PROCEEDINGS OF SCIENCE

Measurements of ϕ_3 at Belle

Kentaro Negishi[*†]
Tohoku Univ.
E-mail: negishi@epx.phys.tohoku.ac.jp

The Belle experiment, running at the KEKB e^+e^- asymmetric energy collider during 1999-2010, has recorded 711 fb^{-1} of data at the $\Upsilon(4S)$ resonance. A combined fit for ϕ_3 with the latest Belle results of the ADS, GLW and GGSZ method is performed. We use $B^\pm \to DK^\pm$ and $B^\pm \to D^*K^\pm$ decays where the D meson (D^0 or $\bar{D}^0$) decays into $K_S^0\pi\pi$, $K\pi$, KK, $\pi\pi$, $K_S^0\pi^0$ and $K_S^0\eta$ final states and D^* decays into $D\pi^0$ and $D\gamma$. Belle obtains its most precise measurement to date, $\phi_3 = (68^{+15}_{-14})^\circ$. In addition a new ADS analysis of $B^\pm \to DK^\pm$ following by $D \to K\pi\pi^0$, is reported.

The European Physical Society Conference on High Energy Physics -EPS-HEP2013
18-24 July 2013
Stockholm, Sweden

*Speaker.
†on behalf of the Belle collaboration

PoS(EPS-HEP 2013)364

1. Introduction

In the Standard Model (SM), the Cabbibo-Kobayashi-Maskawa (CKM) mechanism [1] has been well established, but some measurements of the mechanism warrant further investigation. For example, two angles of the CKM unitarity triangle, ϕ_1 and ϕ_2, have now been measured with high precision [2]. The ϕ_3 determination from data is much less accurate. Its determination is however theoretically clean due to no loop contributions; ϕ_3 can be determined using tree-level processes only, exploiting the interference between $b \to c\bar{u}d$ and $b \to u\bar{c}d$ transitions that occurs when the D^0 and $\bar{D}^0$ decay to the same final state (Fig. 1). Therefore, the angle ϕ_3 provides a SM benchmark, and

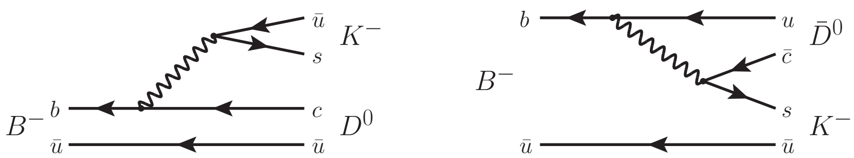

Figure 1: Feynman diagrams for $B^- \to D^0K^-$ and $B^- \to \bar{D}^0K^-$.

its precise measurement is crucial in order to disentangle non-SM contributions to other processes, via global CKM fits. The size of the interference depends on the ratio (r_B) of the magnitudes of the two tree diagrams and δ_B, the strong phase difference between them. These hadronic parameters will be extracted from data together with the angle ϕ_3. The value of r_B is expected to be 0.1 from the ratio of CKM matrix elements $|V^*_{ub}V_{cs}|/|V^*_{cb}V_{us}| \sim 0.38$ and the color suppression, whereas δ_B can not be calculated precisely from theory. Note that r_B and δ_B can take different values for different B decays: the values of $B^\pm \to DK^\pm$ and $B^\pm \to D^*K^\pm$ are not the same. Several different D decays have been studied in order to maximize the sensitivity to ϕ_3. One of the approaces is the use of D decays to CP eigenstates, a method proposed by M. Gronau, D. London, and D. Wyler, which is referred to as the GLW method [3]. An alternative approach was proposed by D. Atwood, I. Dunietz, and A. Soni, which is referred to as the ADS method [4]. Instead of using D^0 decays to CP eigenstates, the ADS method uses Cabibbo-favored and doubly Cabibbo-suppressed D decays. In the decays $B^\pm \to [K^\mp\pi^\pm]_DK^\pm$, the suppressed B decay is followed by a Cabibbo-favored D^0 decay. Therefore, the interfering amplitudes are of similar magnitude, and one can expect a large CP asymmetry. But those decay mode branching fractions tend to be small. Another approach, proposed by Giri, Grossman, Soffer and Zupan, [5] that is referred to as the GGSZ method, is to use three-body decays of the D. The advantage is that ϕ_3, δ_B and r_B can be obtained from a single decay. At present the GGSZ method using $D \to K_S\pi^+\pi^-$ decays gives the best sensitivity to ϕ_3. Latest Belle results using the full data sample taken at the $\Upsilon(4S)$ (corresponding to $772\times\ 10^6$ $B\bar{B}$ pairs) are described in these proceedings and the value of ϕ_3 obtained by combining these results is presented.

