Abstract

The decays $B_{d,s}^0 \to K^{(*)}\bar{K}^{(*)}$ can be used to measure the angle $\alpha$ of the CKM unitarity triangle. The theoretical error from $SU(3)$ breaking is expected to be small, so that the determination of $\alpha$ is clean. Moreover, since $B_{d,s}^0 \to K^{(*)}\bar{K}^{(*)}$ are pure penguin decays, they are particularly sensitive to the presence of new physics.

\footnote{Talk presented by Alakabha Datta at the 5th International Conference on Hyperon, Charm and Beauty Hadrons.}
1 CP phase $\alpha$ from $B_{d,s}^0 \to K(\ast)\bar{K}(\ast)$

The first evidence of CP violation in the $B$ system was recently observed with the measurement of one of the angles of the Cabibbo-Kobayashi-Maskawa (CKM) unitarity triangle: $\sin 2\beta = 0.78 \pm 0.08$, which is consistent with the standard model (SM). Future efforts will focus on the measurement of the remaining two angles of the unitarity triangle, $\alpha$ and $\gamma$, in order to test the SM explanation of CP violation.

There are two standard techniques for the extraction of $\alpha$. The first method uses the CP asymmetry in $B_0^d(t) \to \pi^+\pi^-$ to obtain $\alpha$. Unfortunately, there is a penguin contribution, making it necessary to perform an isospin analysis of $B \to \pi\pi$ decays. This requires the measurement of $B_0^d \to \pi^0\pi^0$, which is expected to have a small branching ratio. Hence, it may be difficult to obtain $\alpha$ using this method. The second method uses a Dalitz-plot analysis of $B_0^d(t) \to \rho\pi \to \pi^+\pi^-\pi^0$ decays. However, the unknown non-resonant background and the correct description of $\rho \to \pi\pi$ decays are factors that can seriously affect a clean determination of $\alpha$ using this method.

In this talk, we present a new method for determining $\alpha$ [4]. As a starting point, consider the pure $b \to d$ penguin decay $B_0^d \to K^0\bar{K}^0$, for which the underlying quark transition is $\bar{b} \to \bar{d}ss$. The amplitude $A_d$ for $B_0^d \to K^0\bar{K}^0$, $A_d$, can be written as

$$A_d = P_u V_u^d + P_c V_c^d + P_t V_t^d = (P_u - P_c)V_u^d + (P_t - P_c)V_t^d,$$  \hspace{1cm} (1)

where $V_q^d \equiv V_{qb}^* V_{qd}$, and $P_u,c,t$ are the penguin amplitudes. In passing from the first line to the second, we have used the unitarity of the CKM matrix, $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$, to eliminate the $V_{cb}^* V_{cd}$ term. The amplitude $\bar{A}_d$ describing the conjugate decay $\bar{B}_0^d \to K^0\bar{K}^0$ can be obtained from the above by changing the signs of the weak phases.

By making time-dependent measurements of $B_0^d(t) \to K^0\bar{K}^0$, one can obtain the three observables

$$X \equiv \frac{1}{2} \left( |A_d|^2 + |\bar{A}_d|^2 \right)$$

$$Y \equiv \frac{1}{2} \left( |A_d|^2 - |\bar{A}_d|^2 \right)$$

$$Z_I \equiv \text{Im} \left( e^{-2i\beta} A_d^* \bar{A}_d \right).$$ \hspace{1cm} (2)

The three independent observables depend on four theoretical parameters: $P_{uc} \equiv |P_u - P_c|$, $P_{tc} \equiv |P_t - P_c|$, the relative weak phase between the two amplitudes, $\alpha$, and the relative strong phase. Hence one cannot obtain CP phase information from these measurements [5]. However, substituting Eq. 4 in Eq. 3, one can obtain

$$P_{tc}^2 |V_t^d|^2 = \frac{Z_I \cos 2\alpha + Z_r \sin 2\alpha - X}{\cos 2\alpha - 1},$$ \hspace{1cm} (3)
where

$$Z_R \equiv \text{Re}\left(e^{-2i\beta}A_d^*\bar{A}_d\right).$$

The quantity $Z_R$ is related to the three observables in Eq. 2 by

$$Z_R^2 = X^2 - Y^2 - Z_I^2.$$

Now consider a second pure $b \to d$ penguin decay of the form $B_0^0 \to K^*\bar{K}^*$. Here $K^*$ represents the ground state vector meson, $K^*(892)$, or any excited neutral kaon, such as $K_1(1270)$, etc. This second decay can be treated in a similar fashion as the first one above, with unprimed parameters and observables being replaced by primed ones. One can then combine measurements of the two decays to obtain

$$r_d \equiv \frac{P_{tc}^2}{P_{tc'}^2} = \frac{Z_I\sin 2\alpha + Z_R\cos 2\alpha - X}{Z_I'\sin 2\alpha + Z_R'\cos 2\alpha - X'} = f(\alpha).$$

The equation above, $r_d = f(\alpha)$, could then be solved for $\alpha$ if we knew $r_d$. Note that the CKM elements on the left-hand side of Eq. 3 cancel in constructing the ratio $r_d$.

