Flavour Physics at B-factories

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Abstract. Recent results for heavy flavour physics at the B-factories are presented together with their status and prospects.

1. The B-factories.
The high luminosity B-factories, one at SLAC in US and another at KEK in Japan were built in the last century to establish the final proof of the Kobayashi-Maskawa model of quark flavour [1]. Since they started their operations in 1999, every effort has been made to achieve higher and higher luminosity. By 2003 the luminosity of each factory reached their design goal and both experiments eventually discovered unmistakable signature of the CP violation in B meson decay predicted by the KM model [2]. Their constant challenges for further high luminosity have been continued as displayed in Fig. 1 along with the determination of the KM unitarity triangle dramatically improved.

1.1. PEPII collider/BaBar experiment
PEPII is an asymmetric energy $e^+e^-$ collider (3.1 GeV positron on 9.0 GeV electron) with a head-on collision scheme operated at SLAC. They have accumulated more than 460 fb$^{-1}$ integrated luminosity by the summer of 2007 with the world highest beam current of about 5 ampere in total. Taming this tremendous current, which sometimes broke the various vacuum components in an unpredictable way, is always the major issue for higher luminosity. Thanks to very smooth trickle injection, the effective delivery of luminosity is seven times better than projected in the design report.

They are planning to maximize the delivered luminosity until end of operations at the end of September 2008 with achieving further increase of peak luminosity by a higher beam current with lower emittance, lower $\beta^*$ and shorter bunch length [3].

Fig. 1 Improvements of peak luminosity in the B factories.
1.2. KEKB collider/Belle experiment

KEKB is an asymmetric $e^+e^-$ collider (3.5 GeV positron on 8.0 GeV electron) with a finite angle (22 mrad) collision scheme operated at KEK. They have accumulated more than 700 fb$^{-1}$ integrated luminosity with the world highest peak luminosity of $1.7 \times 10^{34}$ cm$^{-2}$sec$^{-1}$. For further higher luminosity, disruption of the smallest cross section beam due to their finite crossing angle should be reduced significantly. The crab crossing of the beam are studied intensively along with the Belle data taking, where the beam bunches are tilted with respect to their orbit by the special structure RF cavity (Crab cavity) as illustrated in Fig. 2. With the benefit of the crab crossing, higher than $2 \times 10^{34}$ cm$^{-2}$sec$^{-1}$ luminosity is expected to accumulate data of 1 ab$^{-1}$ as a near term plan. The major upgrade of the KEKB will follow with the projected luminosity as high as $10^{36}$cm$^{-2}$sec$^{-1}$ [4].

2. Update of the CP measurements and the K-M matrix

There are no big news in the recent results on the CP measurements. Among those the CP measurement for the decay $B \rightarrow D^+D^-$ may draw some attention. As the final state is accessible for both $B^0$ and $\bar{B}^0$ mesons, the time dependent CP violation may arise as expressed in,

$$ p = \frac{e^{-|\Delta t|/\tau}}{4\tau} \left[ 1 + q \left( S \sin(\Delta m\Delta t) + A \cos(\Delta m\Delta t) \right) \right] $$

where $\Delta t$ is a decay time with respect to the instant the flavour tagged as $B^0$ ($q=-1$) or $\bar{B}^0$ ($q=+1$). Since the dominant contribution to the process is the tree-level $b \rightarrow c\bar{c}d$ transition, $S$ and $A$ are calculated to be $-\sin2\phi_1(-\sin2\beta)$ and zero, respectively, with minor modification for $S$ by less than a few percent and an slight increase in $A$ by about 0.03 due to the penguin contribution [5]. The measurement by the Belle experiment shows some discrepancy from the expectation indicating a finite direct CP violation as $(S,A)=(-1.13\pm0.37\pm0.09, +0.91\pm0.23\pm0.06)$ while the recent BaBar result gives $(-0.54\pm0.34\pm0.06, +0.11\pm0.22\pm0.07)$ (3$\sigma$ distance among them) [6]. More data is necessary to resolve this puzzle.

The angle determination of the KM unitarity triangle has been improved year by year and the precisions now reach at the level of 4% for $\sin2\phi_1$ ($\sin2\beta$), although those for $\phi_2$ ($\alpha$) or $\phi_3$ ($\gamma$) are still marginal as illustrated in Fig. 3 where the triangle is constrained only by the angle measurements [7].