2. GGSZ results

Assuming no CP asymmetry in neutral D decays, the amplitude for $B^+ \to [K^0_S\pi^+\pi^-]_DK^+$

decay as a function of Dalitz plot variables of $m_+^2 = m^2_{K_S^0\pi^+}$ and $m_-^2 = m^2_{K_S^0\pi^-}$ is

$$f_{B^+} = f_D(m_+^2, m_-^2) + r_B e^{i\phi_3 + i\delta_B} f_D(m_-^2, m_+^2), \tag{2.1}$$

where $f_D(m_+^2, m_-^2)$ is the amplitude of the $\bar{D}^0 \to K_S^0\pi^+\pi^-$ decay. Similarly, the amplitude for $B^- \to [K_S^0\pi^+\pi^-]_D K^-$ decay is

$$f_{B^-} = f_D(m_-^2, m_+^2) + r_B e^{-i\phi_3 + i\delta_B} f_D(m_+^2, m_-^2). \tag{2.2}$$

With a large sample of flavor-tagged $\bar{D}^0 \to K_S^0\pi^+\pi^-$ decays produced in continuum $c\bar{c}$ production from e^+e^- annihilation events, the $\bar{D}^0 \to K_S^0\pi^+\pi^-$ decay amplitude f_D can be determined. Once f_D is known, a simultaneous fit to B^+ and B^- data allows the contributions of r_B, and δ_B to be separated. This method has a two-fold ambiguity in the solutions: (ϕ_3, δ_B) and ($\phi_3 + 180°$, $\delta_B + 180°$). Due to the fact that r_B is bounded to be positive, the direct extraction of r_B, δ_B and ϕ_3 can be biased. To avoid these biases, the Cartesian coordinates have been introduced, $x_\pm = r_B\cos(\delta_B \pm \phi_3)$ and $y_\pm = r_B\sin(\delta_B \pm \phi_3)$. A combined GGSZ analysis of B^+ and B^- samples results in the ($x_\pm$, $y_\pm$) values given in Table 1 and Fig. 2.

Observables	$B \to DK$	$B \to D^*K$
x_+	$-0.107 \pm 0.043 \pm 0.011$	$+0.083 \pm 0.022 \pm 0.011$
y_+	$-0.067 \pm 0.059 \pm 0.018$	$+0.157 \pm 0.109 \pm 0.018$
x_-	$+0.105 \pm 0.047 \pm 0.011$	$-0.036 \pm 0.127 \pm 0.011$
y_-	$+0.177 \pm 0.060 \pm 0.018$	$-0.249 \pm 0.118 \pm 0.018$

Table 1: Results of Belle GGSZ analyses.

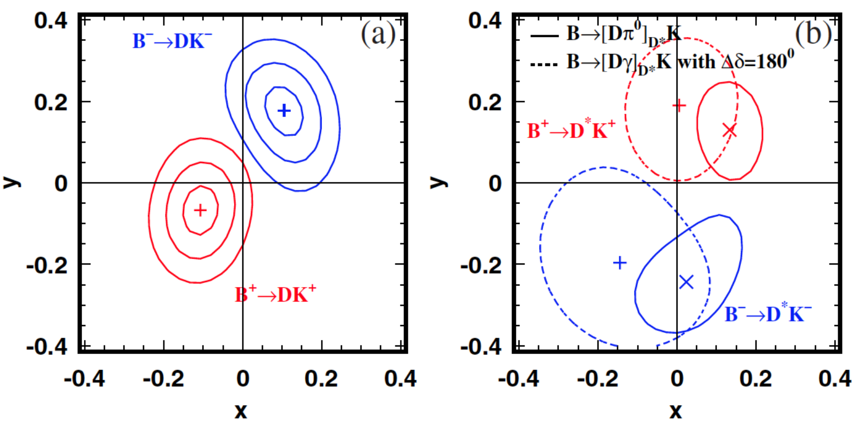

Figure 2: Results of Belle GGSZ analyses.

