Improved Measurement of the Partial-Rate CP Asymmetry in $B^+ \rightarrow K^0\pi^+$ and $B^- \rightarrow \bar{K}^0\pi^-$ Decays

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We report an improved measurement of the partial-rate CP asymmetry in $B^{\pm} \to K^{(--)0} \pi^{\pm}$ decays. The analysis is based on a data sample of 85 million $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB $e^+e^-$ storage ring. We measure $A_{CP}(K^{(--)0} \pi^{\pm}) = 0.07^{+0.09}_{-0.08} - 0.03^{+0.01}_{-0.02}$, where the first and second errors are statistical and systematic, respectively; the corresponding 90% confidence-level interval is $-0.10 < A_{CP}(K^{(--)0} \pi^{\pm}) < 0.22$.

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In the Kobayashi-Maskawa (KM) model $^1$, CP violation arises from a complex phase in the quark-mixing matrix of the weak interaction. This idea is strongly supported by the observation of mixing-induced CP violation at the $B$-factories $^2$. Direct CP violation (DCPV) is also expected in the KM scheme and has been observed in the $K$ meson system $^3$. However, DCPV has not yet been observed in the $B$ meson system.

Charmless hadronic $B$ decays can provide opportunities to observe DCPV $^4, ^5, ^6, ^7, ^8$. Many of these decays include contributions from both $b \to u$ tree and $b \to s$ penguin diagrams and the interference between these two processes can produce a partial-rate CP asymmetry:

$$A_{CP} = \frac{\Gamma(B \to f) - \Gamma(B \to f^{\text{c.c.}})}{\Gamma(B \to f) + \Gamma(B \to f^{\text{c.c.}})} = \frac{2|A_T||A_P| \sin \delta \sin \phi}{|A_T|^2 + |A_P|^2 + 2|A_T||A_P| \cos \delta \cos \phi}.$$ 

Here $\Gamma(B \to f)$ denotes the partial width of either a $B^0$ or $B^+$ meson decaying into a flavor-specific final state $f$ and $\Gamma(B \to f^{\text{c.c.}})$ represents that of the charge conjugate decay; $A_T$ and $A_P$ represent the tree and penguin amplitudes; and
δ and φ stand for the CP-conserving and CP-violating relative phases, respectively, between \( A_T \) and \( A_P \). In order to have a sizable \( A_{CP} \), both phase differences have to be non-zero, i.e. \( \delta \neq 0 \) and \( \phi \neq 0 \), and the tree and penguin amplitudes should be of comparable size \( (|A_T| \sim |A_P|) \).

The decay \( B^+ \to \bar{K}^0 \pi^+ \) is almost a pure \( b \to s \) penguin process and, thus, no sizable asymmetry is expected in the context of the Standard Model (SM) \(^8\). However, our previously published result, based on an analysis of a 29 fb\(^{-1}\) data sample, was \( A_{CP}(\bar{K}^0 \pi^+) = 0.46 \pm 0.15 \pm 0.02 \) \(^9\). An asymmetry of this magnitude cannot be explained in the SM, even with the inclusion of interference of the basic penguin amplitude with a large \( B^+ \to (K^+ \pi^0)_{tree} \to \bar{K}^0 \pi^+ \) re-scattering process \(^11\), and would be an indication of a new physics contribution in the penguin loop \(^12\). It is important to verify whether the central value persists with improved precision.

In this paper, we report an updated measurement of the partial-rate CP asymmetry in \( B^+ \to \bar{K}^0 \pi^+ \) decays based on a 78 fb\(^{-1}\) data sample collected at the \( \Upsilon(4S) \) resonance, corresponding to 85.0 ± 0.5 million \( B \overline{B} \) pairs, with the Belle detector \(^13\) at the KEKB \( e^+e^- \) storage ring \(^14\). This is approximately three times as much data as the sample that was used for the previous measurement and significantly improves the statistical precision. Throughout this paper, the partial-rate CP asymmetry \( A_{CP}(\bar{K}^0 \pi^+) \) is defined as

\[
A_{CP}(\bar{K}^0 \pi^+) = \frac{N(K_0^0 \pi^-) - N(K_0^0 \pi^+)}{N(K_0^0 \pi^-) + N(K_0^0 \pi^+)},
\]

where \( N(K_0^0 \pi^-) \) denotes the yield of \( B^- \to K_0^0 \pi^- \) decay and \( N(K_0^0 \pi^+) \) represents that of the charge conjugate mode.

The Belle detector is a large-solid-angle spectrometer that consists of a three-layer silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of threshold Čerenkov counters with silica aerogel radiators (ACC), time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect \( K_S^0 \) mesons and to identify muons (KLM). A detailed description of the Belle detector can be found elsewhere \(^13\).

