Toward the second stage at B factory

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Abstract

The measurement and precision at B physics experiment are reviewed by taking into account of the numbers of B mesons to be produced in the future experimental projects. With $10^9$ or more B mesons we will be able to fix the parameters in Kobayashi-Maskawa matrix elements or find a signal of new physics.

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1 Measurements at B factories

The gauge interaction in the standard model (SM) has been well understood and analyzed through the experiments so far made. The coming experiments are aimed for the detailed research of Yukawa interaction and Higgs interaction to fully understand SM and explore new physics beyond it. The quark flavor mixing matrix proposed by Kobayashi and Maskawa (KM) \cite{1} is closely related to Yukawa and Higgs sector. Precise determination of the KM matrix elements gives us valuable insight about SM and new physics. The physics of hadrons containing $b$ quark, so called B physics, is indispensable for the determination of KM matrix elements with the third generation quarks. So B physics is taken up as one of the main projects in many of the accelerator experiments to be done in the near future: Two anti-symmetric $e^+ e^−$ colliders dedicated for B physics are now under construction at KEK \cite{2} and SLAC \cite{3}. A dedicated experiment is planned by using the proton beam of the $ep$ collider HERA at DESY \cite{4}. These new experiments will begin physics run in 1999. CLEO group has been working on B physics and reported valuable results by using the symmetric $e^+ e^−$ collider CESR at Cornell \cite{5}. The CESR will be upgraded for more luminosity and do physics run (CESR phase-III). The Tevatron $p\bar{p}$ collider has also been giving information on B physics and will be upgraded with main injector \cite{6}. B physics will be explored also at the high-energy high-luminosity $pp$ collider LHC now under construction at CERN \cite{7}. Above is summarized in Table 1 with the year and possible number of B meson produced.

| year | # of B | facilities |
|------|--------|------------|
| $\leq 2000$ | $10^7$~$8$ | Tevatron, CESR phase-III, HERA-B, KEK-B, SLAC-B |
| $\geq 2010$ | $10^9$ | + LHC-B, Tevatron (Main Injector) |

Table 1 : Experimental facilities of B physics and number of B mesons to be produced.

The B physics experiments can be divided into two stages. We get $10^7$~$8$ B mesons at the first stage within this century, where the main goal is to obtain the first evidence of CP violation in B meson system. It is promising because of the existence of the so called golden mode, $B^0, \bar{B}^0 \to J/\Psi K_S$, which has relatively large branching ratio ($O(10^{-4})$) and can be identified by clean signal; $J/\Psi \to l^+ l^−, K_S \to \pi^+ \pi^−$. A decade after the beginning of the 21st century we will obtain more than $10^9$ of B, and then we will be able to fix the KM matrix elements more precisely which enables us to explore new physics beyond SM. This is the second stage. In this paper we summarize the precision of KM matrix determination when experiments are done well as proposed, and see how new physics search can be made.

To begin with, let us review briefly what are measured in B physics experiments. KM matrix $V$ appears in the interaction among quark charged currents and $W$ boson

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \left[ \bar{u}_{L_i} \gamma^\mu (V)_{ij} d_{L_j} W_\mu^+ + \bar{d}_{L_j} \gamma^\mu (V^*)_{ij} u_{L_i} W_\mu^- \right].$$ (1)
The matrix $V$ is a $3 \times 3$ unitarity matrix in the three generation standard model, so that the following condition holds:

$$V_{ub}^*V_{ud} + V_{cb}^*V_{cd} + V_{tb}^*V_{td} = 0.$$  

We have so-called unitarity triangle by expressing the above condition in complex plane. The parameters in KM matrix can be determined through the measurements of the sides and the angles of this triangle. The KM matrix elements $|V_{ud}|$ and $|V_{cd}|$ have already been measured to 0.1 % and 7 %, respectively [8]. The elements $|V_{cb}|$ and $|V_{ub}|$ can be obtained through the semi-leptonic decays of $B$ meson, $b \to c\ell\bar{\nu}$ and $b \to u\bar{\nu}\ell$. The magnitude of $B^0$-$\bar{B}^0$ mixing gives the side $|V_{tb}^*V_{td}|$ because the top quark contribution dominates in the the box diagram [7]. The length of this side can be calculated by utilizing three generation unitarity also from the ratio $|V_{td}/V_{ts}|$ which can be measured through $\Gamma(b \to d\gamma)/\Gamma(b \to s\gamma)$ or the ratio of $B^0$-$\bar{B}^0$ mixing to $B^0_s$-$\bar{B}^0_s$ mixing. The angles can be obtained through the CP violation measurements: CP violation in the mode $B^0,\bar{B}^0 \to J/\Psi K_S$ gives $\sin 2\phi_1$ [4]. The mode $B^0,\bar{B}^0 \to \pi\pi$ or $\rho\pi$ gives $\sin 2\phi_2$ in the same way [10]. The rest of the angle $\phi_3$ can be measured through the direct CP violation in $B^\pm \to (D^0,\bar{D}^0,D_{CP})K^\pm$ [10]. It can also be obtained in $B^0_s,\bar{B}^0_s \to \rho K_S$ decay when $B^0_s$ mason is available [10].

