Improved Measurements of Direct CP Violation in $B \to K^+\pi^-$, $K^+\pi^0$ and $\pi^+\pi^0$ Decays

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Abstract

We report an improved measurement of direct CP violation in the decay $B^0 \to K^+\pi^-$, and a search for CP violation in the decays $B^+ \to K^+\pi^0$ and $B^+ \to \pi^+\pi^0$. The measured CP violating asymmetries are $A_{CP}(K^+\pi^-) = -0.113 \pm 0.022\text{(stat.)} \pm 0.008\text{(syst.)}$, $A_{CP}(K^+\pi^0) = 0.04 \pm 0.04\text{(stat.)} \pm 0.02\text{(syst.)}$ and $A_{CP}(\pi^+\pi^0) = 0.02 \pm 0.08\text{(stat.)} \pm 0.01\text{(syst.)}$, where the latter correspond to the intervals $-0.03 < A_{CP}(K^+\pi^0) < 0.11$ and $-0.12 < A_{CP}(\pi^+\pi^0) < 0.15$ at 90% confidence level. These results are obtained from a data sample that contains 386 million $B\bar{B}$ pairs that was collected near the $\Upsilon(4S)$ resonance, with the Belle detector at the KEKB asymmetric energy $e^+e^-$ collider. All of the results are preliminary.

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In the Standard Model (SM) CP violation arises via the interference of at least two diagrams with comparable amplitudes but different CP conserving and violating phases. Mixing induced CP violation in the B sector has been established in $b \to c\bar{c}s$ transitions \[1, 2\]. Direct CP violation is expected to be sizeable in the B meson system \[3\]. The first experimental evidence for direct CP violation was shown by Belle for the decay mode $B^0 \to \pi^+\pi^-$ \[4\]. This result suggests large interference between tree and penguin diagrams and the existence of final state interactions \[5\]. In addition, both Belle \[6\] and BABAR \[7\] have recently reported evidence for direct CP violation in the decay $B^0 \to K^+\pi^-$. The partial rate CP violating asymmetry is defined as:

$$A_{CP} = \frac{N(\bar{B} \to f) - N(B \to f)}{N(\bar{B} \to f) + N(B \to f)},$$

where $N(\bar{B} \to f)$ is the yield for the $\bar{B} \to K\pi/\pi\pi$ decay and $N(B \to f)$ denotes that of the charge-conjugate mode. Theoretical predictions with different approaches suggest that $A_{CP}(K^+\pi^-)$ could be either positive or negative \[8\]. Although there are large uncertainties related to hadronic effects in the theoretical predictions, results for $A_{CP}(K^+\pi^-)$ and $A_{CP}(K^+\pi^0)$ are expected to have the same sign and comparable magnitudes \[8\]. However, our previous measurements show that $A_{CP}(K^+\pi^-)$ and $A_{CP}(K^+\pi^0)$ are opposite in sign (although $A_{CP}(K^+\pi^0)$ is consistent with no asymmetry), and their central values are found to deviate from each other by 2.4σ. These findings are consistent with those reported by BABAR \[9\]. It is suggested that the disagreement may be due to the contribution of the electroweak penguin process or other mechanisms \[10\]. Therefore, it is important to verify whether the discrepancy persists with improved precision. In this Letter, we report $A_{CP}$ measurements using 386 million $B\bar{B}$ pairs collected with the Belle detector at the KEKB $e^+e^-$ asymmetric-energy (3.5 on 8 GeV) collider \[11\] operating at the $\Upsilon(4S)$ resonance.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electro-magnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a super-conducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect $K^0_S$ mesons and to identify muons (KLM). The detector is described in detail elsewhere \[12\]. Two inner detector configurations were used. For the first sample of 152 million $B\bar{B}$ pairs (Set I), a 2.0 cm radius beampipe and a 3-layer silicon vertex detector were used; for the latter 234 million $B\bar{B}$ pairs (Set II), a 1.5 cm radius beampipe, a 4-layer silicon detector and a small-cell inner drift chamber were used \[13\].

