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CP Violation Studies with the Neutral B Meson Decays

Tatsuya Nakada

Paul Scherrer Institut
CH-5232 Villigen PSI, Switzerland

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Paul Scherrer Institute
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Switzerland

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Abstract

The origin of CP violation is still one of the unsolved problems of elementary particle physics. It is now widely accepted that the B meson system is the best place to test whether CP violation can be accommodated within the standard model. In this article, we summarise the necessary measurements to test the standard model using CP violation in the neutral B meson decays.

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1 Introduction

Parity violation was discovered in 1957 [1] in nuclear β decays and pion and muon decays [2]. In the charged current interaction of the standard electroweak theory, parity and charge conjugation symmetries are maximally violated due to the $V - A$ structure [3]. All the experimental results up to now are in full agreement with the theory.

A surprising discovery of the CP violating $K_L \rightarrow \pi^+\pi^-$ decays [4] was made in 1964. Soon after the discovery, a superweak model [5] was proposed. It introduces a new interaction with a complex coupling constant. This interaction is much weaker than the weak interaction and solely responsible for the observed CP violation in this model. The currently observed CP violation in the kaon system is fully compatible with the superweak model.

The standard model with three fermion families can also accommodate CP violation through the complex quark mixing matrix, Cabibbo-Kobayashi-Maskawa (CKM) matrix [6]. This 3×3 unitary matrix has four independent variables; three rotation angles and one phase angle. They are parameters of the standard model and their values are not given by the model itself. If the phase is not 0 or π , CP violation is generated in the charged current interaction.

From the measured decay widths of various particles, moduli of the CKM elements are determined [7]. Once sufficient numbers of the moduli of elements are known, the four parameters can be extracted. Two of the three rotation angles are now well determined. The third angle has a large error and the phase is still consistent with zero. Only if we assume that the observed CP violation in the K_L decays is generated by the standard model, a non zero value of the phase can be obtained with a large uncertainty. This clearly indicates that we still do not know whether the standard model is responsible for CP violation.

If the future kaon experiments [8] discover $\epsilon' \neq 0$, the superweak model is eliminated, at least as the main source for CP violation. However, the standard model prediction of ϵ' [9] is very small due to an unfortunate cancellation of the different diagrams and even the impressive sensitivities of the future experiments may not be sufficient. Moreover, theoretical uncertainties in the prediction are large due to the difficulty in evaluating hadronic matrix elements.

Therefore, CP violation studies in the kaon system alone appear to be inadequate to answer the following question: **What is the origin of CP violation?** Can CP violation be fully accommodated within the standard model or does it require physics beyond the standard model? It could be also a combination of the two. The answer can only be obtained by a quantitative comparison between theoretical predictions and experimental results.

How about the neutral B meson system [10]? Unlike the kaon decays where the $\Delta I = 1/2$ decay amplitude dominates, no dominant decay amplitudes are present in the B meson system. Therefore, CP violation is expected in many different decay modes of the B mesons. The standard model predicts a definite pattern of CP violation for those final states once all the four parameters of the CKM matrix are determined. Therefore, a

consistency test can be made by examining this predicted pattern. Theoretical predictions for some of the decay modes have little uncertainty introduced by the strong interactions. Those channels can be used to test the predictions quantitatively.

In this article, we review how one can exploit the potential of the B meson system in order to solve the mystery of CP violation [11].

2 Time dependent B meson decays

In this section, we present a short phenomenological description of the neutral B meson system [12]. The discussion applies to both B_d - and B_s meson systems unless specified.

Similar to the neutral kaon system, a general solution for the neutral B meson system at a time t , $|\Psi(t)\rangle = a(t)|B\rangle + b(t)|\bar{B}\rangle$ where $a(t)$ and $b(t)$ are functions of t , is given by solving the differential equation

$$i \frac{\partial}{\partial t} \begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = \left(\mathbf{M} - i \frac{\mathbf{\Gamma}}{2} \right) \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}.$$

The $|B\rangle$ represents the B^0 or B_s^0 state and $|\bar{B}\rangle$ represents the $\bar{B}^0$ or $\bar{B}_s^0$ state. The mass matrix $\mathbf{M}$ and the decay matrix $\mathbf{\Gamma}$ are 2×2 Hermitian matrices. Solutions for the initially pure B and $\bar{B}$ are given by

$$\begin{aligned} |B(t)\rangle &= f_+(t)|B\rangle + \zeta f_-(t)|\bar{B}\rangle \\ &= \frac{\sqrt{1+|\zeta|^2}}{2} (|B_l\rangle e^{-i\lambda_l t} + |B_h\rangle e^{-i\lambda_h t}) \\ |\bar{B}(t)\rangle &= \frac{1}{\zeta} f_-(t)|B\rangle + f_+(t)|\bar{B}\rangle \\ &= \frac{\sqrt{1+|\zeta|^2}}{2\zeta} (|B_l\rangle e^{-i\lambda_l t} - |B_h\rangle e^{-i\lambda_h t}) \end{aligned} \tag{1}$$

where the functions $f_{\pm}(t)$ are defined to be

$$f_{\pm}(t) = \frac{1}{2} (e^{-i\lambda_l t} \pm e^{-i\lambda_h t}).$$

The masses and decay widths for the two mass eigenstates of the neutral B meson system, B-heavy (B_h) and B-light (B_l), are denoted by m_h and m_l and Γ_h and Γ_l respectively and we have $\lambda_{l,h} = m_{l,h} - i\Gamma_{l,h}/2$. The two mass eigenstates are given by

$$\begin{aligned} |B_h\rangle &= \frac{1}{\sqrt{1+|\zeta|^2}} (|B\rangle - \zeta|\bar{B}\rangle) \\ |B_l\rangle &= \frac{1}{\sqrt{1+|\zeta|^2}} (|B\rangle + \zeta|\bar{B}\rangle). \end{aligned}$$

with the linear coefficient ζ ,

$$\zeta = \sqrt{\frac{M_{12}^* - i\Gamma_{12}^*/2}{M_{12} - i\Gamma_{12}/2}}$$

where M_{12} and Γ_{12} are the off-diagonal elements of $\mathbf{M}$ and $\mathbf{\Gamma}$.

