Measurements of CKM angle $\phi_3$ at BELLE

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We report recent results on $\phi_3$ measurement at the Belle collaboration. The analyses reported here are based on a large data sample that contains 657 million $B\bar{B}$ pairs collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider at the $\Upsilon(4S)$ resonance.

I. INTRODUCTION

In the Standard Model (SM), quark flavour mixing occurs via the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1]. CP violation in the SM occurs due to the presence of a complex phase in the CKM matrix. Precision measurements of the parameters of CKM matrix are of utmost importance to constrain the SM and measure the amount of CP violation. The CKM parameter $\phi_3$ ($\gamma$), defined as $\phi_3 = \arg(-V_{ub}V_{ub}^*/V_{cd}V_{cd}^*)$ is CKM angle measured with least precision. We report the recent measurements of $\phi_3$ by the Belle collaboration based on a large data sample that contains 657 million $B\bar{B}$ pairs in this report.

II. MEASUREMENT OF CP VIOLATION PARAMETERS USING $B^0(\bar{B}^0) \to D^{(*)\pi^\pm}$ DECAYS

The study of the time-dependent decay rates of $B^0(\bar{B}^0) \to D^{(*)\pi^\pm}$ provides a theoretically clean method for extracting $\sin(2\phi_1 + \phi_3)$ [2], where $\phi_1$ and $\phi_3$ are angles of the CKM Unitarity Triangle. As shown in Fig. 1, this decay can be mediated by both Cabibbo-favoured (CFD) and doubly-Cabibbo-suppressed (DCSD) processes, whose amplitudes are proportional to $V_{cb}^*V_{ud}$ and $V_{ub}^*V_{cd}$ respectively, which have a relative weak phase $\phi_3$.

The time-dependent decay rates are given by [3]

$$P(B^0 \to D^{(*)\pi^\pm}) = \frac{1}{8\tau_{B^0}} e^{-|\Delta t|/\tau_{B^0}} \times \left[ 1 \mp C \cos(\Delta m \Delta t) - S^{\pm} \sin(\Delta m \Delta t) \right],$$

$$P(\bar{B}^0 \to D^{(*)\pi^\pm}) = \frac{1}{8\tau_{B^0}} e^{-|\Delta t|/\tau_{B^0}} \times \left[ 1 \pm C \cos(\Delta m \Delta t) + S^{\pm} \sin(\Delta m \Delta t) \right].$$

(1)

Here $\Delta t$ is the difference between the time of the decay and the time that the flavour of the $B$ meson is tagged, $\tau_{B^0}$ is the average neutral $B$ meson lifetime, $\Delta m$ is the $B^0$-$\bar{B}^0$ mixing parameter, and $C = (1 - R^2_{D^{(*)}\pi}) / (1 + R^2_{D^{(*)}\pi})$, where $R_{D^{(*)}\pi}$ is the ratio of the magnitudes between the DCSD and CFD (we assume the magnitudes of both the CFD and DCSD amplitudes are the same for $B^0$ and $\bar{B}^0$ decays). The CP violation parameters are given by $S^{\pm} = -R_{D^{(*)}\pi} \sin(2\phi_1 + \phi_3 \pm \delta_{D^{(*)}\pi}) / (1 + R^2_{D^{(*)}\pi})$ for $D^{(*)}\pi$, where $\delta$ is the strong phase difference between CFD and DCSD. Since the predicted value of $R_{D^{(*)}\pi}$ is small, $\sim 0.02$ [4], we neglect terms of $O(R^2_{D^{(*)}\pi})$ (and hence take $C = 1$).
The strong phase $\delta$ for $D^*\pi$ is predicted to be small \( [3, 4] \). Since $R_{D^+\pi}$ is expected to be suppressed, the amount of $CP$ violation in $D^*\pi$ decays, which is proportional to $R_{D^+\pi}$, is expected to be small and a large data sample is needed in order to obtain sufficient sensitivity. We employ a partial reconstruction technique \( [5] \) for the $D^*\pi$ analysis, wherein the signal is distinguished from background on the basis of kinematics of the ‘fast’ pion ($\pi_f$) from the decay $B \rightarrow D^*\pi$, and the ‘slow’ pion from the subsequent decay of $D^* \rightarrow D\pi$; the $D$ meson is not reconstructed at all. In order to tag the flavour of the associated $B$ meson, we require the presence of a high-momentum lepton ($l$), required to have momenta in the range $1.1 \text{ GeV}/c < p_l < 2.3 \text{ GeV}/c$ in the event. We perform a simultaneous unbinned fit to the same-flavour (SF) events, in which $\pi_f$ and $l$ have the same charge, and opposite-flavour (OF) events, in which the $\pi_f$ and $l$ have the opposite charge \( [7] \). The results are shown in Fig. 2. We obtain the $CP$ violation parameters as $S^+ = +0.057 \pm 0.019 \pm 0.012$, $S^- = +0.038 \pm 0.020 \pm 0.010$, where the first errors are statistical and the second errors are systematic.