The $B$ candidate selection is the same as that described in Ref. \[14\]. Charged tracks are required to originate from the interaction point (IP). Charged kaons and pions are identified using $dE/dx$ information and Čerenkov light yields in the ACC. The $dE/dx$ and ACC information are combined to form a $K$-π likelihood ratio, $R(K\pi) = L_K/(L_K + L_\pi)$, where $L_{K/\pi}$ is the likelihood of kaon/pion. Charged tracks with $R(K\pi) > 0.6$ are regarded as kaons and $R(K\pi) < 0.4$ as pions. Furthermore, charged tracks that are positively identified as electrons are rejected. The $K/\pi$ identification efficiencies and misidentification rates are determined from a sample of kinematically identified $D^{*+} \to D^0\pi^+, D^0 \to K^-\pi^+$ decays. Table \[1\] shows the results. It is clear that the detection efficiency for $K^+/\pi^+$ is greater than for $K^-/\pi^-; this small efficiency bias will be corrected in the $A_{CP}$ measurement.

Candidate $\pi^0$ mesons are reconstructed by combining two photons with invariant mass
TABLE I: Performance of \( K - \pi \) identification measured using \( D^{*+} \rightarrow D^0\pi^+, D^0 \rightarrow K^-\pi^+ \) decays.

|        | Set I |        |        |
|--------|-------|--------|--------|
|        | Eff. (%) | Fake rate (%) | Eff. (%) | Fake rate (%) |
| \( K^+ \) | 83.76 ± 0.18 | 5.10 ± 0.12 | 81.92 ± 0.15 | 6.29 ± 0.10 |
| \( K^- \) | 84.76 ± 0.18 | 5.69 ± 0.12 | 82.79 ± 0.14 | 6.71 ± 0.10 |
| \( \pi^+ \) | 91.24 ± 0.15 | 10.72 ± 0.15 | 89.88 ± 0.12 | 12.28 ± 0.12 |
| \( \pi^- \) | 90.53 ± 0.15 | 10.08 ± 0.15 | 89.08 ± 0.13 | 11.83 ± 0.12 |

between 115 MeV/\( c^2 \) and 152 MeV/\( c^2 \), which corresponds to \( \pm 2.5 \) standard deviations. Each photon is required to have a minimum energy of 50 MeV in the barrel region (32° < \( \theta_\gamma \) < 129°) or 100 MeV in the end-cap region (17° < \( \theta_\gamma \) < 32° or 129° < \( \theta_\gamma \) < 150°), where \( \theta_\gamma \) denotes the polar angle of the photon with respect to the beam line. To further reduce the combinatorial background, \( \pi^0 \) candidates with small decay angles (\( \cos \theta^* > 0.95 \)) are rejected, where \( \theta^* \) is the angle between a \( \pi^0 \) boost direction from the laboratory frame and its \( \gamma \) daughters in the \( \pi^0 \) rest frame.

Two variables are used to identify \( B \) candidates: the beam-constrained mass, \( M_{bc} = \sqrt{E_{beam}^2 - p_B^2} \), and the energy difference, \( \Delta E = E_B^* - E_{beam}^* \), where \( E_{beam}^* \) is the beam energy and \( E_B^* \) and \( p_B^* \) are the reconstructed energy and momentum of the \( B \) candidates in the center-of-mass (CM) frame. Events with \( M_{bc} > 5.20 \) GeV/\( c^2 \) and \( -0.3 \) GeV < \( \Delta E \) < 0.5 GeV are selected for the final analysis.

The dominant background is from \( e^+e^- \rightarrow q\bar{q} \) (\( q = u, d, s, c \)) continuum events. To distinguish the signal from the jet-like continuum background, event topology variables and \( B \) flavor tagging information are employed. We combine a set of modified Fox-Wolfram moments \[13\] into a Fisher discriminant. The probability density functions (PDF) for this discriminant, and the cosine of the angle between the \( B \) flight direction and the \( z \) axis, are obtained using signal and continuum Monte Carlo (MC) events. These two variables are then combined to form a likelihood ratio \( R = L_s/(L_s + L_q\bar{q}) \), where \( L_s(q\bar{q}) \) is the product of signal (\( q\bar{q} \)) probability densities. Additional background discrimination is provided by \( B \) flavor tagging. The standard Belle flavor tagging algorithm \[14\] gives two outputs: a discrete variable indicating the flavor of the tagging \( B \) and the MC-determined dilution factor \( r \), which ranges from zero for no flavor information to unity for unambiguous flavor assignment. An event that contains a lepton (\( r \) close to unity) is more likely to be a \( B\bar{B} \) event so a looser \( R \) requirement can be applied. We divide the data into \( r > 0.5 \) and \( r < 0.5 \) regions. The continuum background is reduced by applying a selection requirement on \( R \) for events in each \( r \) region of Set I and Set II according to the figure-of-merit defined as \( N_{s}\text{exp}/\sqrt{N_{s}\text{exp} + N_{q\bar{q}}\text{exp}} \), where \( N_{s}\text{exp} \) denotes the expected signal yields based on our previous branching fraction measurements \[14\] and \( N_{q\bar{q}}\text{exp} \) denotes the expected \( q\bar{q} \) yields from sideband data (\( M_{bc} < 5.26 \) GeV/\( c^2 \)). A typical requirement suppresses 92--99% of the continuum background while retaining 48--67% of the signal.