If CP violation is absent, B_h and B_l are CP eigenstates and their eigenvalues are expected to be -1 and $+1$ from the standard electroweak interactions. For the B_d meson system, the mass difference between B_h and B_l is measured to be [13]

$$\Delta m(B_d) = m_h - m_l = (3.26 \pm 0.21) \times 10^{-4} \text{ eV}$$

from the frequency of B^0 - $\bar{B}^0$ oscillations. We introduce the following expressions for the decay widths:

$$\Delta\Gamma \equiv \Gamma_l - \Gamma_h, \quad \bar{\Gamma} \equiv \frac{\Gamma_l + \Gamma_h}{2}.$$

The average decay widths are measured to be [14]

$$\bar{\Gamma}(B_d) = (4.09 \pm 0.22) \times 10^{-4} \text{ eV}, \quad \bar{\Gamma}(B_s) = (4.27 \pm 0.41) \times 10^{-4} \text{ eV}$$

and $\Delta\Gamma > 0$ is expected as in the kaon system. No experimental measurement on $\Delta\Gamma$ is available and the standard model predicts $\Delta\Gamma/\Delta m$ to be very small as shown later.

CP violation in B^0 - $\bar{B}^0$ oscillations is present if $|\zeta|$ deviates from unity. For the case of $\Delta\Gamma \ll \Delta m$, it can be shown that

$$\zeta \approx \left[1 - \frac{1}{2} \Im m \left(\frac{\Gamma_{12}}{M_{12}} \right)\right] e^{-i(\arg M_{12} + \pi)}.$$

The standard model predicts that CP violation in the oscillations is very small due to $|\Gamma_{12}| \ll |M_{12}|$ and $|\sin(\arg M_{12} - \arg \Gamma_{12})| \ll 1$ (GIM mechanism [15]). Since new physics does not contribute to $|\Gamma_{12}|$, CP violation in the oscillations remains small even if there exist new particles which contribute to M_{12} increasing the value of $\sin(\arg M_{12} - \arg \Gamma_{12})$. Thus, we **neglect CP violation in the oscillation** and assume

$$\zeta \approx e^{-i(\arg M_{12} + \pi)}. \quad (2)$$

For the initially pure B , time dependent decay rates into a final state “f” and into its CP conjugated state “ $\bar{f}$ ” are denoted by $R_f(t)$ and $R_{\bar{f}}(t)$ respectively. Similarly, we introduce $\bar{R}_f$ and $\bar{R}_{\bar{f}}$ for the initially pure $\bar{B}$ state. Note that R_f ($R_{\bar{f}}$) and $\bar{R}_{\bar{f}}$ ($\bar{R}_f$) are CP conjugate to each other. Therefore, any difference between the two is a proof of CP violation.

Using equations (1), four time dependent decay rates are derived to be

$$\begin{aligned} R_f(t) &\propto e^{-\bar{\Gamma}t} \left(\cosh \frac{\Delta\Gamma t}{2} - \Re e \Lambda \sinh \frac{\Delta\Gamma t}{2} + L \cos \Delta m t - \Im m \Lambda \sin \Delta m t \right) \\ R_{\bar{f}}(t) &\propto e^{-\bar{\Gamma}t} \left(\cosh \frac{\Delta\Gamma t}{2} - \Re e \bar{\Lambda} \sinh \frac{\Delta\Gamma t}{2} + \bar{L} \cos \Delta m t - \Im m \bar{\Lambda} \sin \Delta m t \right) \\ \bar{R}_f(t) &\propto e^{-\bar{\Gamma}t} \left(\cosh \frac{\Delta\Gamma t}{2} - \Re e \Lambda \sinh \frac{\Delta\Gamma t}{2} - L \cos \Delta m t + \Im m \Lambda \sin \Delta m t \right) \\ \bar{R}_{\bar{f}}(t) &\propto e^{-\bar{\Gamma}t} \left(\cosh \frac{\Delta\Gamma t}{2} - \Re e \bar{\Lambda} \sinh \frac{\Delta\Gamma t}{2} - \bar{L} \cos \Delta m t + \Im m \bar{\Lambda} \sin \Delta m t \right) \end{aligned} \quad (3)$$

where

$$L = \frac{1 - |\lambda|^2}{1 + |\lambda|^2}, \quad \bar{L} = \frac{1 - |\bar{\lambda}|^2}{1 + |\bar{\lambda}|^2},$$

and

$$A = \frac{2\lambda}{1 + |\lambda|^2}, \quad \bar{A} = \frac{2\bar{\lambda}}{1 + |\bar{\lambda}|^2}$$

with

$$\lambda = \zeta \frac{\bar{A}_f}{A_f}, \quad \bar{\lambda} = \zeta \frac{\bar{A}_{\bar{f}}}{A_{\bar{f}}}. \quad (4)$$

The decay amplitudes, A_f and $A_{\bar{f}}$ correspond to $B \rightarrow f$ and $\rightarrow \bar{f}$ and similarly $\bar{A}_f$ and $\bar{A}_{\bar{f}}$ to $\bar{B} \rightarrow f$ and $\rightarrow \bar{f}$. The absence of CP violation in the oscillation, i.e. $|\zeta| = 1$, is assumed in the derivation. For the B_d system, we can introduce the approximations $\cosh \Delta\Gamma t/2 = 1$ and $\sinh \Delta\Gamma t/2 = 0$.

The four decay rates are reduced to two when the decay final state is a CP eigenstate f^{CP} :

$$\begin{aligned} R(t) &\propto e^{-\bar{\Gamma}t} \left(\cosh \frac{\Delta\Gamma t}{2} - \Re A^{\text{CP}} \sinh \frac{\Delta\Gamma t}{2} + L^{\text{CP}} \cos \Delta m t - \Im A^{\text{CP}} \sin \Delta m t \right) \\ \bar{R}(t) &\propto e^{-\bar{\Gamma}t} \left(\cosh \frac{\Delta\Gamma t}{2} - \Re A^{\text{CP}} \sinh \frac{\Delta\Gamma t}{2} - L^{\text{CP}} \cos \Delta m t + \Im A^{\text{CP}} \sin \Delta m t \right) \end{aligned}$$

where

$$L^{\text{CP}} = \frac{1 - |\lambda^{\text{CP}}|^2}{1 + |\lambda^{\text{CP}}|^2}, \quad \text{and} \quad A^{\text{CP}} = \frac{2\lambda^{\text{CP}}}{1 + |\lambda^{\text{CP}}|^2}. \quad (5)$$

The complex parameter, λ^{CP} , is defined as

$$\lambda^{\text{CP}} = \zeta \frac{\bar{A}_{f^{\text{CP}}}}{A_{f^{\text{CP}}}} \quad (6)$$

where $A_{f^{\text{CP}}}$ and $\bar{A}_{f^{\text{CP}}}$ are the B and $\bar{B} \rightarrow f^{\text{CP}}$ decay amplitudes.

