Measurements of $B^0 \to J/\psi \pi^0$ and other CP violating modes at Belle

Bilas Pal
Brookhaven National Laboratory, Upton, NY
(On behalf of the Belle Collaboration)

We report the recent measurements of $B^0 \to J/\psi \pi^0$ and other CP violation modes based on the data collected by the Belle experiment at the KEKB collider. The CP asymmetry parameters for the decay $B^0 \to J/\psi \pi^0$ have previously been measured by BaBar and Belle experiments, but the results of mixing induced CP asymmetry $|S| = -\eta_f \sin(2\phi_1)$ were not in good agreement with each other. Furthermore, the BaBar result lies outside the physically allowed region. Previous Belle measurements were based on $535 \times 10^6$ $B\bar{B}$ pairs. We updated the measurements using the final Belle data set of $772 \times 10^6$ $B\bar{B}$ pairs. The CP asymmetry parameters from a charmed $B^0 \to K^0 \pi^0 \pi^0$ decay using final Belle data set and measurement of $\cos(2\phi_1)$ in $B^0 \to D^{(*)} l^0 \nu$ using joint BaBar and Belle analysis are also discussed.

INTRODUCTION

In the standard model (SM) of electroweak interaction, charge-parity (CP) violation arises from an irreducible complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. The Belle and BaBar experiments have established CP violating effects in the $B$ meson system. Both experiments use their measurements of the mixing-induced CP violation in $b \to c\bar{c}s$ transitions to precisely determine the parameter $\sin(2\phi_1)$, where $\phi_1$ is defined as arg$[-V_{cd}V_{cb}/V_{td}V_{tb}]$, with $V_{ij}$ is the CKM matrix element of quarks $i$, $j$. In this proceeding an overview of recent measurements of the CKM angles $\phi_1$ is presented.

BRANCHING FRACTION AND CP ASYMMETRIES OF $B^0 \to J/\psi \pi^0$

At the quark level, the decay $B^0 \to J/\psi \pi^0$ proceeds via $b \to c\bar{d}$ “tree” and “penguin” amplitudes, as shown in Fig. 1. Both amplitudes are suppressed in the Standard Model (the first one is color- and Cabibbo-suppressed), and thus the branching fraction is small. The tree-level amplitude has the same weak phase as that of the $b \to c\bar{e}s$ amplitude governing, e.g., $B^0 \to J/\psi K^0_S$ decays, while the penguin amplitude has a different weak phase. The former dominates mixing-induced CP violation, while the addition of the latter gives rise to direct CP violation.

![Fig. 1: (a) Tree and (b) penguin amplitudes for the decay $B^0 \to J/\psi \pi^0$.](image)

In the process $\Upsilon(4S) \to B^0 \bar{B}^0$, one of the two $B$ mesons can decay into a CP eigenstate $f_{CP}$ at time $t_{CP}$, while the other can decay into a flavor-specific state $f_{tag}$ at time $t_{tag}$. The decay time evolution for the $B \to f_{CP}$ is [2]

$$P(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \times \left(1 + q[S \sin(\Delta m_d \Delta t) + A \cos(\Delta m_d \Delta t)]\right),$$

where $\Delta t = t_{CP} - t_{tag}$ is the difference in proper decay times between the two $B$ mesons; $q = +1 (-1)$ for signal $B^0$ ($\bar{B}^0$) decays; $\Delta m_d$ is the mass difference between the two mass eigenstates of the $B^0$-$\bar{B}^0$ system; and $\tau_{B^0}$ is the $B^0$ lifetime. The parameters $S$ and $A$ are CP-violating and characterize mixing-induced and direct CP violation, respectively. In the absence of the penguin amplitude, $A = 0$ and $S = -\eta_f \sin(2\phi_1)$, where $\eta_f$ is the CP eigenvalue of the final state (for $J/\psi \pi^0$ final state, $\eta_f = +1$). However, this amplitude and any new physics (NP) process having a different weak phase will shift $S$ and $A$ from these values. Thus, measuring these parameters provides a way to search for NP. The values of $S$ and $A$ measured in $B^0 \to J/\psi \pi^0$ decays can also be used to constrain the small penguin contribution to $B^0 \to J/\psi K^0_S$ decays [3–8]. This small contribution is important as the decay $B^0 \to J/\psi K^0_S$ provides the most precise determination of $\phi_1$.