Backgrounds from \( \Upsilon(4S) \rightarrow B\bar{B} \) events are investigated using a large MC sample. After the \( R \) requirement, we find a small charmless three-body background at low \( \Delta E \), and reflections from other \( B^0 \rightarrow \pi^+\pi^- \) decays due to \( K^-\pi^- \) misidentification.

The signal yields are extracted by applying unbinned two dimensional maximum likelihood (ML) fits to the \( (M_{bc}, \Delta E) \) distributions of the \( B \) and \( \bar{B} \) samples. The likelihood for
Discrepancies between the signal peak positions in data and MC are calibrated using of the signals; hence, their PDFs are described by smoothed two-dimensional histograms. A large MC sample is used to investigate the background from charmless mesons. The parameters that describe the shape of the signal PDFs are fixed in all categories, which, in turn, corresponds to either signal, \( q \bar{q} \) continuum, a reflection due to \( K-\pi \) misidentification, or background from other charmless three-body \( B \) decays.

The yields and asymmetries for the signal and backgrounds are allowed to float in all modes. Since the \( K^+\pi^0 \) and \( \pi^+\pi^0 \) reflections are difficult to distinguish with \( \Delta E \) and \( M_{bc} \), we fit these two modes simultaneously with a fixed reflection-to-signal ratio based on the measured \( K-\pi \) identification efficiencies and fake rates. All the signal PDFs (\( P(M_{bc},\Delta E) \)) are obtained using MC simulations based on the Set I and Set II detector configurations. The same signal PDFs are used for events in two different \( r \) regions. No strong correlations between \( M_{bc} \) and \( \Delta E \) are found for the \( B \to K^+\pi^- \) signal. Therefore, its PDF is modeled by a product of a single Gaussian for \( M_{bc} \) and a double Gaussians for \( \Delta E \). For the modes with a \( \pi^0 \) meson in the final state, there are correlations between \( M_{bc} \) and \( \Delta E \) in the tails of the signals; hence, their PDFs are described by smoothed two-dimensional histograms. Discrepancies between the signal peak positions in data and MC are calibrated using \( B^+ \to \bar{D}^0\pi^+ \) decays, where the \( \bar{D}^0 \to K^+\pi^-\pi^0 \) sub-decay is used for the modes with a \( \pi^0 \) meson while \( \bar{D}^0 \to K^+\pi^- \) is used for the \( K^+\pi^- \) mode. The MC-predicted \( \Delta E \) resolutions are verified using the invariant mass distributions of high momentum \( D \) mesons. The decay mode \( \bar{D}^0 \to K^+\pi^- \) is used for \( B^0 \to K^+\pi^- \), and \( \bar{D}^0 \to K^+\pi^-\pi^0 \) for the modes with a \( \pi^0 \) in the final state. The parameters that describe the shape of the signal PDFs are fixed in all of the fits.

The continuum background in \( \Delta E \) is described by a first or second order polynomial while the \( M_{bc} \) distribution is parameterized by an Argus function \( f(x) = x\sqrt{1-x^2} \exp[-\xi(1-x^2)] \), where \( x = M_{bc} \) divided by half of the total center of mass energy. The continuum PDF is the product of an Argus function and a polynomial, where parameters \( \xi \) and the coefficients of the polynomial are free parameters. These free parameters are \( r \)-dependent. A large MC sample is used to investigate the background from charmless \( B \) decays and a smoothed two-dimensional histogram is taken as the PDF. The functional forms of the PDFs are the same for the \( B \) and \( \bar{B} \) samples.