3 Unitarity triangles and phases of CKM elements

Using the Wolfenstein parameterization [16], the CKM matrix given by

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

can be approximated as

$$V \approx \begin{pmatrix} 1 - \frac{\lambda_c^2}{2} & \lambda_c & A\lambda_c^3(\rho - i\eta) \\ -\lambda_c & 1 - \frac{\lambda_c^2}{2} & A\lambda_c^2 \\ A\lambda_c^3 \left[1 - (\rho + i\eta) \left(1 - \frac{\lambda_c^2}{2} \right) \right] & -A\lambda_c^2 \left[\left(1 - \frac{\lambda_c^2}{2} \right) + \lambda_c^2(\rho + i\eta) \right] & 1 \end{pmatrix} \quad (7)$$

Figure 1: Unitarity triangles originally suggested by J. D. Bjorken.

with $\lambda_c = \sin \theta_C \approx 0.22$ where θ_C is the well measured Cabibbo angle [6]. Higher orders in λ_c are ignored. Two unitarity relations

$$\begin{aligned} V_{td}V_{tb}^* + V_{cd}V_{cb}^* + V_{ud}V_{ub}^* &= 0 \\ V_{td}V_{ud}^* + V_{ts}V_{us}^* + V_{tb}V_{ub}^* &= 0 \end{aligned}$$

can be expressed as

$$\begin{aligned} \frac{1}{A\lambda_c^3}V_{td} - 1 + \frac{1 - \lambda_c^2/2}{A\lambda_c^3}V_{ub}^* &= 0 \\ \frac{1 - \lambda_c^2/2}{A\lambda_c^3}V_{td} - \frac{1}{A\lambda_c^2}V_{ts} + \frac{1}{A\lambda_c^3}V_{ub}^* &= 0 \end{aligned}$$

Figure 1 illustrates the two equations in the complex plane. In conclusion, with the parameterization given in equation (7) we have the following situation:

$$\arg V_{ub} = -\gamma, \quad \arg V_{td} = -\beta, \quad \arg V_{ts} = \pi + \gamma - \gamma' \equiv \delta\gamma + \pi$$

and all the rest of the CKM matrix elements are real. The angles α , β , γ and γ' are defined in figure 1.

Measurements of $|V_{cb}|$ give A and together with $|V_{ub}|$ and $|V_{td}|$ the three angles α , β and γ are completely determined. The elements V_{cb} and V_{ub} are measured by studying B meson decays and $|V_{td}|$ by B^0 - $\bar{B}^0$ oscillations [7].

4 Standard Model Predictions

In the standard model, M_{12} is given by the box diagram shown in figure 2-a and derived as [17]

$$\begin{aligned} M_{12}(B_D) &= -\frac{G_F^2 m_W^2 B_{B_D} f_{B_D}^2 m_{B_D}}{12\pi^2} \\ &\times \left[\sum_{i=t,c,u} (V_{ib}V_{iD}^*)^2 E(x_i) + \sum_{\substack{i \neq j \\ i,j=t,c,u}} (V_{ib}V_{iD}^*)(V_{jb}V_{jD}^*) E(x_i, x_j) \right] \end{aligned}$$

Figure 2: a) Box diagram for the $\bar{B} \rightarrow B$ transition amplitude. b) Tree diagram for $b \rightarrow c + W^-$ which is not colour suppressed.

where m_{B_D} and f_{B_D} are the mass and decay constants of the B_d ($D=d$) or B_s mesons ($D=s$) respectively. The B parameter, B_{B_D} , corrects for the vacuum insertion approximation and $E(x_i)$ and $E(x_i, x_j)$ are functions of the parameters $x_i = (m_i/m_W)^2$ where $m_{i(W)}$ is the i -quark (W -boson) mass. Due to the large top quark mass, $E(x_t)$ dominates. The CKM elements give $|V_{tb}V_{td}^*| \approx |V_{cb}V_{cd}^*| \approx |V_{ub}V_{ud}^*| \approx \lambda_c^3$ for B_d , and $|V_{tb}V_{ts}^*| \approx |V_{cb}V_{cs}^*| \approx \lambda_c^2$ and $|V_{ub}V_{us}^*| \approx \lambda_c^4$ for B_s . In conclusion, only the top quark must be considered in the box diagram and the phase of M_{12} is given by

$$\arg M_{12} = \pi + \begin{cases} 2 \arg V_{tb}V_{td}^* & = 2\beta + \pi & : B_d \\ 2 \arg V_{tb}V_{ts}^* & = -2\delta\gamma + \pi & : B_s \end{cases}$$

Using equation (2), it follows that

$$\arg \zeta = \begin{cases} -2\beta & : B_d \\ 2\delta\gamma & : B_s \end{cases}$$

Since the b -quark mass is relatively large, Γ_{12} can be estimated from the absorptive part of the box diagram arising from the c - and u -quarks. For both B_d and B_s , it follows that

$$\frac{\Delta\Gamma}{\Delta m} = \left| \frac{\Gamma_{12}}{M_{12}} \right| \approx \frac{3\pi m_b^2}{2m_W^2 E(x_t)}$$

For $m_b = 5$ GeV, $m_W = 80$ GeV and $m_t = 200$ GeV, we obtain

$$\frac{\Delta\Gamma}{\Delta m} \approx 6 \times 10^{-3} \quad \text{for } B_d \text{ and } B_s. \quad (8)$$

Using the measured values of $\Delta m(B_d)$ and $\bar{\Gamma}(B_d)$, it follows that

$$\frac{\Delta\Gamma}{\bar{\Gamma}} \approx 5 \times 10^{-3} \quad \text{for } B_d$$

and $\Delta\Gamma$ can be neglected in the decay time distribution for the B_d system.

Figure 3: Penguin decay diagram contributing to $B_d \rightarrow J/\psi K_S$, $B_d \rightarrow \pi^+ \pi^-$, $B_s \rightarrow J/\psi \phi$ or $B_s \rightarrow \rho K_S$ decays.

From the box diagram, $\Delta m(B_s)$ is calculated to be

$$\Delta m(B_s) = \frac{B_{B_s} f_{B_s}^2 m_{B_s}}{B_{B_d} f_{B_d}^2 m_{B_d}} \left| \frac{V_{ts}}{V_{td}} \right|^2 \Delta m(B_d) \approx 22 \times \Delta m(B_d).$$

Using equation (8) and the measured B_s lifetime [14], it follows that

$$\frac{\Delta \Gamma}{\Gamma} \approx 0.1 \quad \text{for } B_s.$$

The effect of $\Delta \Gamma$ is still not large, but can no longer be neglected.