2 Precision of measurements

Here we summarize the present status of these measurements [12] and the precision reach in the coming experiments. The precision is estimated based on the simulation results given in 1996 BELLE progress reports [13] by assuming everything goes well in experimental side.

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3 There are two notations for the angles of unitarity triangle. The one used here is $\phi_{1,2,3}$ and another ($\alpha$, $\beta$ and $\gamma$) is taken in ref. [8]. I prefer the former notation as $\alpha$, $\beta$ and $\gamma$ are often used to express another quantities.
2.1  $|V_{cb}|$

$|V_{cb}|$ is obtained through semi-leptonic $b \to c$ decay in both inclusive and exclusive modes. Determination of $|V_{cb}|$ by using inclusive mode suffers from relatively large ($\sim 10\%$) theoretical uncertainty; calculation of higher order QCD correction, estimation of non-perturbative effects, values of $b$ quark mass and so on. Heavy quark symmetry allows us less uncertain determination of $|V_{cb}|$ in exclusive mode [14]. The value of form factor at zero-recoil limit can be predicted from the symmetry. With more statistics exclusive mode should become promising for the precise determination of $|V_{cb}|$. Present data from exclusive $B \to D^* l \nu$ decay is as follows [15];

$$|V_{cb}| = (34.3 \pm 2.4 \pm 1.3) \times 10^{-3}, \quad (3)$$

where the first error is experimental and the second due to theoretical uncertainty [16]. We now have about 7% experimental error and 3% theoretical error concerning on QCD correction and finite mass correction. The statistical error can be reduced to 0.3% with $10^8$ B meson due to simulation. Then assuming the systematic error is same order as the statistical error, the experimental error will be reduced to about 1% or less. The experimental error will become negligible in comparison with the theoretical error with more than $10^9$ B in the next century unless there emerges drastic theoretical improvement.

2.2  $|V_{ub}|$

$|V_{ub}|$ is obtained in a similar manner as $|V_{cb}|$ by using $b \to u$ semi-leptonic decay. The high energy lepton at the lepton energy spectrum is used to identify $b \to u$ transition in inclusive mode. CLEO has succeeded in identifying exclusive mode; $B \to \pi l \nu, \rho l \nu$ [17], and got

$$|V_{ub}| = (3.3 \pm 0.2 \pm 0.3 \pm 0.4 \pm 0.7) \times 10^{-3}, \quad (4)$$

where the first and second error is experimental and the third theoretical mainly due to hadron model dependence. Inclusive mode measurement has given similar value ($|V_{ub}| = (3.2 \pm 0.8) \times 10^{-3}$). We have at present experimental and theoretical errors of both about 20%. Here heavy quark symmetry cannot be used to get a value of form factor. So large theoretical ambiguity cannot be avoided with present technique. Experimental error can be reduced to about 10% with statistics of $10^8$ B mesons. Theoretical error will be dominant also here in the future.

2.3  $|V_{tb}V_{td}|$

Ten years has passed since the first discovery of $B^0-\overline{B^0}$ mixing. The accumulated data now gives the mass difference between two mass eigenstates of neutral B mesons as

$$\Delta M_B = 0.460 \pm 0.018 \text{ ps}^{-1}, \quad (5)$$
where the error is experimental only. This 4% error will be reduced to about 1% or less with more than $10^8$ B meson. The mass difference $\Delta M_B$ is related to $|V_{tb}^*V_{td}|$ in SM as follows:

$$\Delta M_B = 2|\langle B^0|H^{eff}|B^0\rangle| \propto |V_{tb}^*V_{td}|^2 B_B f_B^2,$$

where $B_B f_B^2 M_B/3 \equiv \langle B^0|(\bar{d}_L \gamma_{\mu} b_L)|B^0\rangle$. The hadron matrix element $B_B f_B^2$ is from non-perturbative strong interaction which is hard to calculate precisely. Therefore the error in the determination of $|V_{tb}^*V_{td}|$ is dominated by theoretical uncertainty which is now about 20% in lattice QCD calculation.