**III. MEASUREMENT OF $\phi_3$ FROM $B^\pm \rightarrow DK^\pm$ DECAYS**

$CP$ asymmetries in the decays $B \rightarrow DK$ was first discussed by I. Bigi, A. Carter, and A. Sanda \( [8] \). Several methods have been proposed since then for $\phi_3$ measurement in such decays \( [2, 4, 10, 11] \). $\phi_3$ is accessible via interference of $V_{cb}$ and $V_{ub}$ amplitudes. The effects of $CP$ violation can be enhanced, if the common final states of the $D^0$ and $\bar{D}^0$ decays following to $B^+ \rightarrow D^0K^-$ and $B^- \rightarrow \bar{D}^0K^-(b \rightarrow c)$ are chosen so that the interfering amplitudes have comparable magnitudes (ADS method \( [11] \)) (Fig. 3). The ratio of these interfering amplitudes, defined as $r_B$ is the ratio of the amplitudes of $B^+ \rightarrow D^0K^-(b \rightarrow u)$ and $B^- \rightarrow \bar{D}^0K^-(b \rightarrow c)$ decays. The feasibility for measuring $\phi_3$ crucially depends on the size of $r_B$, which is predicted to be around 0.1-0.2 by taking a product of the ratio of the CKM matrix elements $|V_{ub}V_{cs}^*/V_{cb}V_{us}^*|$ and the color suppression factor.

For the ADS method, we define observables, the charge averaged rate ($R_{ADS}$) and the partial rate asymmetry ($A_{ADS}$) as $R_{ADS} = \frac{B(B^+\rightarrow F_{D}K^-)+B(B^-\rightarrow \bar{F}_{\bar{D}}K^+)}{B(B^+\rightarrow F_{D}K^-)+B(B^-\rightarrow \bar{F}_{\bar{D}}K^+)}$ and $A_{ADS} = \frac{B(B^+\rightarrow F_{D}K^-)-B(B^-\rightarrow \bar{F}_{\bar{D}}K^+)}{B(B^+\rightarrow F_{D}K^-)+B(B^-\rightarrow \bar{F}_{\bar{D}}K^+)}$, where $[F]_D$ indicates that the state $F$ originates from the $D^0$ or $\bar{D}^0$ meson. These observables are related to the physical parameters by $R_{ADS} = r_B^2 + r_D^2 + 2r_BR_D\cos(\delta_B+\delta_D)\cos\phi_3$ and $A_{ADS} = 2r_BR_D\sin(\delta_B+\delta_D)\sin\phi_3/R_{ADS}$, where $r_D$ and $\delta_D$ are the ratio of the magnitudes and the strong phase difference of the $D$ decay amplitudes, respectively and $\delta_B$ is the ratio of the strong phase difference of the $B$ decay amplitudes. We obtain $R_{ADS} = [8.0^{+3.4}_{-2.7}(\text{stat}) + 2.0 - 2.8(\text{syst})] \times 10^{-3}$.
we obtain a resting upper limit on $r_B$. By taking a +2σ variation on $r_D$ and conservatively assuming $\cos \phi_3 \cos(\delta_B + \delta_D) = -1$, we obtain $r_B < 0.19$ at 90% confidence level.