Using the standard model, the phase difference between M_{12} and Γ_{12} is given by

$$\arg M_{12} - \arg \Gamma_{12} = \pi + \frac{8}{3} \left(\frac{m_c}{m_b} \right)^2 \eta \times \begin{cases} \frac{1}{(1-\rho)^2 + \eta^2} & : B_d \\ \lambda_c^2 & : B_s \end{cases}$$

Combining these results with equation (8), we conclude that CP violation in the B - $\bar{B}$ oscillation should be smaller than 10^{-3} in the standard model.

Phases of the quark decay amplitudes generated by the tree diagrams are trivially given. For $b \rightarrow c + W^-$ and $b \rightarrow u + W^-$ followed by $W^- \rightarrow i + \bar{j}$ where $i = s, d$ and $\bar{j} = \bar{c}, \bar{u}$ (figure 2-b), we have

$$\arg A_{b \rightarrow c} = \arg V_{cb} = 0 \quad \text{and} \quad \arg A_{b \rightarrow u} = \arg V_{ub} = -\gamma. \quad (9)$$

For the $\bar{b}$ quark, we have

$$\arg A_{\bar{b} \rightarrow \bar{c}} = 0 \quad \text{and} \quad \arg A_{\bar{b} \rightarrow \bar{u}} = \gamma.$$

Penguin diagrams [18] shown in figure 3 also contribute to some of the decay modes. Decay amplitudes can be written as

$$\begin{aligned} A_{b \rightarrow d+g} &\propto V_{tb} V_{td}^* F(x_t) + V_{cb} V_{cd}^* F(x_c) + V_{ub} V_{ud}^* F(x_u) & : d - \text{penguin} \\ A_{b \rightarrow s+g} &\propto V_{tb} V_{ts}^* F(x_t) + V_{cb} V_{cs}^* F(x_c) + V_{ub} V_{us}^* F(x_u) & : s - \text{penguin} \end{aligned} \quad (10)$$

where $F(x_i)$ is a known function of the i -quark mass and g stands for the gluon. It has been shown that $F(x_c) = F(x_u) \equiv F$ to a good approximation [19]. Using the unitarity relations, equations (10) can be simplified to

$$A_{b \rightarrow d+g} \propto V_{tb} V_{td}^* [F(x_t) - F] \quad \text{and} \quad A_{b \rightarrow s+g} \propto V_{tb} V_{ts}^* [F(x_t) - F].$$

Finally, the phases of the penguin decay amplitudes for the b -quark are given by

$$\arg A_{b \rightarrow d+g} = -\arg V_{td} = \beta \quad \text{and} \quad \arg A_{b \rightarrow s+g} = 0 \quad (11)$$

and similar for the $\bar{b}$ -quark,

$$\arg A_{\bar{b} \rightarrow \bar{d}+g} = -\beta \quad \text{and} \quad \arg A_{\bar{b} \rightarrow \bar{s}+g} = 0$$

5 Measurement of angle α

Two-pion final states such as $\pi^+\pi^-$ and $\pi^0\pi^0$ are CP eigenstates. The decay $\bar{B}^0 \rightarrow \pi^+\pi^-$ can be generated by the $b \rightarrow u + W^-$ tree and the $b \rightarrow d + g$ penguin diagrams. The weak interaction phases for the two processes are given by equations (9) and (11) and the decay amplitude can be expressed as [20]

$$\bar{A}_{\pi^+\pi^-} = e^{-i\gamma} e^{i\delta_T} T \left[1 + \frac{P}{T} e^{i(\gamma+\beta)} e^{i(\delta_P-\delta_T)} \right]$$

where T and P are the kinematical factors for the $\bar{B}^0 \rightarrow \pi^+\pi^-$ tree and penguin decay amplitudes and δ_T and δ_P are their strong interaction phases respectively. The decay amplitude for B^0 is given by

$$A_{\pi^+\pi^-} = e^{i\gamma} e^{i\delta_T} T \left[1 + \frac{P}{T} e^{-i(\gamma+\beta)} e^{i(\delta_P-\delta_T)} \right].$$

If we can neglect higher orders in P/T , the parameters $L_{\pi^+\pi^-}$ and $\Lambda_{\pi^+\pi^-}$ defined by equations (5) are approximated as

$$\begin{aligned} L_{\pi^+\pi^-} &= 2 \frac{P}{T} \sin(\delta_P - \delta_T) \sin \alpha \\ \Lambda_{\pi^+\pi^-} &= \left[1 + 2i \frac{P}{T} \cos(\delta_P - \delta_T) \sin \alpha \right] e^{2i\alpha} \end{aligned}$$

and the time dependent decay rates for the initially pure B^0 and $\bar{B}^0$ are given by

$$\begin{aligned} R_{\pi^+\pi^-}(t) &\propto e^{-\bar{\Gamma}t} (1 + L_{\pi^+\pi^-} \cos \Delta m t - \Im m \Lambda_{\pi^+\pi^-} \sin \Delta m t) \\ \bar{R}_{\pi^+\pi^-}(t) &\propto e^{-\bar{\Gamma}t} (1 - L_{\pi^+\pi^-} \cos \Delta m t + \Im m \Lambda_{\pi^+\pi^-} \sin \Delta m t). \end{aligned}$$

In the absence of the penguin diagram ($P = 0$), we obtain

$$L_{\pi^+\pi^-} = 0, \quad \Im m \Lambda_{\pi^+\pi^-} = \sin 2\alpha \quad (\text{no penguin})$$

Figure 4: Tree diagrams for $\bar{B}^0 \rightarrow \pi^+\pi^-$, $\pi^0\pi^0$ and $B^- \rightarrow \pi^-\pi^0$; 1) not suppressed by colour and 2) suppressed by colour. The relevant penguin diagram is also shown.

i.e. no CP violation in the decay amplitude, and $\Im m\mathcal{A}_{\pi^+\pi^-}$ measures the angle 2α . If the strong phases are identical for the tree and penguin diagrams, $L_{\pi^+\pi^-}$ still remains 0, i.e. no CP violation in the decay amplitude even with a presence of the penguin contribution. The value of $\Im m\mathcal{A}_{\pi^+\pi^-}$ is no longer identical to $\sin 2\alpha$. Once the ratio P/T is known, $\sin \alpha$ can be extracted from the experimentally available parameters $L_{\pi^+\pi^-}$ and $\Im m\mathcal{A}_{\pi^+\pi^-}$.