The combined result of ϕ_3 from $B^\pm \to DK^\pm$ and $B^\pm \to D^*K^\pm$ is $\phi_3 = (78^{+11}_{-12} \pm 4 \pm 9)^\circ$ [6], where the three uncertainties are statistical, systematic and that due to the $D \to K_S^0\pi^+\pi^-$ decay model assumptions, respectively. The last source of uncertainty can be eliminated by binning the

Dalitz plot (Refs. [5, 7]), using information on the averaged strong phase difference δ_D between D^0 and $\bar{D}^0$ decays in bin; this information can be determined using the quantum-correlated $\psi(3770)$ data. The results have been published by CLEO-c [8]. The measured strong phase difference is used to obtain the model-independent result [9], $\phi_3 = (77 \pm 15 \pm 4 \pm 4)^\circ$ where the last uncertainty is due to the statistical precision of the CLEO-c results.

3. ADS results

For the ADS method, Belle has studied the $B \to D^{(*)}K$ decays where $D \to K^-\pi^+$. The observables measured in the ADS method are the ratio of the suppressed and allowed branching fractions:

$$\begin{aligned} \mathscr{R}_{\text{ADS}} = & \frac{\Gamma(B^\pm \to [K^\mp\pi^\pm]_D K^\pm)}{\Gamma(B^\pm \to [K^\pm\pi^\mp]_D K^\pm)} \\ = & \; r_B^2 + r_D^2 + 2 r_B r_D \cos\phi_3 \cos\delta, \end{aligned} \tag{3.1}$$

and

$$\begin{aligned} \mathscr{A}_{\text{ADS}} = & \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) - \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)} \\ = & \; 2 r_B r_D \sin\phi_3 \sin\delta / \mathscr{R}_{\text{ADS}}, \end{aligned} \tag{3.2}$$

where r_D is the ratio of the doubly Cabibbo-suppressed and Cabibbo-allowed D^0 decay amplitudes and δ is the sum of strong phase differences in B and D decays: $\delta = \delta_B + \delta_D$. Recently, Belle reported the ADS analysis using their final data sample of 772×10^6 $B\bar{B}$ pairs [10], and these results are summarized in Table 2. This analysis includes the two B decays: $B^\pm \to DK^\pm$ with D

Mode	$\mathscr{R}_{\text{ADS}}$ $[\times 10^{-2}]$	$\mathscr{A}_{\text{ADS}}$
$B^\pm \to DK^\pm$	$1.63^{+0.44+0.07}_{-0.41-0.13}$	$-0.39^{+0.26+0.04}_{-0.28-0.03}$
$B^\pm \to D^*K^\pm$, $D^* \to D\pi^0$	$1.0^{+0.8+0.1}_{-0.7-0.2}$	$+0.4^{+1.1+0.2}_{-0.7-0.1}$
$B^\pm \to D^*K^\pm$, $D^* \to D\gamma$	$3.6^{+1.4}_{-1.2} \pm 0.2$	$-0.51^{+0.33}_{-0.29} \pm 0.08$

Table 2: Results of Belle ADS analyses.

decaying to $K^+\pi^-$ and $K^-\pi^+$. The use of two additional decay modes, $D^* \to D\pi^0$ and $D^* \to D\gamma$, provides an extra handle on the extraction of ϕ_3 as explained in Ref. [11]. This effect (larger ratio for $B^\pm \to D^*K^\pm$ with $D^* \to D\gamma$ and opposite asymmetry between both $B^\pm \to D^*K^\pm$ channels) is becoming visible in the results from Belle [13].