There are other methods to obtain the length of the side $V_{tb}^*V_{td}$ if we assume KM matrix is $3 \times 3$ unitary as in SM. Given the Wolfenstein parameterization of KM matrix [18],

$$V = \begin{pmatrix}
1 - (\lambda^2/2) & \lambda & A\lambda^3(\rho - i\eta)
\end{pmatrix},
$$

we have

$$|V_{tb}^*V_{td}|/|V_{cb}^*V_{cd}| = \sqrt{(1 - \rho)^2 + \eta^2},$$

$$|V_{td}/V_{ts}| = \lambda \sqrt{(1 - \rho)^2 + \eta^2}.$$

The value of $\lambda = |V_{us}|$ is well known, so that $|V_{td}/V_{ts}|$ gives the length of the side. $|V_{td}/V_{ts}|$ can be obtained from the ratio of $B^0$-$\bar{B}^0$ mixing to $B_s^0$-$\bar{B}_s^0$ mixing, or the ratio of radiative penguin decays of $b$ quark.

$$\Delta M_B/\Delta M_{Bs} \propto |V_{td}/V_{ts}|^2,$$

$$|A(b \to d\gamma)/A(b \to s\gamma)| \propto |V_{td}/V_{ts}|.$$

Both $\Delta M_{Bs}$ and $b \to d\gamma$ decay have not yet measured, but will be obtained in the future experiments. One can expect about 20% experimental error with $10^8$ B mesons. Theoretical uncertainty lies in the evaluation of $SU(3)$ flavor symmetry breaking effect and long-distance effects. It depends on the theoretical development which of the measurements gives most precise value of the length of the side.

### 2.4 $\phi_1$

The angle $\phi_1$ is measured in the time dependent CP asymmetry in $B^0, \bar{B}^0 \to J/\Psi K_S$ decay.

$$A_{sym}[f_{CP}] \equiv \frac{\Gamma[B^0(t) \to f_{CP}] - \Gamma[\bar{B}^0(t) \to f_{CP}]}{\Gamma[B^0(t) \to f_{CP}] + \Gamma[\bar{B}^0(t) \to f_{CP}]}$$

$$= \frac{2}{(2 + c_d)} \left[ \text{Im}\left(\frac{q}{p}\rho\sin(\Delta M_B t) - \frac{c_d}{2}\cos(\Delta M_B t)\right) \right],$$

where $\Delta M_B$ is the mass difference of $B^0$ and $\bar{B}^0$ and $c_d$ is the CKM factor for $d$ quark.
where $f_{CP} = J/\Psi K_S$ state here, and

$$
\frac{q}{p} \equiv \frac{|M_{12}^B|}{M_{12}^B}, \quad M_{12}^B = \langle B^0 | \mathcal{H}^{B=2} | \overline{B^0} \rangle,
$$

$$
\rho \equiv \frac{A(B^0 \to f_{CP})}{A(B^0 \to f_{CP})}, \quad |\rho|^2 \equiv 1 + c_d,
$$

and we have neglected the absorptive part of $\langle B^0 | \mathcal{H}^{B=2} | \overline{B^0} \rangle$, which is a good approximation in B meson system. The weak phase of the decay amplitude is given by $\arg[V_{cb} V_{cs}^*]$. There is almost no direct CP violation ($c_d = 0$) in SM because the phase of the penguin amplitude, $b \to s c \bar{c}$, is same as $\arg[V_{cb} V_{cs}^*]$ up to tiny correction. Uncertainty in hadron matrix element is cancelled by taking the ratio, so there is no theoretical ambiguity. We have

$$
\frac{\text{Asy}[J/\Psi K_s]}{\sin(\Delta M_{Bt})} = \text{Im} \left[ \frac{|M_{12}^B| V_{cb} V_{cs}^* V_{cd}^* V_{cs}}{M_{12}^B V_{cb} V_{cs} V_{cd}^*} \right] e^{-2i\delta_1} = -\sin(\phi_M + 2\phi_c + 2\delta_1),
$$