No further experimental input can be obtained on the penguin amplitude from the $\pi^+\pi^-$ alone. Let us now extend our analysis including $\pi^0\pi^0$ and $\pi^\pm\pi^0$ final states [21]. Figure 4 shows the quark diagrams contributing dominantly to $B_d \rightarrow \pi^+\pi^-$, $\pi^0\pi^0$ and $B^\pm \rightarrow \pi^\pm\pi^0$ decays. Compared to the first tree diagram 1), the second tree diagram 2) is colour suppressed. We denote the moduli of the first and the second tree decay amplitudes by T_a and T_s . Due to this colour suppression, the branching ratio for $B_d \rightarrow \pi^0\pi^0$ is expected to be ~ 10 times smaller than that for $B_d \rightarrow \pi^+\pi^-$ making experimental observation difficult.

The penguin diagrams contribute to both $B_d \rightarrow \pi^+\pi^-$ and $\pi^0\pi^0$ decays but do not contribute to $B^\pm \rightarrow \pi^\pm\pi^0$ due to the isospin symmetry. We can now derive the $\bar{B}^0$ and B^- decay amplitudes to be

$$\begin{aligned}\bar{A}_{+-} &= e^{-i\gamma} e^{\delta_a} T_a \left[1 + \frac{P}{T_a} e^{i(\gamma+\beta)} e^{i(\delta_P-\delta_a)} \right] \\ \bar{A}_{00} &= e^{-i\gamma} e^{\delta_s} \frac{T_s}{\sqrt{2}} \left[-1 + \frac{P}{T_s} e^{i(\gamma+\beta)} e^{i(\delta_P-\delta_s)} \right] \\ \bar{A}_{-0} &= e^{-i\gamma} e^{\delta_a} \frac{T_a}{\sqrt{2}} \left[1 + \frac{T_s}{T_a} e^{i(\delta_s-\delta_a)} \right]\end{aligned}$$

Note the following relation:

$$\bar{A}_{-0} = \frac{1}{\sqrt{2}} \bar{A}_{+-} - \bar{A}_{00}.$$

Similarly for the B^0 and B^+ decays, we obtain

$$A_{+-} = e^{i\gamma} e^{\delta_a} T_a \left[1 + \frac{P}{T_a} e^{-i(\gamma+\beta)} e^{i(\delta_P-\delta_a)} \right]$$

$$\begin{aligned}
A_{00} &= e^{i\gamma} e^{\delta_s} \frac{T_s}{\sqrt{2}} \left[-1 + \frac{P}{T_s} e^{-i(\gamma+\beta)} e^{i(\delta_P-\delta_s)} \right] \\
A_{+0} &= e^{i\gamma} e^{\delta_a} \frac{T_a}{\sqrt{2}} \left[1 + \frac{T_s}{T_a} e^{i(\delta_s-\delta_a)} \right]
\end{aligned}$$

and

$$A_{+0} = \frac{1}{\sqrt{2}} A_{+-} - A_{00}.$$

With $\pi^+\pi^-$ alone, we had three unknown parameters, i.e. γ , P/T and $\delta_P - \delta_T$ and two measurable quantities, i.e. $L_{\pi^+\pi^-}$ and $\Im m A_{\pi^+\pi^-}$. Therefore, one parameter P/T had to be given from outside in order to obtain γ and $\delta_P - \delta_T$. By including $\pi^0\pi^0$ and $\pi^\pm\pi^0$, two new unknowns, T_s and δ_s , are introduced. If the time dependent decay rates for the initially pure B^0 and $\bar{B}^0$ can be measured, two new quantities, $L_{\pi^0\pi^0}$ and $\Im m A_{\pi^0\pi^0}$, become available. The decays of $B^\pm \rightarrow \pi^\pm\pi^0$ provide the third information related to T_s/T_a and δ_s . Since there are five measurable parameters, five unknowns can be determined. Therefore, γ can now be obtained without external information.

A similar study can be done by constructing the decay amplitudes using the isospin eigenstates [22]. As in the kaon system, the two-pion final states are in $I = 0$ or $I = 2$ states where I is the total isospin. The $\bar{B}^0$ and B^- decay amplitudes can be written as

$$\begin{aligned}
\bar{A}_{+-} &= \sqrt{\frac{2}{3}} \bar{A}_0 e^{i\delta_{I=0}} + \sqrt{\frac{1}{3}} \bar{A}_2 e^{i\delta_{I=2}} \\
\bar{A}_{00} &= \sqrt{\frac{1}{3}} \bar{A}_0 e^{i\delta_{I=0}} - \sqrt{\frac{2}{3}} \bar{A}_2 e^{i\delta_{I=2}} \\
\bar{A}_{-0} &= \bar{A}_2^- e^{i\delta_{I=2}}
\end{aligned}$$

where $\bar{A}_i$'s are the amplitudes for the decays into $I = i$ two-pion final states and δ_i 's are corresponding final state interaction phases. The isospin decay amplitudes can be expressed by the $\Delta I = 1/2$ and $3/2$ transition amplitudes. The transition amplitude for $\Delta I = 5/2$ is absent in the lowest order standard weak interaction Hamiltonian. It follows that [23]

$$\bar{A}_0 = \frac{1}{\sqrt{2}} \bar{a}_{1/2}, \quad \bar{A}_2 = \frac{1}{\sqrt{2}} \bar{a}_{3/2}, \quad \bar{A}_2^- = \sqrt{\frac{3}{4}} \bar{a}_{3/2}$$

and

$$\begin{aligned}
\bar{A}_{+-} &= \sqrt{\frac{1}{3}} \bar{a}_{1/2} e^{i\delta_{I=0}} + \sqrt{\frac{1}{6}} \bar{a}_{3/2} e^{i\delta_{I=2}} \\
\bar{A}_{00} &= \sqrt{\frac{1}{6}} \bar{a}_{1/2} e^{i\delta_{I=0}} - \sqrt{\frac{1}{3}} \bar{a}_{3/2} e^{i\delta_{I=2}} \\
\bar{A}_{-0} &= \sqrt{\frac{3}{4}} \bar{a}_{3/2} e^{i\delta_{I=2}}.
\end{aligned}$$