4. GLW results

In the study of the GLW method, the modes of interest are D decays into CP eigenstates [3] such as K^+K^-, $\pi^+\pi^-$ (CP-even) and $K_S^0\pi^0$, $K_S^0\eta^0$ (CP-odd). To extract ϕ_3 using the GLW method, the following observables sensitive to CP violation are used: the asymmetries

$$\begin{aligned} \mathscr{A}_{CP\pm} = & \frac{\Gamma(B^- \to D_{CP\pm}K^-) - \Gamma(B^+ \to D_{CP\pm}K^+)}{\Gamma(B^- \to D_{CP\pm}K^-) + \Gamma(B^+ \to D_{CP\pm}K^+)} \\ = & \pm \frac{2 r_B \sin\phi_3 \sin\delta_B}{1 + r_B^2 \pm 2 r_B \cos\phi_3 \cos\delta_B}, \end{aligned} \tag{4.1}$$

and

$$\mathscr{R}_{CP\pm} = 2\frac{\Gamma(B^- \to D_{CP\pm}K^-) + \Gamma(B^+ \to D_{CP\pm}K^+)}{\Gamma(B^- \to \bar{D}^0K^-) + \Gamma(B^+ \to D^0K^+)} = 1 + r_B^2 \pm 2r_B \cos\phi_3 \cos\delta_B. \tag{4.2}$$

Among these four observables, $\mathscr{A}_{CP\pm}$ and $\mathscr{R}_{CP\pm}$, only three are independent (since $\mathscr{A}_{CP+}\mathscr{R}_{CP+} = -\mathscr{A}_{CP-}\mathscr{R}_{CP-}$). Recently, Belle updated the GLW analysis using their final data sample of 772×10^6 $B\bar{B}$ pairs [13]. These results include the two B decays: $B^\pm \to D^0K^\pm$ and $B^\pm \to D^{*0}K^\pm$, where $D^{*0} \to D^0\pi^0$ and $D^0\gamma$. The signs of the $\mathscr{A}_{CP+}$ and $\mathscr{A}_{CP-}$ asymmetries should be opposite which is now confirmed by the Belle experiment (Table 3).

Observables	$B \to DK$	$B \to D^*K$
$\mathscr{R}_{CP+}$	$1.03 \pm 0.07 \pm 0.03$	$1.19 \pm 0.13 \pm 0.03$
$\mathscr{R}_{CP-}$	$1.13 \pm 0.09 \pm 0.05$	$1.03 \pm 0.13 \pm 0.03$
$\mathscr{A}_{CP+}$	$+0.29 \pm 0.06 \pm 0.02$	$-0.14 \pm 0.10 \pm 0.01$
$\mathscr{A}_{CP-}$	$-0.12 \pm 0.06 \pm 0.01$	$+0.22 \pm 0.11 \pm 0.01$

Table 3: Results of Belle GLW analyses.

5. ϕ_3 combination from Belle measurements

We combine the available Belle observables of the $D^{(*)}K$ system obtained from the GGSZ method (model-dependent results shown in Table 1), the ADS method (Table 2) and the GLW method (Table 3) using the frequentist procedure described in Ref. [12]. The $1-\mathrm{CL}$ curves obtained for the angle ϕ_3, as well as for the hadronic parameters (δ_B and r_B) of $B \to DK$ mode, are shown in Fig. 3 and the 68% C.L. intervals are summarized in Table 4. Belle obtains its most precise ϕ_3 measurement to date: $\phi_3 = (68^{+15}_{-14})^\circ$.

Method	ϕ_3 [°]	δ_B [°]	r_B
GGSZ	82^{+18}_{-23}	141^{+27}_{-36}	$0.168^{+0.063}_{-0.064}$
GGSZ+ADS	68 ± 22	123^{+27}_{-33}	$0.104^{+0.020}_{-0.021}$
GGSZ+ADS+GLW	68^{+15}_{-24}	116^{+18}_{-21}	$0.112^{+0.014}_{-0.015}$

Table 4: Confidence intervals (68% C.L.) for the angle ϕ_3 and the hadronic parameters of DK (δ_B and r_B) obtained by the combination of the $D \to D^{(*)}K$ results of the Belle collaboration.