The analysis procedure is the same as described in Ref. \(^8\). Candidate \( B^\pm \) mesons are reconstructed using high momentum \( \pi^\pm \) and \( K^\pm \) mesons. For candidate \( \pi^\pm \) mesons, charged tracks are required to originate from the interaction region based on their impact parameters.

In Belle, high momentum \( \pi^\pm \) and \( K^\pm \) mesons are distinguished by their associated Čerenkov light yield \((N_{p.e.})\) in the ACC and the ionization energy loss \((dE/dx)\) in the CDC. These quantities are used to form a particle identification (PID) likelihood ratio \( R_\pi = L_\pi/(L_\pi + L_K) \), where \( L_\pi \) denotes the product of the individual likelihoods of \( N_{p.e.} \) and \( dE/dx \) for \( \pi^\pm \) mesons; \( L_K \) is the product for \( K^\pm \) mesons. For the \( R_\pi \) requirement used in this analysis, \( \pi^\pm \) mesons are identified with an efficiency of 91% and there is a 10% \( K^\pm \) misidentification rate. The efficiency and fake rate are estimated by comparing the \( \bar{D} \) yields in a sample of \( D^+ \)-tagged \( \bar{D} \) decays before and after the application of the high momentum PID requirements. A similar likelihood ratio that also includes the energy deposit in the ECL is used to identify electrons; positively identified electrons are rejected. Candidate \( K_S^0 \) mesons are reconstructed using pairs of oppositely charged tracks that have an invariant mass \((m_{\pi\pi})\) in the range \( 480 < m_{\pi\pi} < 516 \text{ MeV}/c^2 \). A candidate must have a displaced vertex and flight direction consistent with a \( K_S^0 \) originating from the IP.

Signal candidates are identified using the beam-energy constrained mass \( m_{bc} = \sqrt{E_{beam}^2 - p_T^2} \) and the energy difference \( \Delta E = E_B^* - E_{beam} \), where \( E_{beam} = 5.29 \text{ GeV} \) and \( p_T \) and \( E_B^* \) are the momentum and energy of the reconstructed \( B \) meson in the \( e^+e^- \) center-of-mass frame.

The dominant background comes from the \( e^+e^- \to q\overline{q} \) \((q = u, d, s, c)\) continuum process; backgrounds from \( b \to c \) decays are negligible because the momenta of the decay products are smaller than those of the signal \( K_S^0 \) and \( \pi^\pm \). We discriminate the signal from the \( q\overline{q} \) background by the event topology. This is quantified by the Super-Fox-Wolfram (SFW) variable \(^2\), which is formed from modified Fox-Wolfram moments that are combined using a Fisher discriminant \(^16\) into a single variable. The angle of the \( B \)-meson’s flight direction with respect to the beam axis \((\theta_B)\) provides additional discrimination. A likelihood ratio \( R_s = L_s/(L_s + L_{\overline{q}\overline{q}}) \) is calculated, where \( L_s \) \((L_{\overline{q}\overline{q}})\) denotes the product of the individual SFW and \( \theta_B \) likelihoods for signal \((q\overline{q})\) background. The probability density functions (PDFs) are derived from GEANT-based Monte Carlo (MC) simulations \(^17\) for the signal and \( m_{bc} \) sideband \((5.2 < m_{bc} < 5.26 \text{ GeV}/c^2)\) data for the \( q\overline{q} \) background. We make a requirement on \( R_s \) that eliminates 88% of the \( q\overline{q} \) background while retaining 73% of the signal.

Signal yields are extracted from the \( \Delta E \) distributions of events in the \( m_{bc} \) signal region \((5.271 < m_{bc} < 5.287 \text{ GeV}/c^2)\), separately for the \( K_S^0 \) and \( K_S^0 \) final states. The signal reconstruction efficiency \(^18\) is estimated to be 12% based on the MC. The \( \Delta E \) distributions are fitted using a binned maximum likelihood fit with three components: the signal, \( q\overline{q} \) background, and other charmless \( B \) decays, as shown in Fig. \(^1\). The signal PDF
is modeled with a Gaussian distribution taken from the signal MC and calibrated using a $B^\pm \to \bar{D}^0(\to K^{\pm}\pi^\mp)\pi^\pm$ sample where a similar reconstruction procedure is applied. For the $q\bar{q}$ background, the PDF is modeled with a second-order polynomial with a shape that is determined from the $m_{bc}$ sideband data. For other charmless $B$ decays, the PDF is taken from a smoothed histogram of a large MC sample. (The enhancement in the lower $\Delta E$ region is due to charmless $B$ decay modes with an additional $\pi$ meson.) Except for the signal peak positions, the same PDF shape parameters are used for both $B^+$ and $B^-$ samples. The signal peak positions are determined separately for the $B^+$ and $B^-$ samples since a small systematic difference between the two samples is observed. (This is discussed below.) In the fit procedure, all of the PDF shape parameters are fixed and all the normalizations are free parameters. The signal yields are found to be $N(K_S^0\pi^+) = 104.4^{+13.2}_{-12.5}$ and $N(K_S^0\pi^-) = 119.1^{+13.8}_{-13.1}$, and the partial-rate $CP$ asymmetry is determined to be $A_{CP}(\bar{K}^0\pi^\pm) = 0.07^{+0.09}_{-0.08}$.