where $\phi_M \equiv \arg[M_{12}^B]$, $\phi_c \equiv \arg[V_{cb} V_{cd}]$ and $\delta_1 \equiv \arg[V_{ud} V_{us}^*] - \arg[V_{cd} V_{cs}^*] + \pi$ [19]. In SM $\phi_M = -2\arg[V_{tb} V_{td}]$, so that the righthand-side of eq. (16) becomes $-\sin 2\phi_1$ up to negligible correction of $\delta_1 = O(10^{-3})$. The simulation tells us we get the error $\delta(\sin 2\phi_1) = 0.08$ with $10^8$ B mesons.

## 2.5 $\phi_2$

The CP angle $\tilde{\phi}_2$ is measured in a similar manner as $\phi_1$ by using $B^0, \overline{B^0} \to \pi\pi$ decay. One difference is that there is a penguin contribution which cause direct CP violation here. If we can neglect it, we have an asymmetry;

$$
\frac{\text{Asy}[\pi\pi]}{\sin(\Delta M_{Bt})} = -\text{Im} \left[ \frac{|M_{12}^B| V_{ub} V_{ud}^*}{M_{12}^B V_{ub} V_{ud}} \right] = \sin(\phi_M + 2\phi_u),
$$

where $\phi_u \equiv \arg[V_{ub} V_{ud}^*]$. The righthand-side of the above equation becomes $\sin[2(\pi - \phi_2) = -\sin 2\phi_2$ in SM. We will get $\delta(\sin 2\phi_2) = 0.15$ with $10^8$ B mesons according to the simulation. The error will get smaller as statistics increases. When the penguin contribution is not negligible, we need isospin analysis to remove the penguin pollution [20]. It needs $\pi^0\pi^0$ identification which is a challenge for experiment, and the precision gets worse. We can use $\rho\pi$ mode instead which is easier for experiment. The precision given by the simulation is $\delta\phi_2 = 20^\circ$ with $10^8$ B mesons.

## 2.6 $\phi_3$

The rest of the CP angles $\tilde{\phi}_3$ is to be measured at B factories from the decays $B^\pm \to \{D^0, \overline{D^0}, D_{CP}\} K^\pm$ or $B^0(\overline{B^0}) \to \{D^0, \overline{D^0}, D_{CP}\} K_s$ [11], where $D_{CP}$ is a CP eigenstate of neutral D meson which is identified by its decay into $K_S \pi^0, K_S \omega, K_S \phi$ or $K^+ K^-$. This is a
direct CP violation process where two amplitudes, \( A(b \to c\bar{u}s) \) and \( A(b \to u\bar{c}s) \) interfere. The corresponding weak phase is given by

\[
- \arg \left[ \frac{V_{cb}^* V_{us} V_{cs} V_{us}^*}{V_{ub}^* V_{cs}^* V_{cs} V_{us}} \right] = - \arg \left[ (V_{cb}^* V_{cd})(V_{ub} V_{ud}^*)(V_{us}^* V_{ud})(V_{cs} V_{cd}^*) \right]
\]

which becomes \( \phi_3 \) up to tiny correction of \( \delta_1 \) in SM. There is no theoretical ambiguity here. The precision according to the simulation is \( \delta \phi_3 = 25^\circ \) and \( 15^\circ \) for neutral B and charged B mode, respectively with \( 10^8 \) B mesons. (There is one comment here. In the simulation the ratio \( \Gamma(B^- \to D^0 K_S)/\Gamma(B^- \to D^0 K_S) \) is taken freely from 0.1 to 1.0. But it might be more small, \( O(10^{-2}) \) [21]. Then the precision gets worse.)