6. New Belle results

We have a new result related to ϕ_3, $B^\pm \to [K\pi\pi^0]_DK^\pm$, with ADS method. In $B^\pm \to [K\pi\pi^0]_DK^\pm$ decay, observables $\mathscr{R}_{\mathrm{ADS}}$ (Eq. 3.1) and $\mathscr{A}_{\mathrm{ADS}}$ (Eq. 3.2) are written in

$$\mathscr{R}_{\mathrm{ADS}} = \frac{\Gamma(B^- \to [K^+\pi^-\pi^0]_DK^-) + \Gamma(B^+ \to [K^-\pi^+\pi^0]_DK^+)}{\Gamma(B^- \to [K^-\pi^+\pi^0]_DK^-) + \Gamma(B^+ \to [K^+\pi^-\pi^0]_DK^+)} = r_B^2 + r_D^2 + 2R_{K\pi\pi^0} r_B r_D \cos\phi_3 \cos(\delta_B + \delta_D^{K\pi\pi^0}), \tag{6.1}$$

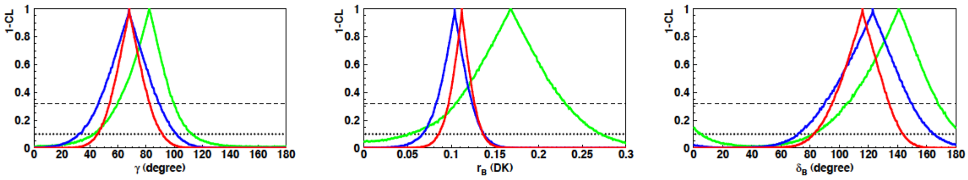

Figure 3: $1-\mathrm{CL}$ curves for ϕ_3 (left), r_B (center) and δ_B (right) from the Belle $D^{(*)}K$ results. The green curve is for the GGSZ results, the blue for GGSZ and ADS results using δ_D from mixing and CLEO-c measurements, the red for GGSZ, ADS and GLW results.

and

$$\mathscr{A}_{\mathrm{ADS}} = \frac{\Gamma(B^- \to [K^+\pi^-\pi^0]_D K^-) - \Gamma(B^+ \to [K^-\pi^+\pi^0]_D K^+)}{\Gamma(B^- \to [K^+\pi^-\pi^0]_D K^-) + \Gamma(B^+ \to [K^-\pi^+\pi^0]_D K^+)} = 2R_{K\pi\pi^0} r_B r_D \sin\phi_3 \sin(\delta_B + \delta_D^{K\pi\pi^0})/\mathscr{R}_{\mathrm{ADS}}, \quad (6.2)$$

where $R_{K\pi\pi^0}$ is called the coherence factor, $\delta_D^{K\pi\pi^0}$ is D decay strong-phase difference averaged over $K\pi\pi^0$ phase space, and $r_D = \Gamma(D^0 \to K^+\pi^-\pi^0)/\Gamma(D^0 \to K^-\pi^+\pi^0) = (2.20 \pm 0.10) \times 10^{-3}$. The CLEO collaboration report values of $R_{K\pi\pi^0}$ and $\delta_D^{K\pi\pi^0}$ [14], which can be used to constrain ϕ_3 in conjunction with these measurements.

This analysis [15] uses the full $\Upsilon(4S)$ data sample recorded by the Belle experiment. The suppressed mode signal yield obtained is 77 ± 24 events, which corresponds to the first evidence for an ADS signal (with a significance of 3.2σ). The ratio of the suppressed and allowed modes and asymmetry are summarized in Table 5 and the signal yield fit result are shown in the combined fit, the results of which are reported in Fig. 4. Note that This result are not included in Table 4.

Observables	$B^\pm \to [K\pi\pi^0]_D K^\pm$
$\mathscr{R}_{\mathrm{ADS}}$	$(1.98 \pm 0.62 \pm 0.23) \times 10^{-2}$
$\mathscr{A}_{\mathrm{ADS}}$	$0.41 \pm 0.30 \pm 0.05$

Table 5: Results of Belle $B^\pm \to [K\pi\pi^0]_D K^\pm$ ADS analysis.

