MEASUREMENTS OF ϕ_3 (γ) AT BELLE

Y. HORII
(BELLE COLLABORATION)
Department of Physics, Tohoku University
6-3, Aramaki Aoba, Aoba-ku, Sendai, Miyagi 980-8578, Japan
E-mail: yhorii@awa.tohoku.ac.jp

We report recent results by the Belle collaboration for the determination of the CP-violating angle ϕ_3 (γ).

1. Introduction

Precise measurements of the parameters of the standard model are fundamentally important and may reveal new physics. The Cabibbo-Kobayashi-Maskawa (CKM) matrix[1] consists of weak interaction parameters for the quark sector, and the phase ϕ_3 (γ) is defined by the elements of the CKM matrix as $\phi_3 \equiv \arg(-V_{ud}V_{ub}{}^*/V_{cd}V_{cb}{}^*)$. This phase is less accurately measured than the two other angles ϕ_1 (β) and ϕ_2 (α) of the unitarity triangle.[a] In this brief note, we report a few studies by Belle collaboration related to measurement of ϕ_3.

2. Measurement of ϕ_3 from $B \to DK$

The possibility of large CP asymmetries in the decays $B \to DK$ are first discussed by I. Bigi, A. Carter, and A. Sanda.[2] Since then, several methods for measuring ϕ_3 using $B \to DK$ decays have been proposed. In the usual quark phase convention where large complex phases appear only in V_{ub} and V_{td},[3] the measurement of ϕ_3 is equivalent to the extraction of the phase of V_{ub} relative to the phases of other CKM matrix elements except for V_{td}. Fig. 1 shows the diagrams for $B^- \to \bar{D}K^-$ ($b \to u$) and $B^- \to DK^-$ ($b \to c$) decays.[b] From the analyses on these de-

[a]The angles ϕ_1 and ϕ_2 are defined as $\phi_1 \equiv \arg(-V_{cd}V_{cb}{}^*/V_{td}V_{tb}{}^*)$ and $\phi_2 \equiv \arg(-V_{td}V_{tb}{}^*/V_{ud}V_{ub}{}^*)$.
[b]Charge conjugate modes are implicitly included unless otherwise stated.

cays, we extract ϕ_3 together with the ratio of the B decay amplitudes $r_B = |A(B^- \to \bar{D}K^-)/A(B^- \to DK^-)|$ as well as the relative strong phase δ_B. The feasibility for measuring ϕ_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.

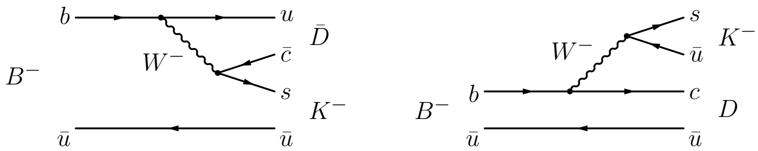

Figure 1. Diagrams for $B^- \to \bar{D}K^-$ and $B^- \to DK^-$ decays.

One of the strategies[4] uses the decays $B^- \to D_{CP\pm}K^-$, where $D_{CP\pm}$ denotes the CP eigenstates $D_{CP\pm} = (D^0 \pm \bar{D}^0)/\sqrt{2}$. The observables are the ratio of charge averaged partial rates $R_{CP\pm} \equiv \frac{B(B^-\to D_{CP\pm}K^-)+B(B^+\to D_{CP\pm}K^+)}{B(B^-\to D^0K^-)+B(B^+\to \bar{D}^0K^+)}$ and the charge asymmetries $A_{CP\pm} \equiv \frac{B(B^-\to D_{CP\pm}K^-)-B(B^+\to D_{CP\pm}K^+)}{B(B^-\to D_{CP\pm}K^-)+B(B^+\to D_{CP\pm}K^+)}$. These are related to ϕ_3, r_B and δ_B as $R_{CP\pm} = 1 + r_B^2 \pm 2r_B \cos\delta_B \cos\phi_3$ and $A_{CP\pm} = \pm 2r_B \sin\delta_B \sin\phi_3/R_{CP\pm}$. We reconstruct the D mesons through the decays to CP eigenstates of K^+K^- and $\pi^+\pi^-$ for D_{CP+} and $K_S^0\pi^0$, $K_S^0\phi$, and $K_S^0\omega$ for D_{CP-}. The results, obtained for a data sample that contains 275×10^6 $B\bar{B}$ pairs, are[5]

$$R_{CP+} = 1.13 \pm 0.16(\text{stat}) \pm 0.08(\text{syst}), \quad (1)$$

$$R_{CP-} = 1.17 \pm 0.14(\text{stat}) \pm 0.14(\text{syst}), \quad (2)$$

$$A_{CP+} = 0.06 \pm 0.14(\text{stat}) \pm 0.05(\text{syst}), \quad (3)$$

$$A_{CP-} = -0.12 \pm 0.14(\text{stat}) \pm 0.05(\text{syst}). \quad (4)$$

Similarly, results are obtained for the decays $B^- \to D^*_{CP\pm}K^-$ with $D^* \to D\pi^0$. At present, the results from this type of method have weak information on ϕ_3 and are used to improve the ϕ_3 constraint by combining with other methods.