By noting that the $\Delta I = 3/2$ transition can occur only through the tree diagram, the weak phase of the $\bar{a}_{3/2}$ is given by $-\gamma$. The phase of $\bar{a}_{1/2}$ is complicated to determine since

both the tree and penguin contribute. In summary, the following relations are obtained for the $\bar{B}^0$, B^0 and $B^\pm$ decay amplitudes:

$$\begin{aligned}\bar{A}_{+-} &= \sqrt{\frac{1}{3}}\bar{a}_{1/2}e^{i\delta_{I=0}} + \sqrt{\frac{1}{6}}\hat{a}_{3/2}e^{-i\gamma}e^{i\delta_{I=2}} \\ \bar{A}_{00} &= \sqrt{\frac{1}{6}}\bar{a}_{1/2}e^{i\delta_{I=0}} - \sqrt{\frac{1}{3}}\hat{a}_{3/2}e^{-i\gamma}e^{i\delta_{I=2}} \\ \bar{A}_{-0} &= \sqrt{\frac{3}{4}}\hat{a}_{3/2}e^{-i\gamma}e^{i\delta_{I=2}}.\end{aligned}$$

and

$$\begin{aligned}A_{+-} &= \sqrt{\frac{1}{3}}a_{1/2}e^{i\delta_{I=0}} + \sqrt{\frac{1}{6}}\hat{a}_{3/2}e^{i\gamma}e^{i\delta_{I=2}} \\ A_{00} &= \sqrt{\frac{1}{6}}a_{1/2}e^{i\delta_{I=0}} - \sqrt{\frac{1}{3}}\hat{a}_{3/2}e^{i\gamma}e^{i\delta_{I=2}} \\ A_{-0} &= \sqrt{\frac{3}{4}}\hat{a}_{3/2}e^{i\gamma}e^{i\delta_{I=2}}\end{aligned}$$

with $|a_{3/2}| = |\bar{a}_{3/2}| \equiv \hat{a}_{3/2}$. It follows that

$$\begin{aligned}\bar{A}_{-0} &= \frac{1}{\sqrt{2}}\bar{A}_{+-} - \bar{A}_{00} \\ A_{+0} &= \frac{1}{\sqrt{2}}A_{+-} - A_{00}.\end{aligned}$$

The decay time distributions for the initially pure B^0 and $\bar{B}^0$ into the $\pi^+\pi^-$ and $\pi^0\pi^0$ final states and the decay width for $B^+ \rightarrow \pi^+\pi^0$ or $B^- \rightarrow \pi^-\pi^0$ are sufficient to obtain all unknowns and determine γ .

Recent works show that by assuming SU(3) symmetry (u, d and s quark) [24], the $\pi\pi$ decay amplitudes can be related to the $K\pi$ decay amplitudes. In this way, the experimentally difficult analysis of $\pi^0\pi^0$ decays can be avoided.

6 Measurement of angle β

The final state $J/\psi K_S$ is by far the best to measure β [10]. The J/ψ signal can be easily reconstructed from lepton pairs giving the B decay vertex. Since J/ψ and K_S signals are narrow, little combinatorial background will be present in the reconstructed B mesons.

The decay amplitude for $\bar{B}^0 \rightarrow J/\psi K_S$ is given by the $b \rightarrow c + W^-$ tree diagram and $b \rightarrow s + g$ penguin diagram. As shown in equations (9) and (11), the weak phases from the two diagrams are identical and equal to 0. The parameter λ defined by equation (6) is now given by

$$\lambda_{J/\psi K_S} = -e^{-2i\beta}$$

where we use that the CP eigenvalue of $J/\psi K_S$ is -1 .

The time dependent decay rates for the initially pure B^0 and $\bar{B}^0$ are given by

$$\begin{aligned} R_{J/\psi K_S}(t) &\propto e^{-\bar{\Gamma}t} \left(1 - \Im m \Lambda_{J/\psi K_S} \sin \Delta m t\right) \\ \bar{R}_{J/\psi K_S}(t) &\propto e^{-\bar{\Gamma}t} \left(1 + \Im m \Lambda_{J/\psi K_S} \sin \Delta m t\right) \end{aligned}$$

with

$$\Lambda_{J/\psi K_S} = -e^{-2i\beta}.$$

This shows that the angle 2β can be extracted from B^0 and $\bar{B}^0 \rightarrow J/\psi K_S$ with little theoretical uncertainty.

The tree diagram contribution to the decay $B_d \rightarrow D^+ D^-$ has also no CKM phase and can be used to measure $\sin 2\beta$. However the penguin diagram contributing to this decay mode, $b \rightarrow d + g$ has a CKM phase, β as shown in equations (11). Therefore, the extraction of $\sin 2\beta$ from this decay mode is not as clean as from $J/\psi K_S$.

7 Measurements of angle γ

7.1 ρK_S

Similar to the $B_d \rightarrow \pi^+ \pi^-$ decay, the decay amplitudes for B_s^0 and $\bar{B}_s^0 \rightarrow \rho K_S$ are given by

$$\begin{aligned} A_{\rho K_S} &= e^{i\gamma} e^{i\delta_{T'}} T' \left[1 + \frac{P'}{T'} e^{-i(\gamma+\beta)} e^{i(\delta_{P'} - \delta_{T'})} \right] \\ \bar{A}_{\rho K_S} &= e^{-i\gamma} e^{i\delta_{T'}} T' \left[1 + \frac{P'}{T'} e^{i(\gamma+\beta)} e^{i(\delta_{P'} - \delta_{T'})} \right] \end{aligned}$$

and the time dependent decay rates for the initially pure B_s^0 and $\bar{B}_s^0$ into ρK_S by

$$\begin{aligned} R_{\rho K_S}(t) &\propto e^{-\bar{\Gamma}t} \left(\cosh \frac{\Delta\Gamma t}{2} - \Re e \Lambda_{\rho K_S} \sinh \frac{\Delta\Gamma t}{2} + L_{\rho K_S} \cos \Delta m t - \Im m \Lambda_{\rho K_S} \sin \Delta m t \right) \\ \bar{R}_{\rho K_S}(t) &\propto e^{-\bar{\Gamma}t} \left(\cosh \frac{\Delta\Gamma t}{2} - \Re e \Lambda_{\rho K_S} \sinh \frac{\Delta\Gamma t}{2} - L_{\rho K_S} \cos \Delta m t + \Im m \Lambda_{\rho K_S} \sin \Delta m t \right) \end{aligned}$$

where

$$\begin{aligned} L_{\rho K_S} &= 2 \frac{P'}{T'} \sin \alpha \sin(\delta_{P'} - \delta_{T'}) \\ \Lambda_{\rho K_S} &= \left[1 + 2i \frac{P'}{T'} \cos(\delta_{P'} - \delta_{T'}) \sin \alpha \right] e^{-2i\gamma'}. \end{aligned}$$

T' and P' are the kinematical factors for the tree and penguin decay amplitudes. Recall that $\Delta\Gamma$ cannot be ignored in the B_s meson system. In the absence of the penguin diagram, i.e. $P' = 0$, we have

$$L_{\rho K_S} = 0 \quad \text{and} \quad \Lambda_{\rho K_S} = e^{-2i\gamma'} \quad \text{no penguin.}$$

Figure 5: The tree diagrams for $B_s^0 \rightarrow D_s^- K^+$ and $\bar{B}_s^0 \rightarrow D_s^- K^+$.