The stability of $A_{CP}(\bar{K}^0\pi^\pm)$ as a function of the the selection requirements is tested by varying the $q\bar{q}$ suppression requirement. As shown in Fig. 2, the value of $A_{CP}(\bar{K}^0\pi^\pm)$ is stable when this requirement is changed.

Detector-based biases in $K_S^0\pi^\pm$ reconstruction are investigated using a sample of inclusive, high momentum continuum $D^\pm \to K_S^0\pi^\pm$ decays, where the daughter particles are required to satisfy the same kinematic requirements and reconstruction criteria as used for the signal. Separate fits to the $D^\pm$ mass distributions, shown in Fig. 3, indicate that the signal mass resolutions for the $B^+$ and $B^-$ samples are consistent, but there is a $1.0 \pm 0.1 \text{ MeV}/c^2$ difference in the mass peak positions. This difference in the peak positions is caused by a difference between the momentum measurement for high momentum negative and positive tracks that is attributed to a residual detector misalignment. After accounting for this difference in peak positions, $A_{CP}(D^\pm \to K_S^0\pi^\pm)$ is determined and listed in Table I. Here the sign convention in the definition of $A_{CP}(D^\pm \to K_S^0\pi^\pm)$ follows that of $A_{CP}(\bar{K}^0\pi^\pm)$. The observed $(2.0 \pm 0.8)\%$ asymmetry is treated as a possible bias, and $-2.8\%$ is assigned as a systematic error in the $A_{CP}(\bar{K}^0\pi^\pm)$ measurement.

Possible biases in the $B$ reconstruction are examined using a sample of $B^\pm \to \bar{D}^0(\to K^{\pm}\pi^\mp)\pi^\pm$ decays where the entire reconstruction procedure, except for the $K_S^0$ reconstruction, is applied. Fits to the separate $B^+$ and $B^-$ $\Delta E$ distributions, shown in Fig. 4, confirm that the resolutions are consistent between the two samples, while a $3.2 \pm 0.5 \text{ MeV}$ difference in peak positions, due to the same effect that was found in the $D^\pm \to K_S^0\pi^\pm$ sample, is observed. After accounting for the difference in $\Delta E$ peak positions, $A_{CP}(B^\pm \to \bar{D}^0\pi^\pm)$ is determined and listed in Table I. The absence of an asymmetry indicates there is no bias. Biases in the high momentum PID and $q\bar{q}$ suppression are also examined by removing each of them in the $A_{CP}(B^\pm \to \bar{D}^0\pi^\pm)$ measurement. The results are given in Table I. No biases are observed.

Possible asymmetries in the detector response and reconstruction for the $q\bar{q}$ background are checked using events in the $m_{bc}$ sideband region. The application of the entire reconstruction procedure confirms that the $\Delta E$ shapes of the $B^+$ and $B^-$ samples are consistent, and no bias is observed, as indicated in Table I. The absence of $R_\pi$- and $R_\pi$-related biases are confirmed in the same manner as for the $B^\pm \to \bar{D}^0(\to K^{+}\pi^-)\pi^\pm$ sample.

In order to study the sensitivity to the signal and $q\bar{q}$ background PDF shapes, each shape parameter is independently varied by its $1\sigma$ error. In addition, the signal shape parameters are also estimated from the actual $B^\pm \to K_S^0\pi^\pm$ samples by allowing them to be free parameters in the fits. The uncertainty in the contribution from other charmless $B$ decays is estimated from the change in the asymmetry by fitting the region of $\Delta E > -0.1 \text{ GeV}$ without those decays. The resulting relative changes in asymmetries are added in quadrature giving the fitting systematics of $+0.014$ and $-0.006$.