The parameter $S$ for $B^0 \to J/\psi \pi^0$ has previously been measured by Belle [9] and BaBar [10], but the results are not in good agreement. The BaBar result lies outside the physically allowed region, but the uncertainties are large. The previous result from Belle was based on $535 \times 10^6$ $B\bar{B}$ pairs [9]. Here we update that measurement using the final Belle data set and measurement of $\cos(2\phi_1)$ in $B^0 \to D^{(*)} l^0 \nu$ using joint BaBar and Belle analysis, which is defined as anti-parallel to the $e^+$ beam direction. Since the $B^0$ and $\bar{B}^0$ mesons...
are approximately at rest in the $T(4S)$ center-of-mass (CM) system, $\Delta t$ is determined from the displacement in $z$ between the two $B$ decay vertices: $\Delta t = \Delta z/c^2\beta^2$. The vertex position for the $B^0 \to J/\psi \pi^0$ decay is reconstructed using lepton tracks from $J/\psi$ decays. We perform a vertex fit with a constraint to the interaction point (IP) profile. A vertex position for $f_{\text{tag}}$ is obtained using tracks that are not assigned to the $B^0 \to J/\psi \pi^0$ candidate, plus the IP constraint. This constraint allows for reconstruction of an $f_{\text{tag}}$ vertex even in cases when only one track candidate satisfies the requirement on SVD hits. We tag (identify) the flavor of the accompanying $B$ meson using inclusive properties of particles not associated with the signal $B^0 \to J/\psi \pi^0$ decay. The algorithm for flavor tagging is described in Ref. [13]. We divide this background into three categories: (a) $B^0 \to J/\psi K^0_S$, (b) $B^0 \to J/\psi K^0_L$, and (c) $B \to J/\psi X$ other than $B^0 \to J/\psi K^0$. The rest of the background comes from continuum $q\bar{q}$ ($q = u,d,s,c$) events.

We determine $S$ and $A$ by performing an unbinned maximum likelihood fit to the $\Delta t$ distribution of candidate events in the signal region. The PDF for the signal component, $P_{\text{sig}}(\Delta t; S, A, q, \omega_l, \Delta \omega_l)$, is given by Eq. (1) with the parameters $\tau_{\text{PID}}$ and $\Delta m_q$ fixed to the world-average values [16]. We modify this expression to take into account the effect of incorrect flavor assignment, which is parametrized by $\omega_l$ and $\Delta \omega_l$. This PDF is then convolved with the decay-time resolution function $R_{\text{sig}}(\Delta t)$. The resolution function is itself a convolution of four components: the detector resolutions for $z_{J/\psi \pi 0}$ and $z_{\text{tag}}$; the shift of the $z_{\text{tag}}$ vertex position due to secondary tracks from charmed particle decays; and the kinematic approximation that the $B$ mesons are at rest in the CM frame [15]. The PDFs for $B^0 \to J/\psi K^0_s$ and $B^0 \to J/\psi K^0_L$ backgrounds are the same as $P_{\text{sig}}$ but with CP parameters $A$ and $S$ fixed to the recent Belle results [15]. The PDF for $B \to J/\psi X$ background is taken to have the same form as $P_{\text{sig}}$ but with $A$ and $S$ set to zero, and with an effective lifetime $\tau_{\text{eff}}$ determined from MC simulation. The PDF for continuum background is taken to be the sum of two Gaussian functions whose parameters are obtained by fitting events in the sideband region $5.20 \text{ GeV}/c^2 < M_{bc} < 5.26 \text{ GeV}/c^2$ and $0.10 \text{ GeV} < \Delta E < 0.50 \text{ GeV}$. Figure 3 shows the fitted $\Delta t$ distribution and the time-dependent decay rate asymmetry $A_{CP}$, where

$$A_{CP} = \frac{Y_{\text{sig}}^{(q=+1)} - Y_{\text{sig}}^{(q=-1)}}{Y_{\text{sig}}^{(q=+1)} + Y_{\text{sig}}^{(q=-1)}},$$

where $Y_{\text{sig}}^{(q=\pm 1)}$ is the signal yield with $q = \pm 1$.