With the constraints on the sides from other measurements like oscillation and decay rate studies of $B$ and $K$ mesons, the KM triangle is now determined precisely in barely consistent manner as shown in Fig. 4 [7]. It, however, should be noted here that there is a slight tension between the angle $\phi_1$ and the
side $|V_{ub}|$ which is determined mainly through the inclusive or exclusive decay mode of $b\rightarrow ul\nu$ transition. The tension seems to come mostly from the results based on the inclusive decay rate calculation which may have some potential systematic error larger than assumed [8].

The $b\rightarrow sqq$ transition through a penguin diagram draw continued attention for these years since it might exhibit some hints of physics beyond the Standard Model through an extra CP violation phase [9]. The update of the measurements of the time dependent CP violating decay rate $p$ given in this summer for the relevant decay mode like $B\rightarrow K^* K \bar{K}_s$, $\pi^0 \pi^0 K_s$ shows a slightly better agreement with the Standard Model calculation (2.1$\sigma$) than before [10]. Enough sensitivity to extract new physics with this transition may be available in the future upgrade of the B-factories.

3. B meson rare decay

One of the most interesting decay mode of B meson yet to be explored is $B\rightarrow D^{(*)}\tau\nu$. The decay can arise from a simple tree diagram as shown in Fig.5. Possible contribution from new particles like a charged Higgs boson postulated in various extension of the Standard Model may affect the decay property as also illustrated in the figure [11].

The first observation of the decay was reported by the Belle collaboration in the last spring, followed by the BaBar collaboration in this conference. What makes the observation very tough is the missing energies carried by multiple neutrinos included in the decay. Either experiments, therefore, optimizes the full reconstruction method where the decay of one B meson is reconstructed exclusively so that the flavor/charge and kinematics of the other B meson to be studied could be determined unambiguously. Even with the huge statistics of the B factories, it is a big challenge for either experiment to get enough sensitivity by maximizing the reconstruction efficiency.

In the Belle analysis, they first require the event with $D^*$ and $e$ or $\pi$ from $\tau$ to have a large missing energy and missing mass because of multiple neutrinos. Signal yield is evaluated in the mass spectrum of the other (tagged) B meson reconstructed semi exclusively as shown Fig .6. In this way they gain the higher effective efficiency in the reconstruction of the other B meson. The fit of the spectrum gives $60^{+13}_{-12}$ events with a significance of $5.2\sigma$ including systematic uncertainties. The calculated branching fraction for $B\rightarrow D^{\ast}\tau\nu$ is $2.02^{+0.40}_{-0.37} \pm 0.37 \%$ which should be compared with the Standard Model expectation around 1.4 % [12].

The BaBar collaboration takes a different approach [13]. They are using more than thousand decay modes for the full reconstruction of the other B mesons to get the utmost efficiency. With those maximized event sample, yield of the decay modes such as $D_{s}\nu\tau$ and $D_{s}^\ast \nu\tau$ together with the backgrounds from $D_l\nu$, $D_{s}^\ast \nu\tau$ and $D_{s}^\ast l\nu$ are fitted separately to the missing mass spectra. The results are tabulated in Table 1 together with the Belle’s

![Fig. 5 Diagram for $D^{(*)}\tau\nu$ decay in SM (top) and possible contribution from charged Higgs boson (bottom)](image)

![Fig. 6 Reconstructed mass of the tagged B meson. The peaking background represented by a red dashed curve comes mainly from $B\rightarrow D^*\nu\tau$](image)
one.

| Br (%) | Belle | BaBar  | SM |
|--------|-------|--------|----|
| $B \to D^+ \tau \nu$ | – | $0.63\pm0.38\pm0.10\pm0.06$ | 0.7 |
| $B \to D^{0} \tau \nu$ | – | $2.35\pm0.49\pm0.22\pm0.18$ | 1.4 |
| $B^0 \to D^- \tau \nu$ | – | $1.03\pm0.35\pm0.14\pm0.10$ | 0.7 |
| $B^0 \to D^{*+} \tau \nu$ | $2.02\pm0.40\pm0.37\pm0.04$ | $1.15\pm0.52\pm0.04\pm0.04$ | 1.4 |

Table 1 Summary of the branching ratios of $B \to D^{(*)} \tau \nu$ decay mode

In contrast to $B_d$ meson, $B_s$ meson is not yet studied in great detail. In the PDG compilation, for example, so few decay modes of $B_s$ meson are listed and, therefore, new measurements are awaited at the B-factories. In 2005 KEKB/Belle accumulated the data of 1.86 fb$^{-1}$ at $\Upsilon(5S)$ resonance as a pilot run followed by more data of 21.7 fb$^{-1}$ taken in 2006 to study the properties of $B_s$ mesons. There are several first results emerging in this summer. Among them the first observation of radiative decay of $B_s \to \phi \gamma$ is reported with a branching fraction of $5.7^{+1.8+1.2}_{-1.5-1.7} \times 10^{-5}$ [14].