The ρK_S final state is very difficult to reconstruct. The ρ is a wide resonance and K_S decays away from the ρ decay vertex. To make an isospin analysis is also difficult. So this may not be a good channel to measure γ .

7.2 $D_s K$

The uncertainty caused by the penguin diagram can be avoided in the B_s meson decays into $D_s K$ [25]. Both B_s^0 and $\bar{B}_s^0$ can decay into $D_s^- K^+$ with different tree diagrams shown in figure 5. These decay amplitudes are given by

$$\begin{aligned} A_{D_s^- K^+} &= e^{i\delta_1} T_1 \\ \bar{A}_{D_s^- K^+} &= e^{-i\gamma} e^{i\delta_2} T_2 \end{aligned}$$

where T_1 and T_2 represent the kinematics of the two different tree diagrams respectively and δ_1 and δ_2 are the strong interaction phases for the corresponding tree diagrams. The parameter λ defined in equation (4) is given by

$$\begin{aligned} \lambda &= \zeta_{B_s} \frac{\bar{A}_{D_s^- K^+}}{A_{D_s^- K^+}} \\ &= e^{i(-\gamma+2\delta\gamma+\Delta\delta)} \frac{T_2}{T_1} \end{aligned} \quad (12)$$

where $\Delta\delta = \delta_2 - \delta_1$.

For the final state $D_s^+ K^-$, we obtain

$$\begin{aligned} A_{D_s^+ K^-} &= e^{i\gamma} e^{i\delta_2} T_2 \\ \bar{A}_{D_s^+ K^-} &= e^{i\delta_1} T_1 \end{aligned}$$

and

$$\begin{aligned} \bar{\lambda} &= \zeta_{B_s} \frac{\bar{A}_{D_s^+ K^-}}{A_{D_s^+ K^-}} \\ &= e^{i(-\gamma+2\delta\gamma-\Delta\delta)} \frac{T_1}{T_2}. \end{aligned} \quad (13)$$

Note that $|\lambda| = 1/|\bar{\lambda}|$.

Experimentally, four time dependent decay rates of initially pure B_s^0 and $\bar{B}_s^0$ into $D_s^- K^+$ and $D_s^+ K^-$ (equations (3) with $f = D_s^- K^+$ and $\bar{f} = D_s^+ K^-$) can be measured. By fitting the four decay rates, we can extract

$$|\lambda| = \frac{1}{|\bar{\lambda}|} = \frac{T_2}{T_1}$$

and the phases of λ and $\bar{\lambda}$,

$$\begin{aligned} \arg \lambda &= -\gamma + 2\delta\gamma + \Delta\delta \\ \arg \bar{\lambda} &= -\gamma + 2\delta\gamma - \Delta\delta. \end{aligned}$$

The non-negligible value of $\Delta\Gamma$ of the B_s meson system plays an important role in the phase determination. Without the terms proportional to $\sinh(\Delta\Gamma t/2)$ in equation (3), the phases of λ 's are given only by the imaginary parts introducing twofold ambiguities. The presence of $\sinh(\Delta\Gamma t/2)$ add the real parts and the phases of λ and $\bar{\lambda}$ are obtained unambiguously. Once the two phases are determined, γ and $\Delta\delta$ are given by

$$\gamma \approx -\frac{\arg \lambda + \arg \bar{\lambda}}{2}$$

where we ignore the term proportional to λ_c^2 and

$$\Delta\delta = \frac{\arg \lambda - \arg \bar{\lambda}}{2}.$$

7.3 DK^*

The third method to obtain γ is to measure the six branching fractions [26] of B_d decays

$$\begin{aligned} B^0 &\rightarrow D^0 K^{*0}, & \bar{D}^0 K^{*0}, & D_1 K^{*0} \\ \bar{B}^0 &\rightarrow D^0 \bar{K}^{*0}, & \bar{D}^0 \bar{K}^{*0}, & D_1 \bar{K}^{*0} \end{aligned}$$

where D_1 is one of the CP eigenstates of the neutral D meson system given by

$$D_1 = \frac{D^0 + \bar{D}^0}{\sqrt{2}}.$$

Figure 6 shows the decay diagrams for $\bar{B}^0 \rightarrow D^0 \bar{K}^{*0}$ and $\bar{D}^0 \bar{K}^{*0}$.

Note that the final states are b-flavour specific and identify whether it was B^0 or $\bar{B}^0$ at the time of the decay by K^{*0} or $\bar{K}^{*0}$ respectively. Therefore no flavour tag is needed.

The decay amplitudes for $B^0 \rightarrow \bar{D}^0 K^{*0}$ and $D^0 K^{*0}$ are given by

$$A_{\bar{D}^0 K^{*0}} = e^{i\delta_s} T_s, \quad A_{D^0 K^{*0}} = e^{i\gamma} e^{i\delta'_s} T'_s$$

Figure 6: Decay diagrams for $\bar{B}^0 \rightarrow D^0 \bar{K}^{*0}$ and $\bar{B}^0 \rightarrow \bar{D}^0 \bar{K}^{*0}$.

where T_s and T'_s are the kinematical factors for the two colour suppressed tree decay diagrams shown in figure 6, respectively, and δ_s and δ'_s are the corresponding final state phases. For the decay amplitude of $B^0 \rightarrow D_1 K^{*0}$, we obtain

$$\sqrt{2}A_{D_1 K^{*0}} = A_{\bar{D}^0 K^{*0}} + A_{D^0 K^{*0}}.$$

For $\bar{B}^0$ decays, we obtain

$$\bar{A}_{D^0 \bar{K}^{*0}} = e^{i\delta_s} T_s, \quad \bar{A}_{\bar{D}^0 \bar{K}^{*0}} = e^{-i\gamma} e^{i\delta'_s} T'_s$$

and

$$\sqrt{2}\bar{A}_{D_1 \bar{K}^{*0}} = \bar{A}_{D^0 \bar{K}^{*0}} + \bar{A}_{\bar{D}^0 \bar{K}^{*0}}.$$

Note the following relations:

$$|A_{\bar{D}^0 K^{*0}}| = |\bar{A}_{D^0 \bar{K}^{*0}}| \equiv A, \quad |A_{D^0 K^{*0}}| = |\bar{A}_{\bar{D}^0 \bar{K}^{*0}}| \equiv \bar{A} \quad (14)$$

and

$$\begin{aligned} |A_{D_1 K^{*0}}|^2 &= \frac{A^2 + \bar{A}^2 + 2A\bar{A} \cos(\gamma + \Delta)}{2} \equiv A_+^2 \\ |\bar{A}_{D_1 \bar{K}^{*0}}|^2 &= \frac{A^2 + \bar{A}^2 + 2A\bar{A} \cos(\gamma - \Delta)}{2} \equiv A_-^2 \end{aligned} \quad (15)$$

where $\Delta = \delta'_s - \delta_s$.