The efficiency of particle identification is slightly different for positively and negatively charged particles; consequently, the parameter \( \mathcal{A}_{CP} \) in Eq.3 becomes an effective partial rate asymmetry. For the \( K^+\pi^0 \) and \( \pi^+\pi^0 \) modes, this raw asymmetry can be expressed as:

\[
\mathcal{A}_{CP}^{raw} = \frac{\mathcal{A}_t + \mathcal{A}_{CP}}{1 + \mathcal{A}_t \mathcal{A}_{CP}},
\]

where \( \mathcal{A}_{CP} \) is the true partial rate asymmetry and the efficiency asymmetry \( \mathcal{A}_t \) is the efficiency difference between \( K^-\pi^+ \) and \( K^+\pi^- \) divided by the sum of their efficiency. The situation is more complicated for the \( K^+\pi^- \) mode because, in addition to the bias due to the efficiency difference between \( K^-\pi^+ \) and \( K^+\pi^- \), a \( K^-\pi^+ \) signal event can be doubly misidentified as a \( K^+\pi^- \) candidate and dilute \( \mathcal{A}_{CP} \). The efficiency asymmetry results in a
\( A_{CP} \) bias of +0.01, while the small dilution factor due to double misidentification reduces the \( A_{CP} \) by a factor of 0.98.

Table II shows the signal yields and \( A_{CP} \) values for each mode. The asymmetries for the background components are consistent with zero within errors. Projections of the fits are shown in Figs.1-3. The systematic errors from fitting are estimated from the deviations in \( A_{CP} \) after varying each parameter of the signal PDFs by 1 standard deviation. The uncertainty in modeling the three-body background is studied by excluding the low \( \Delta E \) region.
FIG. 2: $M_{bc}$ (top) and $\Delta E$ (bottom) distributions for $B^- \rightarrow K^-\pi^0$ (left) and $B^+ \rightarrow K^+\pi^0$ (right) candidates. The curves are described in the caption of Fig.1.

(< −0.12 GeV) and repeating the fit. Systematic uncertainty due to particle identification is estimated by repeating the fit after varying the $K/\pi$ efficiencies and fake rates by 1 standard deviation. At each step, the deviation in $A_{CP}$ is added in quadrature to provide the systematic errors, which are less than 0.01 for all modes. A possible bias from the fitting procedure is checked in MC and a bias due to the $R$ requirement is investigated using the $B^+ \rightarrow D^0\pi^+$ samples. No significant bias is observed. The systematic uncertainties due to the detector bias are tested using the fit results for the continuum background listed in Table.III. We find a small background asymmetry dependence on the $R$ requirement for the $K^+\pi^-$ mode, and assign the uncertainty from the fit result of the $B^+ \rightarrow D^0\pi^+ (D^0 \rightarrow K^+\pi^-)$
TABLE II: Fitted signal yields, $A_{CP}$ results, and background asymmetries for individual modes.

| Mode    | Signal Yield | $A_{CP}$    | Bkg $A_{CP}$ |
|---------|--------------|-------------|--------------|
| $K^{+}\pi^{\pm}$ | 3026 ± 63  | -0.113 ± 0.022 ± 0.008 | -0.001 ± 0.004 |
| $K^{+}\pi^{0}$  | 1084 ± 45  | +0.04 ± 0.04 ± 0.02  | -0.02 ± 0.01   |
| $\pi^{+}\pi^{0}$ | 454 ± 36  | +0.02 ± 0.08 ± 0.01  | -0.01 ± 0.01   |

sample (±0.007) as the systematic uncertainty due to detector bias. The final systematic errors are then obtained by quadratically summing the errors due to the detector bias and the fitting systematics.

The partial rate asymmetry $A_{CP}(K^{+}\pi^{-})$ is found to be $-0.113 \pm 0.022 \pm 0.008$. The significance including the effect of systematic uncertainty is $4.9\sigma$. This result supersedes our previous measurement $^3$ and remains consistent with the value reported by BABAR, $A_{CP}(K^{+}\pi^{-}) = -0.133 \pm 0.030 \pm 0.009$. The observed $A_{CP}(K^{+}\pi^{0})$ value is consistent with zero at the current level of statistical precision. The difference between the results for $A_{CP}(K^{+}\pi^{-})$ and $A_{CP}(K^{+}\pi^{0})$ persists; their central values differ by 3.1$\sigma$. This suggests a possible contribution from the electroweak penguin process or other mechanisms $^6$. No evidence of direct CP violation is observed in the decay $B^{+} \rightarrow \pi^{+}\pi^{0}$. We set 90% C.L. intervals: $-0.03 < A_{CP}(K^{+}\pi^{0}) < 0.11$ and $-0.12 < A_{CP}(\pi^{+}\pi^{0}) < 0.15$. All of the above results are preliminary.

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FIG. 3: $M_{bc}$ (top) and $\Delta E$ (bottom) distributions for $B^- \rightarrow \pi^- \pi^0$ (left) and $B^+ \rightarrow \pi^+ \pi^0$ (right) candidates. The curves are described in the caption of Fig. 1.
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