4. D-D mixing

As other neutral mesons like K or B, $D^0$ mesons are also expected to mix with its counter partner, $D^\_0$ meson although the mixing strength were considered to be very small because of relatively low mass of b, s or d quarks inserted in the loop diagram of the mixing process. The recent theoretical predictions, however, show the mixing can be significantly large due to some phase space enhancement [15].

The time evolution of a $D^0$ or $D^\_0$ states depends on the mixing parameters $x = (M_1 - M_2)/\Gamma$ and $y = (\Gamma_1 - \Gamma_2)/2\Gamma$, where $M_{1,2}$ and $\Gamma_{1,2}$ are the masses and widths, respectively, of the mass eigenstates. In the Belle measurement, the apparent lifetime of the decays to CP eigenstates, $D^0 \to K^- K^+$ and $D^0 \to \pi^+ \pi^-$, is compared with that of non-CP state transition to evaluate the mixing parameter $y_{CP} = \tau(K\pi)/\tau(KK)-1$, where $\tau(KK)$ and $\tau(K\pi)$ are the lifetimes of $D^0 \to K^- K^+$ (or $\pi^+ \pi^-$) and $D^0 \to K^\_0 K^+$ decays, respectively. They found $y_{CP}$ to be non zero for the first time as shown in Fig. 7

where the best fit gives $y_{CP}$ as $1.31\pm0.32\pm0.25$ % [16].

The BaBar experiment investigates the decay time distribution of the wrong sign (WS) decay of $D^0 \to K^\_0 K^+$ which can proceed either in a doubly Cabbibo suppressed (DCS) diagram or a D-D mixing followed by Cabbibo favored (CF) one. The decay rate of WS with respect to non-mixing exponential decay is expressed as

![Figure 7](image_url)

**Fig. 7** The ratio of decay time distribution for $D^0 \to K^- K^+$ (or $\pi^+ \pi^-$) to $D^0 \to K^\_0 K^+$

![Figure 8](image_url)

**Fig. 8** $R_{WS}$ distribution measured by the BaBar experiment
\[
R_{WS} \equiv \frac{\Gamma_{WS}}{e^{\frac{\phi}{\tau}}} = R_{D} + \sqrt{R_{D} y} \left( \frac{t}{\tau} \right) + \left( \frac{\left( \int_{x}^{y} + y^{2} \right)}{4} \right)^{2}
\]

where \(x'\) and \(y'\) are the transformations of \(x\) and \(y\) with a hadronic phase difference between DCS and CF transition. As seen in Fig. 8, \(R_{WS}\) is not constant but increases in time implying either \(y'\) or \(x'\) could not be zero [17].

The combined fit to all the measurements relevant to D-D mixing so far shows the clear evidence of mixing with more than 5 sigma significance [18].

5. Constraints from \(\tau\) decay on the KM parameters
As pointed out in many places, a B factory is a very good \(\tau\) factory where extremely rich field of lepton flavour physics is to be explored. At the same time hadronic decays of \(\tau\) lepton also provide useful and unique information on hadron dynamics and physics of quark flavours. Among them the importance of the \(V_{us}\) evaluation from the Cabbibo suppressed hadronic decay of \(\tau\) lepton are discussed [19]. Fig. 10 shows some recent results of those studies. Since the uncertainty due to theoretical calculation can be very small, huge data sample from the B-factories will enable the best determination of \(V_{us}\) in near future.

6. Summary
The B-factories have been improving their performance since their start of operation in 1999 to provide as much as 1000 fb\(^{-1}\) of high quality data for heavy flavour physics. After the striking success of the discovery of the CP violation in B-meson to complete the final proof of the Kobayashi-Maskawa model of quark flavours, hundreds of important results on flavour physics have been rushing out.

The upgrade of the B-factories are planned to provide the luminosity 100 times higher than the present one. They are expected to extend the current understanding of the Standard Theory based on the KM model in the manner complementary to the physics explored in LHC and future highest energy colliders.

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