Figure 7: Two triangles constructed from the six measured decay rates: $|A_{\bar{D}^0 K^{*0}}| = |\bar{A}_{D^0 \bar{K}^{*0}}| \equiv A$, $|A_{D^0 K^{*0}}| = |\bar{A}_{\bar{D}^0 \bar{K}^{*0}}| \equiv \bar{A}$, $|A_{D_1 K^{*0}}| \equiv A_+$ and $|\bar{A}_{D_1 \bar{K}^{*0}}| \equiv A_-$. Two different configurations, (a) and (b), are possible.

Once the six branching ratios are measured, the four real numbers A , $\bar{A}$, A_+ and A_- defined in equations (14) and (15) can be calculated. Using those four real numbers, two triangles can be constructed in two different configurations (a) and (b) as shown in figure 7 and the angle 2γ can be extracted. We cannot resolve this twofold ambiguity from the data.

8 Measurement of angle $\delta\gamma$

The very small phase difference between V_{cb} and V_{ts} , $\delta\gamma$ can be investigated using $B_s \rightarrow J/\psi \phi$. Similar to the $B_d \rightarrow J/\psi K_S$ decays, both the tree and penguin diagrams contributing to the $B_s \rightarrow J/\psi \phi$ decay have no weak phase. The CP eigenvalue of $J/\psi \phi$ is given by $(-1)^J$ where J is the relative angular momentum between J/ψ and ϕ . The time dependent decay rates for the initially pure B_s^0 and $\bar{B}_s^0$ into $J/\psi \phi$ are given by

$$\begin{aligned} R_{J/\psi \phi}(t) &\propto e^{-\bar{\Gamma}t} \left(\cosh \frac{\Delta\Gamma t}{2} - \Re A_{J/\psi \phi} \sinh \frac{\Delta\Gamma t}{2} - \Im A_{J/\psi \phi} \sin \Delta m t \right) \\ \bar{R}_{J/\psi \phi}(t) &\propto e^{-\bar{\Gamma}t} \left(\cosh \frac{\Delta\Gamma t}{2} - \Re A_{J/\psi \phi} \sinh \frac{\Delta\Gamma t}{2} + \Im A_{J/\psi \phi} \sin \Delta m t \right) \end{aligned}$$

with

$$A_{J/\psi \phi} = (-1)^J e^{2i\delta\gamma}.$$

The CP violating effect is then expected to be small, i.e. $\Im A_{J/\psi \phi} = 2\eta\lambda^2$. Thus the observation of a large CP violating effect is a sign of new physics.

9 Prospects

Compared to the kaon system, the B meson system provides a wider scope for studying CP violation with many different decay modes. Using those decay channels, a systematic study is possible to test whether the pattern of the observed CP violation effects agrees with that predicted by the standard model.

The $J/\psi K_S$ is the most favourable final state. The standard model prediction does not suffer from theoretical uncertainty. Experimentally, the decay has been seen and is easy to reconstruct. The CP violating effect can be detected in both time integrated decay rates and time dependent decay rates by comparing the initially pure B^0 and $\bar{B}^0$. Since the final state is not flavour specific, a flavour tag of the initial B meson is required. The present understanding of the standard model predicts a large CP asymmetry of $> 10\%$ [7]. It is most likely that CP violation will be observed in the $B_d \rightarrow J/\psi K_S$ decays by e^+e^- B meson factories under construction [27], HERA-B [28] and possibly CDF and D0 [29]. However, since this decay mode is theoretically clean, it is worth to measure the CP violation effect with high precision at LHC [30] in order to extract the phase of the CKM matrix.

In the $D_s K$ decay modes, the strong interaction effects are present but can be measured experimentally from the same data and do not affect the extraction of the CKM phase.

The observation of CP violation in this decay mode is experimentally more difficult than in $J/\psi K_S$. Time dependent decay rates for $D_s^+ K^-$ and $D_s^- K^+$ must be measured for both initially pure B_s^0 and $\bar{B}_s^0$. Since the final states are not flavour specific, a tag is needed. The expected branching ratios for $D_s^+ K^-$ and $D_s^- K^+$ are small requiring a large number of B_s mesons. There is little hope for the e^+e^- B meson factories and HERA-B to collect enough B_s mesons. Since B_s mesons oscillate rapidly, a very good decay time resolution is required in order to extract the CP violation parameters from the oscillation signal. Particle identification capability of the detector is important for the reconstruction of the final state. Although enough B_s mesons will be produced at Tevatron and LHC, general purpose detectors are not suitably equipped to make such a study. Therefore, a dedicated experiment at LHC [31] is needed.

The strong interaction effects in the DK^* decay modes can be measured from the same data and do not affect the extraction of the CKM phase. Only the decay time integrated rates are needed. The six decay final states of interest are flavour specific and no tag is needed. Particle identification is important for the reconstruction of the final states and the relative reconstruction efficiencies for the six decay modes have to be known. Since the branching ratios for reconstructing the six decay modes are very small, the measurement will be limited statistically. Although the e^+e^- B meson factories can study those decay modes, the dedicated experiment at LHC may be the only place to get sufficient statistics.

The $B_d \rightarrow \pi^+\pi^-$ decay mode is theoretically the most difficult one because the penguin diagram affects the extraction of the CKM phase. The effect of the penguin diagram can be measured experimentally, but other decay modes with π^0 's are needed. The e^+e^- B meson factories are best suited for such a study and may see the CP violation effect in $B_d \rightarrow \pi^+\pi^-$. Another decay mode such as $K\pi$ will help to improve the theoretical understanding of the penguin diagram. Once the effects of the penguin diagram are understood, a high statistics data sample for the $B_d \rightarrow \pi^+\pi^-$ decays available at LHC becomes useful. For a clean reconstruction of the $\pi^+\pi^-$ states, particle identification capability of the dedicated experiment at LHC is important.

This discussion outlines the long experimental programme of CP violation studies in the B meson system. After the current experimental efforts on the B meson done at CESR, LEP and Tevatron, a first serious attempt to observe CP violation in the B meson system will start at KEK and SLAC with e^+e^- B meson factories and at DESY with the HERA-B experiment. In the long term, LHC will provide an opportunity to study CP violation in the B meson system with very high statistics.

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