, there can in principle be significant new contributions from new physics [8]. Examples of such new physics include four generations, non-minimal supersymmetry, and models with enhanced chromomagnetic dipole operators. If there is new physics, the phase of the decay amplitude may be changed. In this case, one will find $\beta$ (from $\phi K_S$) is not equal to $\beta$ (from $\Psi K_S$). Therefore, by measuring $\beta$ in $B_d(t) \rightarrow \phi K_S$, it might in fact be possible to find $\alpha + \beta + \gamma \neq \pi$, even at $B$-factories. Note also that, in addition to $\phi K_S$, the final states $\eta' K_S$, $\rho K_S$, $\pi^0 K_S$, $\eta K_S$, etc. may be used. In fact, recent results from CLEO, which show that the branching ratio for $B \rightarrow \eta' K$ is larger than expected, indicate that this method of measuring $\beta$ may be promising [9].

The interesting thing is that what is really being probed here is new physics in the $b \rightarrow s$ flavour-changing neutral current. This same new physics will, in general, contribute to $B_s^0$-$\overline{B}_s^0$ mixing. Thus, this is in some sense a way of detecting new physics in $B_s$ mixing without using $B_s$’s at all!

Having discussed this special case, I now return to the more conventional ways of measuring the CP angles, via tree-level decays of $B$ mesons. Suppose that the CP asymmetries are measured, and evidence for new physics is found. What could this new physics be? We know that the new physics contributes to $B^0$-$\overline{B}^0$ mixing. Therefore a first step is to classify models of new physics according to (i) whether they contribute to $B^0$-$\overline{B}^0$ mixing and (ii) if so, if new phases are involved.

Here is a fairly extensive list of models of new physics, along with a discussion of their effects in $B^0$-$\overline{B}^0$ mixing [3]:

- Four generations: there are new loop-level contributions to the mixing involving internal $t'$ quarks. Since the CKM matrix is now $4 \times 4$, new phases can be introduced.

- $Z$-mediated flavour-changing neutral currents (FCNC’s): if the down-type quarks mix with an exotic vector singlet charge $-1/3$ quark, then the flavour-changing couplings $Zbd$ and $Zbs$ will be induced. In such models, there will be new contributions, with new phases, to $B$ mixing through tree-level $Z$ exchange.

- Multi-Higgs-doublet models:
  - with natural flavour conservation (NFC): in such models there are new contributions to $B$ mixing involving box diagrams with internal charged Higgses. The charged Higgses couple to quarks through the CKM matrix, so no new phases are introduced.
– without NFC: in this case there can be tree-level FCNC’s involving the exchange of a neutral Higgs. Thus there are new contributions, with new phases, in $B$ mixing.

• Left-right symmetric models: except in the most fine-tuned models, which I don’t consider here, the mass of the $W_R$ is at least 1 TeV. This renders its effects in $B$ mixing negligible.

• Supersymmetry:
  – Minimal SUSY: there are many new contributions to $B$ mixing involving box diagrams with internal supersymmetric particles. In the minimal model, all couplings involve the CKM matrix, so that no new phases are introduced.
  – Non-minimal SUSY: in non-minimal models, the new contributions can also have new phases.

The above list shows that there are indeed many models of physics beyond the SM which can contribute to $B^0$-$\bar{B}^0$ mixing, some with new phases, some without. The presence of such new physics will be detected through measurements of the CP asymmetries. However, such measurements will only tell us that new physics is present. While that would be a very exciting development, we still would want to know what the new physics is. How can we distinguish among the various possibilities listed above?

Some progress can be made through a simple observation. Any new physics which affects $B^0$-$\bar{B}^0$ mixing, which is a FCNC process, will also in general affect the rare, flavour-changing decays $b \to sX$ and $b \to dX$ (penguin decays). Therefore, by also looking at penguin decays, it may be possible to identify some models of new physics [3]. In fact, for certain types of new physics, if no deviation from the SM is observed in penguin decays, this would rule out there being any effects in $B$ mixing.

To see how this works, I will examine in detail one model of new physics: $Z$-mediated FCNC’s. As mentioned earlier, there are flavour-changing couplings $Z b \bar{d}$ and $Z b \bar{s}$, parametrized by $U_{db}$ and $U_{sb}$, respectively. These couplings are constrained by $BR(B \to \mu^+\mu^-X) < 5 \times 10^{-5}$, leading to $|U_{qb}/V_{cb}| < 0.044$, or $|U_{qb}| < 0.0017$. The new couplings $U_{qb}$ can have arbitrary phases.