Finally, the most effective constraint on $\phi_3$ comes from the $D \rightarrow K^0\pi^+\pi^-$ decay done using Dalitz analysis method. We report results using two modes: $B^+ \rightarrow DK^+$, and $B^+ \rightarrow DK^+$ with $D^+ \rightarrow D\pi^0$, $D \rightarrow K^0\pi^+\pi^-$ as well as the corresponding charge-conjugate modes. The weak parts of the amplitudes that contribute to the decay $B^+ \rightarrow DK^+$ are given by $V_{cb}^*V_{us} \sim A\lambda^3$ (for the $\overline{D}^0K^+$ final state) and $V_{cb}^*V_{cs} \sim \lambda^3(\rho + i\eta)$ (for $D^0K^+$). The two amplitudes interfere as the $D^0$ and $\overline{D}^0$ mesons decay into the same final state $K_S^0\pi^+\pi^-$. Assuming no $CP$ asymmetry in neutral $D$ decays, the amplitude of the neutral $D$ decay from $B^\pm \rightarrow DK^\pm$ as a function of Dalitz plot variables $m_\psi^2 = m_{K_S^0\pi^+\pi^-}$ and $m_\rho^2 = m_{K_S^0\pi^+\pi^-}^2 - M_\rho^2$ is $M_\rho = f(m_\psi^2, m_\rho^2) + re^{i\phi_3 + i\delta} f(m_\psi^2, m_\rho^2)$, where $f(m_\psi^2, m_\rho^2)$ is the amplitude of the $\overline{D}^0 \rightarrow K_S^0\pi^+\pi^-$ decay, $r_B$ is the ratio of the magnitudes of the two interfering amplitudes, and $\delta_B$ is the strong phase difference between them. The $\overline{D}^0 \rightarrow K_S^0\pi^+\pi^-$ decay amplitude $f$ can be determined from a large sample of flavor-tagged $\overline{D}^0 \rightarrow K_S^0\pi^+\pi^-$ decays produced in continuum $e^+e^-$ annihilation. Once $f$ is known, a simultaneous fit of $B^+$ and $B^-$ data allows the contributions of $r_B$, $\phi_3$ and $\delta_B$ to be separated. The method has a two-fold ambiguity: $(\phi_3, \delta_B)$ and $(\phi_3 + 180^\circ, \delta_B + 180^\circ)$ solutions cannot be separated. We always choose the solution with $0 < \phi_3 < 180^\circ$. Figure 3 shows the projections of the three-dimensional confidence regions onto the $(r_B, \phi_3)$ and $(\phi_3, \delta_B)$ planes for $B^+ \rightarrow DK^\pm$ and $B^\pm \rightarrow D^0K^\pm$ modes using statistical errors only. We perform a combined maximum likelihood fit to the two modes, and obtain $\phi_3 = 76^\circ \pm 12^\circ$ (stat) $\pm 4^\circ$ (syst) $\pm 9^\circ$ (model). The statistical significance of $CP$ violation ($\phi_3 \neq 0$) in our measurement is $(1 - 5.5 \times 10^{-4})$, or 3.5 standard deviations.

IV. CONCLUSION

The precise measurement of $CKM$ angle $\phi_3$ is one of the most challenging, yet interesting pursuits in the $B$-factories. The Belle collaboration has performed $\phi_3$ extraction using several methods, and the most effective constraint
on $\phi_3$ comes from the Dalitz plot analysis of the $K_0^0\pi^+\pi^-$ decay of the neutral $D$ meson produced in $B^\pm \rightarrow D^{(*)}K^\mp$ decays. The recent Belle result for $B^- \rightarrow DK^-$ followed by $D \rightarrow K^+\pi^-$ brings a stringent upper limit on $r_B$, which is consistent with the result obtained by the Dalitz plot analysis. Results on time-dependent $CP$ asymmetries in $B \rightarrow D^{\pm}\pi^\pm$ decays are also reported.

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