Information about the ratio $r_d$ can be obtained by measuring $B_0^0$ decays to the same final states $K^0\bar{K}^0$ and $K^*\bar{K}^*$. Consider first the decay $B_0^0 \to K^0\bar{K}^0$. This is described by a $b \to s$ penguin amplitude, $A_s$, which is given by

$$A_s = P_u^{(s)}V_{us} + P_c^{(s)}V_{cs} + P_t^{(s)}V_{ts} \simeq (P_t^{(s)} - P_c^{(s)})V_{ts},$$

where $V_{us} \equiv V_{ub}^*V_{qs}$, and $P_{u,c,t}^{(s)}$ are the penguin amplitudes. In writing the second line, we have again used the unitarity of the CKM matrix to eliminate the $V_{cb}^*V_{cs}$ piece. Furthermore, the $V_{ub}^*V_{us}$ piece is negligible: $|V_{ub}^*V_{us}| \ll |V_{tb}^*V_{ts}|$. Thus, the measurement of the branching ratio for $B_0^0 \to K^0\bar{K}^0$ yields $|P_t^{(s)} - P_c^{(s)}||V_{ts}|$. Similarly one can obtain $|P_t'^{(s)} - P_c'^{(s)}||V_{ts}'|$ from the branching ratio for $B_0^0 \to K^*\bar{K}^*$. In this way, we can measure

$$r_s \equiv \frac{P_{tc}^{(s)}^2}{P_{tc'}^{(s)}^2},$$

where $P_{tc}^{(s)} \equiv |P_t^{(s)} - P_c^{(s)}|$ and $P_{tc'}^{(s)} \equiv |P_t'^{(s)} - P_c'^{(s)}|$.

Now, the main point is that, up to small $SU(3)$ corrections,

$$r_d = r_s.$$

Note again that the CKM matrix elements cancel in both ratios. The $SU(3)$ breaking in the equality $r_d = r_s$ is at the level of 5% or less. Hence $\alpha$ can be obtained from the equation $r_d \approx r_s = f(\alpha)$. This equation has several solutions and so there are discrete
ambiguities in the extraction of \( \alpha \). However, by comparing several pairs of processes, the discrete ambiguities can be eliminated. In fact, with one theoretical assumption, all the discrete ambiguities can be removed with a single pair of processes [4].

This method can also be used when the final state is not self-conjugate. For example, one can consider the decays \( B^0_d \to K^0\bar{K}^* \) and \( B^0_s \to K^0\bar{K}^* \) [4].

From the above analysis, we therefore see that the CP phase \( \alpha \) can be cleanly extracted from measurements of the decays of \( B^0_d \) and \( B^0_s \) mesons to two different final states consisting of one neutral kaon (i.e. \( K^0 \) or any of its excited states) and one neutral anti-kaon (i.e. \( \bar{K}^0 \) or any excited state). Finally, we note that the \( K^*\bar{K}^* \) final state consists of three helicity states. Each helicity state can be then considered a distinct final state for the purposes of our analysis. Thus, by applying our method to two different \( K^*\bar{K}^* \) helicity states, \( \alpha \) can be obtained from \( B^0_{d,s} \to K^*\bar{K}^* \) decays alone.

The branching ratios of the pure pure \( b \to d \) penguin decays \( B^0_d(t) \to K^{(*)}\bar{K}^{(*)} \) are expected to be quite small, of order \( 10^{-6} \). Hence this method is ideally suited to hadron colliders as they produce an enormous number of \( B \) mesons. Furthermore, in all cases, the kaon or anti-kaon can be detected using its decays to charged \( \pi \)'s or \( K \)'s only; this method does not require the detection of \( \pi^0 \)'s. Therefore hadron colliders will be able to use this technique to measure \( \alpha \) - all that is required is good \( \pi/K \) separation. And if \( \pi^0 \)'s can be detected, this simply increases the detection efficiency for the various final states.