We measure

$$B = (1.62 \pm 0.11 \pm 0.07) \times 10^{-5},$$

$$S = -0.59 \pm 0.19 \pm 0.03,$$

$$A = -0.15 \pm 0.14^{+0.04}_{-0.03},$$

where the first uncertainty is statistical and the second is systematic. The measured value for the branching fraction is the most precise value to date and supersedes the previous measurement [14]. It is consistent with measurements made by other experiments [10, 17]. The measured CP asymmetries are consistent with, and supersede, our previous results [9]. The direct CP asymmetry $A$ is consistent with zero. The mixing-induced CP asymmetry $S$ differs from zero (i.e., no CP violation) by 3.0 standard deviations, and it differs from the BaBar result [10] (which is outside the physical region) by 3.2 standard deviations. The value is consistent with the value of sin $2\alpha_1$ measured using $b \to c\bar{s}s$ decays [18]. These re-
The three-body charmless hadronic $B^0$ decays to a CP-even final state $K_S^0\pi^0\pi^0$ mainly proceed via a $b \to d\bar{s}s$ “penguin” transition. Measurements of $\sin(2\phi_1^{\text{eff}})$ from such decays are generally sensitive to new physics effects, since the new particles in several extensions of the SM may appear as virtual contributions in the loop. We note that there is a $b \to u\bar{t}n\bar{s}$ tree amplitude also contribute to this decay and can shift $\phi_1^{\text{eff}}$ from $\phi_1$. However, this amplitude is doubly Cabibbo-suppressed, and thus the resulting shift is small [19]. Previously, BaBar collaboration studied this decay and measured $\sin(2\phi_1^{\text{eff}}) = -0.72 \pm 0.71 \pm 0.08$ [20]; the sign is opposite to the expectation from the SM, although the statistical uncertainty is large. Here we present the first such measurement using the final Belle data sample [21], which is 3.4 times larger than that of the BaBar.

Since no charged tracks from the decay point of the $B^0$ decays into the CP eigenstate of $K_S^0\pi^0\pi^0$, the vertex is determined from the direction of $K_S^0$ and the constraint from IP. From a fit to the variables of kinematic and continuum suppression, we extract $146.7 \pm 23.6$ signal events. The projections of the fit are shown in Fig. 4. The dominant source of background originates from continuum events. To suppress this background, which tend to be jet-like from spherical $B\bar{B}$ events, a likelihood ratio is calculated using the so-called event shape variables. The remaining background originates from $B\bar{B}$ events. From a fit to the $\Delta t$ (see Fig. 5), we obtain $\sin(2\phi_1^{\text{eff}}) = 0.92^{+0.27}_{-0.31} \pm 0.11$, $A = 0.28 \pm 0.21 \pm 0.04$, where the first uncertainty is statistical and the second is systematic. The value of $S$ is consistent with the value measure from decays mediated by $b \to c\bar{s}s$ transition [18]. The value of $A$ is consistent with zero, i.e., no direct CP violation, as expected in the SM.

### 3.4. Time-dependent asymmetry $A_{CP}$ (see text)

The value of $A_{CP}$ is consistent with zero, i.e., no direct CP violation, as expected in the SM.
the time evolution of the $K^0$ enables measurements of both $\sin(2\phi_1)$ as a function of the three-body Dalitz plot phase space. Knowledge of the variations on the relative strong phase mediates CP violation in the three-body final state from a rich variety of intermediate $CP$ eigenstates and quasi-flavor-specific decays. Recent measurements of $B^0 \to J/\psi \pi^0$ and other $CP$ violating modes ($B^0 \to K^{(*)} \pi^0 \pi^0$ and $B^0 \to D^{(*)} h^0$) using the final dataset of Belle experiments ($B^0 \to D^{(*)} h^0$ analysis is performed using combined BaBar and Belle dataset) are presented. The results of $\sin(2\phi_1)$ from all the three decay modes are consistent with the $\sin(2\phi_1)$ measured in $b \to c\tau\bar{\nu}$ processes. The measurement of $\cos(2\phi_1)$ in $B^0 \to D^{(*)} h^0$ resolves the ambiguity in the determination of the apex of the CKM Unitarity Triangle.

**Acknowledgement:** The author thanks the workshop organizers for hosting a fruitful and stimulating workshop and providing excellent hospitality. This research is supported by the U.S. Department of Energy.

[1] N. Cabibbo, Phys. Rev. Lett. 10, 531 (1963); M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49, 652 (1973).
FIG. 6: Data distributions for (a) $M_{bc}$, (b) $\Delta E$, and (c) $C_{NN}$ (points with error bars) for the BaBar and Belle data samples combined. The solid black lines represent projections of the total fit function, and the colored dotted lines show the signal and background components of the fit as indicated in the legend. In plotting the distributions, each of the other two observables are required to satisfy $M_{bc} > 5.272 \text{ GeV}/c^2$, $|\Delta E| < 100 \text{ MeV}$, or $0 < C_{NN} < 8$ to select signal-enhanced regions.