The effects of CP violation can be enhanced, if the common final states of the $\bar{D}^0$ and D^0 decays following to $B^- \to \bar{D}^0K^-$ and $B^- \to D^0K^-$ are chosen so that the interfering amplitudes have comparable magnitudes (ADS method).[6] For this method, observables are the charge averaged rate $R_{\rm ADS} \equiv \frac{B(B^- \to [F]_D K^-) + B(B^+ \to [\bar{F}]_D K^+)}{B(B^- \to [\bar{F}]_D K^-) + B(B^+ \to [F]_D K^+)}$ and the partial rate asymmetry $A_{\rm ADS} \equiv \frac{B(B^- \to [F]_D K^-) - B(B^+ \to [\bar{F}]_D K^+)}{B(B^- \to [F]_D K^-) + B(B^+ \to [\bar{F}]_D K^+)}$, where $[F]_D$ indicates that the state F originates from the $\bar{D}^0$ or D^0 meson. These observables are related to the physical parameters by $R_{\rm ADS} = r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D) \cos\phi_3$ and $A_{\rm ADS} = 2 r_B r_D \sin(\delta_B + \delta_D) \sin\phi_3 / R_{\rm ADS}$, where r_D and δ_D are the ratio of the magnitudes and the strong phase difference of the D decay amplitudes, respectively. The rate r_D can be measured with D meson decays. To determine ϕ_3, it is needed to combine results for more than two states of F where CP eigenstates can be included in F. The final state $F = K^+\pi^-$ is a particularly useful mode, for which the color-suppressed B decay followed by the Cabibbo-favored D decay interferes with the color-favored B decay followed by the doubly Cabibbo-suppressed D decay. Recently, we have updated the analysis for this mode using a larger data sample (657×10^6 $B\bar{B}$ pairs). The result is[7]

$$R_{\rm ADS} = [8.0^{+6.3}_{-5.7}({\rm stat})^{+2.0}_{-2.8}({\rm syst})] \times 10^{-3}, \quad (5)$$

$$A_{\rm ADS} = -0.13^{+0.97}_{-0.88}({\rm stat}) \pm 0.26({\rm syst}). \quad (6)$$

The signal is not significant, but allows to set an upper limit on r_B (Fig. 2). By taking a $+2\sigma$ variation on r_D and conservatively assuming $\cos\phi_3 \cos(\delta_B + \delta_D) = -1$, we obtain $r_B < 0.19$ at 90% C.L.

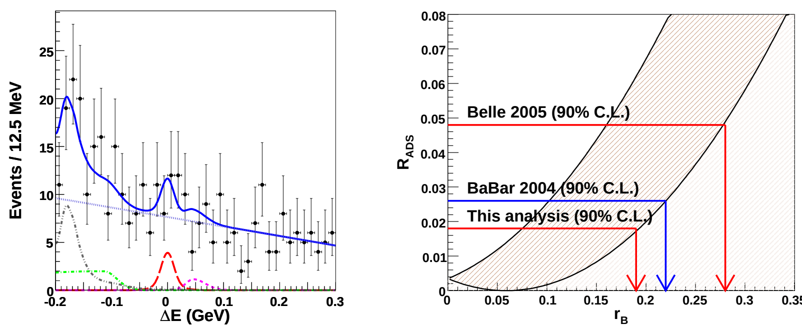

Figure 2. Left: The result of the fit to the energy difference between the signal candidate and the beam, ΔE, for the mode $B^- \to [K^+\pi^-]_D K^-$. Signal component is shown by the long dashed curve. Right: The dependence of $R_{\rm ADS}$ on r_B, together with our upper limits and the previous limits obtained by Belle, *PRL 94, 091601 (2005)*, and BaBar, *PRL 93, 131804 (2004)*. Allowed region is shown by a hatched area.