2 New Physics in \( B^0_{d,s} \to K^{(*)}\bar{K}^{(*)} \)

The decays \( B^0_{d,s} \to K^{(*)}\bar{K}^{(*)} \) are pure penguin decays and hence could be sensitive to new-physics effects. Consider the decays \( B_s \to K^{(*)}\bar{K}^{(*)} \), which are dominated to a very good approximation by a single amplitude in the standard model (see Eq. 6). Hence a measurement of CP violation, such as a direct CP asymmetry, will be a clear sign of new physics in the \( b \to s \) penguin.

New physics in the \( b \to s \) penguin can also affect the more well known decay \( B_d \to \phi K_S \) [3]. However, note that the new-physics operator for \( B_s \to K^{(*)}\bar{K}^{(*)} \) is of the form \( O_d = d\Gamma_1ds\Gamma_2b \), where \( \Gamma_{1,2} \) are some Lorentz operators, while for \( B_d \to \phi K_S \) the new-physics operator is of the form \( O_s = s\Gamma_1ss\Gamma_2b \). There are models of new physics where the operators \( O_s \) and \( O_d \) are related. For example, consider models with an additional vector-singlet charge \(-1/3\) quark \( h \) which mixes with the ordinary down-type quarks \( d \), \( s \) and \( b \). (These models are generally motivated by \( E_6 \) grand unified theories.) This then generates flavour-changing effects through the \( Zb\bar{s} \) FCNC coupling [3]. This coupling will then generate the operators \( O_{s,d} \) but with the same strength.

Models of new physics which contain exotic fermions generally have additional neutral \( Z' \) gauge bosons. If the \( s \)-, \( b \)- and \( h \)-quarks have different quantum numbers under the new \( U(1) \) symmetry, their mixing will also induce FCNC’s due to \( Z' \) exchange [3] which will
then generate $O_{s,d}$, but again with the same strength. Hence in such models CP violation in $B_d \to \phi K_S$ and $B_s \to K^{(*)}\bar{K}^{(*)}$ will be correlated.

On the other hand, consider another model of new physics: R-parity breaking supersymmetry (SUSY). The most general superpotential of the MSSM with $SU(3) \times SU(2) \times U(1)$ gauge symmetry which breaks R-parity is

$$W_R = \frac{1}{2} \lambda_{[ij]k} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2} \lambda''_{[ij]k} U_i^c D_j^c D_k^c + \mu_i L_i H_2. \quad (9)$$

Here $L_i(Q_i)$ and $E_i(U_i, D_i)$ are the left-handed lepton (quark) doublet and lepton (quark) singlet chiral superfields, where $i, j, k$ are generation indices and $c$ denotes a charge-conjugate field. $H_{1,2}$ are the chiral superfields representing the two Higgs doublets. The non-observation of proton decay imposes very stringent conditions on the simultaneous presence of both the baryon-number and lepton-number violating terms in the Lagrangian $[10]$.

The B-violating couplings $\lambda''$ are antisymmetric in the last two indices. Hence the operator $O_s$ cannot be generated at tree level and so there will no significant effects in $B_d \to \phi K_S$. On the other hand, the operator $O_d$ can be generated at tree level and hence can lead to CP violation in $B_s \to K^{(*)}\bar{K}^{(*)}$.

The $L$-violating couplings are given in terms of four-component Dirac spinors by $[11]$

$$\mathcal{L}_{\lambda'} = \lambda'_{ijk} \left[ \bar{e_i}^c d_R^k u_L^j + \bar{u_L^j} d_R^k e_i^c + \bar{d_R^k} e_L^c u_L^j - \bar{\nu_L^j} d_R^k \nu_L^j - (d_R^k)^* (\nu_L^j)^c d_L^k \right]$$

$$+ h.c. \quad (10)$$

In this case both operators $O_s$ and $O_d$ will be generated, but in general with different strengths. Thus, in this model CP violation in $B_d \to \phi K_S$ and $B_s \to K^{(*)}\bar{K}^{(*)}$ can be quite different.

Finally, we return to the measurement of the CP phase $\alpha$ via $B_{d,s}^0 \to K^{(*)}\bar{K}^{(*)}$. If the value of $\alpha$ obtained via this method differs from that measured in $B_d \to \pi\pi$ or $B_d \to \rho\pi$, this will be evidence of new physics in the $b \to d$ or $b \to s$ penguin amplitudes.

### 3 Conclusion

In conclusion, we have presented a new method to measure $\alpha$ using $B_{d,s}^0 \to K^{(*)}\bar{K}^{(*)}$. Because these processes are pure penguin decays, they are particularly sensitive to new physics. We have described several ways of detecting new physics in such decays.

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