FIG. 7: Distributions of the proper time interval (data points with error bars) and the corresponding asymmetries for $B_0^0 \rightarrow D^{(*)+} h^0$ candidates associated with high quality flavor tags for two different regions of the $D \rightarrow K^{0}\pi^{+}\pi^{-}$ phase space and for the BaBar and Belle data samples combined. The background has been subtracted using the sPlot technique, with weights obtained from the fit presented in Fig. 6.

[2] A. B. Carter and A. I. Sanda, CP violation in B meson decays, Phys. Rev. D 23, 1567 (1981); I. I. Y. Bigi and A. I. Sanda, Notes on the observability of CP violations in B decays, Nucl. Phys. B 193, 85 (1981).

[3] S. Faller, M. Jung, R. Fleischer and T. Mannel, The golden modes $B_0^0 \rightarrow J/\psi K_{S,L}$ in the era of precision flavor physics, Phys. Rev. D 79, 014030 (2009) [arXiv:0809.0842 [hep-ph]].

[4] M. Jung, Determining weak phases from $B \rightarrow J/\psi P$ decays, Phys. Rev. D 86, 053008 (2012) [arXiv:1206.2050 [hep-ph]].

[5] K. De Bruyn and R. Fleischer, A roadmap to control penguin effects in $B_d \rightarrow J/\psi K_{S}^{0}$ and $B\bar{d} \rightarrow J/\psi \phi$, JHEP 1503, 145 (2015) [arXiv:1412.6834 [hep-ph]].

[6] Z. Ligeti and D. J. Robinson, Towards more precise determinations of the quark mixing phase $\beta$, Phys. Rev. Lett. 115, 251801 (2015) [arXiv:1507.06671 [hep-ph]].

[7] M. Ciuchini, M. Pierini and L. Silvestrini, The Effect of penguins in the $B_0 \leftrightarrow J/\psi K^0_S$ and $B_0^+ \leftrightarrow J/\psi \phi$ CP asymmetry, Phys. Rev. Lett. 95, 221804 (2005) [hep-ph/0507290].

[8] P. Frings, U. Nierste and M. Wiebusch, Penguin contributions to CP phases in $B_{d,s} \rightarrow J/\psi h^0$ decays to charmonium, Phys. Rev. Lett. 115, 061802 (2015) [arXiv:1503.00859 [hep-ph]].
[16] Y. Amhis et al. (Heavy Flavor Averaging Group Collaboration), Averages of $b$-hadron, $c$-hadron, and $\tau$-lepton properties as of summer 2016, Eur. Phys. J. C 77, 895 (2017) [arXiv:1612.07233 [hep-ex]].

[17] P. Avery et al. (CLEO Collaboration), Study of exclusive two-body $B^0$ meson decays to charmonium, Phys. Rev. D 62, 051101 (2000) [hep-ex/0004032].

[18] M. Tanabashi et al. (Particle Data Group), Review of Particle Physics, Phys. Rev. D 98, 030001 (2018).

[19] H. Y. Cheng, Theoretical issues with $\Delta S$ in three-body $B$ decays, [hep-ph/0702252 [hep-ph]].

[20] B. Aubert et al. (BaBar Collaboration), Measurement of $CP$ asymmetry in $B^0 \to K_S \pi^0 \pi^0$ decays, Phys. Rev. D 76, 071101 (2007) [hep-ex/0702010].

[21] Y. Yusa et al. (Belle Collaboration), Measurement of time-dependent $CP$ violation in $B^0 \to K_S^0 \pi^0 \pi^0$ decays, [arXiv:1810.03336 [hep-ex]].

[22] I. Adachi et al. (BaBar and Belle Collaborations), First evidence for $\cos 2\beta > 0$ and resolution of the CKM Unitarity Triangle ambiguity by a time-dependent Dalitz plot analysis of $B^0 \to D^{(*)}h^0$ with $D \to K^0_S \pi^+ \pi^-$ decays, [arXiv:1804.06152 [hep-ex]].

[23] A. Bondar, T. Gershon and P. Krokovny, A Method to measure $\phi_1$ using $B^0 \to Dh^0$ with multibody $D$ decay, Phys. Lett. B 624, 1 (2005) [hep-ph/0503174].