The method to use a three-body D meson decay, such as $F = K_S^0 \pi^+ \pi^-$, is important in extracting ϕ_3.[8] The resonances in the D decays provide the necessary variation of phase differences. We parameterize the amplitude as a sum of two-body decay amplitudes plus a non-resonant decay amplitude and fit to the Dalitz distribution obtained in the high-statistics sample of $D^{*+} \to D^0\pi^+$. The most effective constraint on ϕ_3 comes from this method. From the combination of the results for $B^- \to DK^-$, $B^- \to D^*K^-$ with $D^* \to D\pi^0$, and $B^- \to DK^{*-}$ with $K^{*-} \to K^0_S\pi^-$ based on a data sample that contains 386×10^6 $B\bar{B}$ pairs, we obtain[9]

$$\phi_3 = 53^\circ\ {}^{+15^\circ}_{-18^\circ}(\text{stat}) \pm 3^\circ(\text{syst}) \pm 9^\circ(\text{model}). \tag{7}$$

Of the two possible solutions, we choose the one with $0 < \phi_3 < 180^\circ$. The third error is due to the D decay modeling. Obtained values for r_B are $0.159^{+0.054}_{-0.050} \pm 0.012 \pm 0.049$ for $B^- \to DK^-$, $0.175^{+0.108}_{-0.099} \pm 0.013 \pm 0.049$ for $B^- \to D^*K^-$, and $0.564^{+0.216}_{-0.155} \pm 0.041 \pm 0.084$ for $B^- \to DK^{*-}$. The result of r_B for $B^- \to DK^-$ is consistent with the upper limit obtained by the analysis for $B^- \to [K^+\pi^-]_D K^-$.

3. Measurement of $2\phi_1 + \phi_3$ from $B \to D^{(*)\pm}\pi^\mp(\rho^\mp)$

Because both B^0 and $\bar{B}^0$ decay to $D^{(*)+}\pi^-(\rho^-)$ (Fig. 3), we can study the interference of $b \to u$ and $b \to c$ transitions using $B^0 \to D^{(*)+}\pi^-(\rho^-)$ and $B^0 \to \bar{B}^0 \to D^{(*)+}\pi^-(\rho^-)$ decays.[10] From coefficients of the time-dependent decay rates, we obtain the values of $S^\pm = 2(-1)^L r \sin(2\phi_1 + \phi_3 \pm \delta)/(1+r^2)$, where L is the orbital angular momentum of the final state, r is the ratio of the magnitudes of suppressed to favored amplitudes, and δ is the strong phase. The values of r and δ are not necessarily the same for different final states.

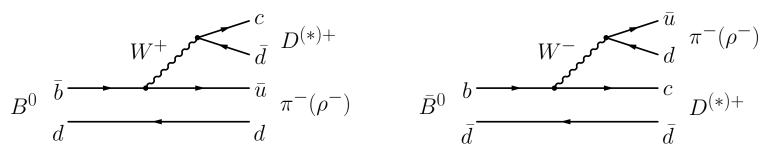

Figure 3. Diagrams for $B^0 \to D^{(*)+}\pi^-(\rho^-)$ and $\bar{B}^0 \to \bar{D}^{(*)+}\pi^-(\rho^-)$ decays. We approach ϕ_3 using the interference between these two decays with B^0-$\bar{B}^0$ mixing.

For $B \to D^{(*)+}\pi^-$, the results are obtained for a data sample that contains 386×10^6 $B\bar{B}$ pairs as[11]

$$S^+(D^*\pi) = 0.049 \pm 0.020 \pm 0.011, \quad (8)$$

$$S^-(D^*\pi) = 0.031 \pm 0.019 \pm 0.011, \quad (9)$$

$$S^+(D\pi) = 0.031 \pm 0.030 \pm 0.012, \quad (10)$$

$$S^-(D\pi) = 0.068 \pm 0.029 \pm 0012. \quad (11)$$

Since we have two measurements (S^+ and S^-) which depend on three unknowns (r, $2\phi_1 + \phi_3$, δ) for each of the $D^*\pi$ and $D\pi$ modes, there is not sufficient information to solve for the phase $2\phi_1 + \phi_3$. One way to constrain is to use $SU(3)$ symmetry to estimate r by relating modes to B decays involving D_s mesons. We obtain 68% (95%) C.L. lower limits on $|\sin(2\phi_1 + \phi_3)|$ of 0.44 (0.13) and 0.52 (0.07) from the $D^*\pi$ and $D\pi$ modes, respectively.

4. Conclusion

The extraction of ϕ_3 is challenging even with modern high luminosity B factory. Several methods are performed by the Belle collaboration, and the most effective constraint on ϕ_3 comes from the Dalitz plot analysis on the decay $B^- \to D^{(*)}K^{(*)-}$ followed by $D \to K_S^0\pi^+\pi^-$. The recent result for $B^- \to DK^-$ followed by $D \to K^+\pi^-$ brings a stringent upper limit on r_B, which is consistent with the result obtained by the Dalitz plot analysis. Time-dependent analysis on $B \to D^{(*)+}\pi^-$ is also performed and provides lower limits on $|\sin(\phi_1 + \phi_3)|$.

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