7. Conclusion

Belle is a good environment for B physics because it has the largest $\Upsilon(4S)$ data of the world. The ϕ_3 determination is needed as a SM benchmark. $\phi_3 = (68^{+15}_{-14})^\circ$ is the combined result of Belle, and a new $B^\pm \to [K\pi\pi^0]_D K^\pm$ ADS result has been presented. Moreover many other analyses for ϕ_3 measurement using the full Belle data sample are ongoing.

References

[1] N. CAbibbo, *Phys. Rev. Lett.* **10**, 531 (1963); M. Kobayashi and T. Maskawa, *Prog. Theor. Phys.* **49**, 652 (1973).

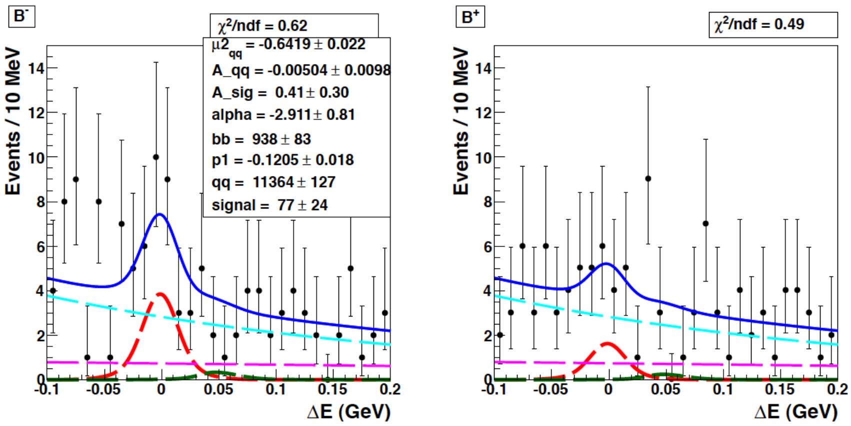

Figure 4: Results of Belle $B^{\pm} \to [K\pi\pi^0]_D K^{\pm}$ analysis. The plotted variable ΔE peaks at zero for signal decays.

[2] Y. Amhis *et al*. (Heavy Flavor Averaging Group), arXiv:1207.1158 and online update at http://www.slac.stanford.edu/xorg/hfag.

[3] M. Gronau, D. London, D. Wyler, *Phys. Rev. Lett. B* **253**, 483 (1991); M. Gronau, D. London, D. Wyler, *Phys. Rev. Lett. B* **265**, 172 (1991).

[4] D. Atwood, I. Dunietz, A. Soni, *Phys. Rev. Lett.* **78**, 3357 (1997).

[5] A. Giri, Yu. Grossman, A. Soffer, J. Zupan, *Phys. Rev. D* **68**, 2003,054018; A. Bondar. Proceedings of BINP Special Analysis Meeting on Dalitz Analysis, 24-26 Sep. 2002, unpublished.

[6] A. Poluektov *et al*. (Belle Collaboration), *Phys. Rev. D* **81**, 2010,112002.

[7] A. Bondar, A. Poluektov, *Eur. Phys. J. C* **47** (2006), 347; A. Bondar, A. Poluektov, *Eur. Phys. J. C* **55** (2008), 51.

[8] R. A. Briere *et al*. (CLEO Collaboration), *Phys. Rev. D* **80**, 032002 (2009).

[9] H. Aihara *et al*. (Belle Collaboration), *Phys. Rev. D* **85**, 112014 (2012).

[10] Y. Horii *et al*. (Belle Collaboration), *Phys. Rev. Lett*. **106**, 231803 (2011).

[11] A. Bondar and T. Gershon, *Phys. Rev. D* **70**, 091503 (2004).

[12] J. Charles *et al*. (CKMfitter Group), *Eur. Phys. J. C* **41** (2005), 1 and online update at http://ckmfitter.in2p3.fr/.

[13] Preliminary results presented at Lepton Photon 2011 (BELLE-CONF-1112) by the Belle collaboration.

[14] N. Lowrey *et. al.* (CLEO Collaboration), *Phys. Rev. D* **80**, 03115 (2009).

[15] M. Nayak *et. al.* (Belle Collaboration), arXiv: 1310.1741 (2013).