2.7 Precision with \( 10^9 \) B

Here we summarize the precision of each measurement. Precision with \( 10^9 \) B meson is estimated by naively scaling with \( 1/\sqrt{\text{number}} \).

|          | \( \delta(V_{cb}) \) | \( \delta(V_{ub}) \) | \( \delta(V_{ub}^* V_{cd}) \) | \( \delta(\sin 2\phi_1) \) | \( \delta(\sin 2\phi_2) \) | \( \delta(\phi_3) \) |
|----------|----------------------|----------------------|-------------------------------|----------------------|----------------------|----------------------|
| exp. error \( 10^8 \) B | 1 %                   | 10 %                 | 1 %                           | 0.08                 | \( \geq 0.15 \)      | \( \geq 15^\circ \)  |
| exp. error \( 10^9 \) B | \(< 1 \) %            | \(< 3 \) %           | \(< 1 \) %                     | 0.03                 | \( \geq 0.05 \)      | \( \geq 5^\circ \)   |
| Theo. error | \( 3 \) %            | 20 %                 | 20 %                          | 0                    | 0                    | 0                    |

Table 2 : Expected precision of measurements

Note that this estimation is optimistic in experiment and no theoretical development is assumed. The precision of sides is limited by theoretical error which is due to uncertainty in hadron effect evaluation, while that of angles by experimental error due to small branching ratio and difficulty in identification of decay modes. The experimental error will be able to get smaller as statistics grows, so the angle measurement seems to be promising for the precise determination of the unitarity triangle, or KM matrix elements. But there is a possibility of mis-determination of the unitarity triangle with angle measurement alone if some new physics exists other than SM [22].

Before closing this section one more comment should be given. Unitarity triangle is often drawn rescaled by \( |V_{cb}^* V_{cd}| \). There is about 7 % error in the present value of \( |V_{cd}| \) [8]. So we need more precise determination of \( |V_{cd}| \) in the precise determination of triangle by sides even if we get precise values of \( |V_{cb}|, |V_{ub}| \) and \( |V_{tb}^* V_{td}| \).

3 Looking for new physics

Here we discuss how to check SM and explore new physics as the data of unitarity triangle become available and more precise. At present we have the data of sides and CP violation in
K meson mixing. They are consistent with one another in SM. It would be difficult to find inconsistency with these data alone without great advance in theoretical treatment even if the statistics of experimental data gets higher.

After the B factories begin physics run, $\phi_1$ will be the first to be obtained among the three CP angles. Many of new physics can affect $B^0$-$\overline{B^0}$ mixing, so there is a possibility of finding inconsistency among $\phi_1$ and other data. New physics is likely to appear at the loop level as the new particle is in general too heavy to contribute at the tree level. When new physics contributes to $M_{12}^B$ with different phase from that in SM, $\phi_1$ deviates from the SM value. For example, if $\phi_1$ should be proved to be negative, it is inconsistent with the CP violation in K meson system ($\epsilon_K$). In other case it might be found too large to be consistent. They are schematically shown in Fig.(2). The $B^0$-$\overline{B^0}$ mixing matrix elements $M_{12}^B$ has almost the same phase with that of SM in multi Higgs model with natural flavor conservation and minimal SUSY standard model [23], so these models are not likely to show up in this stage. While the models with extra quarks [24], left-right model [25] can significantly alter the phase of $M_{12}^B$ and might be explored.

With more than $10^9$ B meson data the second stage of B physics begins. All the angles and sides would be obtained then with high precision. Also other data of B physics, radiative $b$ decays and so on, would be also available then. We can make a systematic study of new physics search [26].

If the data agree with one another very well, SM is confirmed also in Yukawa sector. Then we can check the hadron physics by comparing the experimental value with theoretical value. For example, the hadron matrix element of $B^0$-$\overline{B^0}$ mixing, $B_B f_B^2$, can be obtained from experimental value of $\Delta M_B$, $m_t$ once KM matrix elements are fixed by other methods. It should be compared with the value predicted by lattice QCD. There are many works on the

Figure 2: Two cases of inconsistency. The measured $\phi_1$ is too large in the case (A), negative in the case (B).
quark mass matrices. We can check the predictions of KM matrix elements, and discriminate appropriate mass matrices, which is beneficial for the explore of higher theory, GUTs and strings. More severe constraint on new physics is obtained, which gives helpful information for the future experimental projects.

4 Concluding remarks

10^9 or more B meson data can give a significant impact on the particle physics. When the proposed experimental projects on B physics goes well in every respects, we will be able to obtain 10^9 B in 2010 or so. Then we can fix KM matrix elements precisely or find a signal of new physics beyond SM. This goal can be attained more shortly if we get more clear identification of decay modes and theoretical development in hadron physics treatment are realized. Even in the worst case where only one CP angle (φ_1) is obtained, we can find or constrain new physics which contributes significantly to $B^0$-$\bar{B}^0$ mixing. The second stage of B physics with 10^9 B will be as promising as LEP experiments.
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