In this model there are new, tree-level contributions to $B^0$-$\bar{B}^0$ mixing through $Z$ exchange. Comparing to the SM, we find

\[
\frac{\Delta M_d^Z}{\Delta M_d^W} = (0.9 - 26) \left[ \frac{|U_{db}/V_{cb}|}{0.04} \right]^2, \quad \frac{\Delta M_s^Z}{\Delta M_s^W} = 0.15 \left[ \frac{|U_{sb}/V_{cb}|}{0.04} \right]^2.
\]

Therefore $B^0_d$-$\bar{B}^0_d$ mixing can be dominated by $Z$-FCNC’s, with new phases; $B^0_s$-$\bar{B}^0_s$ mixing is still due mainly to $W$ box diagrams, but the new contribution is non-negligible, so the new phases may be important.
Let us now examine the contribution of $Z$-FCNC’s to penguin decays. The constraint $|U_{qb}| < 0.0017$ is derived from the experimental limit $BR(B \to \mu^+\mu^-X) < 5 \times 10^{-5}$. Therefore if the new coupling takes its maximum allowed value, the model “predicts” the same branching ratio. This is, in fact, a huge effect – it is a smoking-gun signal. For the $b \to s$ decay, this is roughly 10 times bigger than in the SM, while for the $b \to d$ decay, it is an enhancement of about a factor of 100. Furthermore, if the branching ratios for the decays $B \to X_s\ell^+\ell^-$ and $B \to X_d\ell^+\ell^-$ are found to be consistent with the SM, this puts such stringent constraints on the $|U_{qb}|$ that it rules out the possibility of any effects in $B^0$-$\bar{B}^0$ mixing.

There are smoking-gun enhancements in other decays as well. For the presently-allowed values of the $|U_{qb}|$,

- $BR(B_s^0 \to \ell^+\ell^-)$ is enhanced by about a factor of 20.
- $BR(B_d^0 \to \ell^+\ell^-)$ is enhanced by about a factor of 300-400.
- $BR(b \to s$ EWP’s) is enhanced by about a factor of 25.
- $BR(b \to d$ EWP’s) is enhanced by about a factor of 500.

‘EWP’ stands for electroweak penguin decays. These are penguin decays which are dominated in the SM by a virtual $Z$, e.g. $B^+ \to \phi\pi^+$ and $B_s^0 \to \phi\pi^0$. There are no large effects of $Z$-mediated FCNC’s in $b \to s\gamma$ or in other hadronic penguins.

The point of all this is to demonstrate that, if there are significant new-physics effects in $B^0$-$\bar{B}^0$ mixing, then this same new physics is also likely to have important effects in $B$ penguin decays. Table 1 contains a summary of the effects of various models of new physics on both $B^0$-$\bar{B}^0$ mixing and penguin decays [3].

| Model               | Contribution to $B^0$-$\bar{B}^0$ Mixing? | New Phases? | Contributions to Penguins? | Modes                                                                 |
|---------------------|------------------------------------------|-------------|-----------------------------|------------------------------------------------------------------------|
| 4 generations       | Yes                                      | Yes         | Yes                         | EWP’s                                                                  |
| Z-FCNC’s            | Yes                                      | Yes         | Yes                         | $b \to q\ell^+\ell^-$,                                                |
|                     |                                          |             |                             | $B^0 \to \ell^+\ell^-$,                                               |
| MHDM w/ NFC         | Yes                                      | No          | Yes                         | EWP’s                                                                  |
|                     |                                          |             |                             | $b \to s\ell^+\ell^-$,                                                |
|                     |                                          |             |                             | $B^0 \to \ell^+\ell^-$,                                               |
| MHDM w/o NFC        | Yes                                      | Yes         | No                          | —                                                                       |
| Left-Right Symm.    | No                                       | No          | No                          | —                                                                       |
| MSSM                | Yes                                      | No          | No                          | —                                                                       |
| Non-min. SUSY        | Yes                                      | Yes         | Yes                         | ?                                                                       |
To sum up, there are many signals of new physics in CP asymmetries: $\text{Asym}(B^0_s \rightarrow \Psi \phi) \neq 0$; $\alpha + \beta + \gamma \neq \pi$; $\text{Asym}(B^0_d \rightarrow \Psi K_s) \neq \text{Asym}(B^0_d \rightarrow \phi K_s)$ [\beta]$; $\text{Asym}(B^0_d \rightarrow D^\pm K^\mp) \neq \text{Asym}(B^\pm \rightarrow D K^\mp) [\gamma]$; $\alpha + \beta + \gamma = \pi$ but $\alpha$, $\beta$ and $\gamma$ are inconsistent with the SM (e.g. $\sin 2 \beta < 0$); $\alpha + \beta + \gamma = \pi$, $\alpha$, $\beta$ and $\gamma$ are consistent with the SM, but are inconsistent with measurements of the sides of the UT; etc.

The main way in which new physics can enter is via new contributions to $B^0$-$\bar{B}^0$ mixing. (There is an exception: for pure penguin decays, such as $B^0_d \rightarrow \phi K_s$, there can be new decay amplitudes.) There are many models of new physics which can yield such new contributions. In this talk I have considered four generations, Z-mediated FCNC’s, multi-Higgs-doublet models with and without natural flavour conservation, minimal and non-minimal supersymmetry.

Assuming that some signal for new physics is seen in the measurements of CP asymmetries, one can partially distinguish among the various models by looking at the rates for rare penguin decays. CP asymmetries and penguin decays thus give complementary information regarding the identity of the new physics.

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