Because of the difference between the results presented here and the sizable asymmetry in our previous measurement, the asymmetries of different data sub-samples are examined. Figure 7 shows $A_{CP}(\bar{K}^0\pi^\pm)$ for each data sub-sample together with $A_{CP}(D^\pm \to K_S^0\pi^\pm)$ as a reference. The variation of $A_{CP}(\bar{K}^0\pi^\pm)$ is independent of that in $A_{CP}(D^\pm \to K_S^0\pi^\pm)$ and is consistent with statistical fluctuations.

The total systematic error in the $A_{CP}(\bar{K}^0\pi^\pm)$ is evaluated from the quadratic sum of the $K_S^0\pi^\pm$ reconstruction bias and $\Delta E$ fitting systematics. Finally, the asymmetry

$$A_{CP}(\bar{K}^0\pi^\pm) = 0.07^{+0.09}_{-0.08}^{+0.01}_{-0.03}$$

is obtained and a 90% confidence level interval

$$-0.10 < A_{CP}(\bar{K}^0\pi^\pm) < 0.22,$$

is set, where Gaussian statistics are assumed and the systematic error is added linearly.
In conclusion, we have measured the partial-rate CP asymmetry in $B^\pm \to K^0\pi^\pm$ with 85 million $BB$ pairs collected on the $\Upsilon(4S)$ resonance at the Belle experiment. The resulting $A_{CP}(K^0\pi^\pm) = 0.07^{+0.09}_{-0.08}^{+0.01}_{-0.04}$ is consistent with zero at the current level of statistical precision. The 90% confidence level interval $-0.10 < A_{CP}(K^0\pi^\pm) < 0.22$ is set, which is consistent with other measurements \cite{9, 10}. This result has a statistical precision below 10% and supersedes our previous measurement \cite{2}. We do not observe a significant partial-rate CP asymmetry in $B^\pm \to K^0\pi^\pm$ and attribute the sizable $A_{CP}(K^0\pi^\pm)$ found previously in a much smaller data sample to a statistical fluctuation.

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\begin{table}[h]
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\begin{tabular}{ll}
\hline
Samples & $A_{CP} [%]$ \\
\hline
$D^\pm \to K_S^0\pi^\pm$ & 2.0 $\pm$ 0.8 \\
$B^\pm \to \bar{D}^0(\to K^+\pi^-)\pi^+$ & 0.6 $\pm$ 1.7 \\
& w/o $R_\pi$ \\
& w/o $R_s$ \\
$B^\pm \to K_S^0\pi^\pm m_{bc}$ sideband data & 0.0 $\pm$ 1.4 \\
& w/o $R_\pi$ \\
& w/o $R_s$ \\
\hline
\end{tabular}
\caption{Summary of the detector-based bias tests. For tests other than those with the $D^\pm \to K_S^0\pi^\pm$ sample, $A_{CP}$ values determined without the high momentum PID ($R_+$) and $q\bar{q}$ suppression ($R_+$) requirements are also listed.}
\end{table}
FIG. 1: The $\Delta E$ distributions for the $B^\pm \to K_S^0 \pi^\pm$ candidates divided into $B^-$ (left) and $B^+$ (right) samples. The fit results are shown as the solid, dashed and dotted curves for the total, signal and $q\bar{q}$ background, respectively; the hatched area indicates the contribution from other charmless $B$ decays.

FIG. 2: $A_{CP}(K^0 \pi^\pm)$ as a function of the signal efficiency of the $q\bar{q}$ suppression ($R_s$) selection. The horizontal line and hatched area indicate the $A_{CP}(K^0 \pi^\pm)$ value and its statistical error for the $R_s$ requirement used in the actual measurement. Note that the statistical errors for the different data points are strongly correlated.

FIG. 3: The mass spectra for the $D^\pm \to K_S^0 \pi^\pm$ candidates separated into $D^-$ (left) and $D^+$ (right) samples, where the kinematic requirements and daughter particle reconstruction are the same as used for the $B^\pm \to K_S^0 \pi^\pm$ signal. The fit results are shown as the solid, dashed and dotted curves for the total, $D^\pm \to K_S^0 \pi^\pm$ and combinatorial background, respectively.
FIG. 4: The $\Delta E$ distributions for $B^\pm \to \bar{D}^0 (\to K^{\pm} \pi^\mp)\pi^\pm$ candidates separately for the $B^-$ (left) and $B^+$ (right) samples after application of the entire reconstruction procedure other than that for the $K_S^0$. The fit results are shown as the solid, dashed and dotted curves for the total, $B^\pm \to \bar{D}^0 (\to K^{\pm} \pi^\mp)\pi^\pm$ and combinatorial background, respectively. The enhancement in the lower $\Delta E$ region contains backgrounds from $B \to D^*\pi^\pm$ and $D^0\rho$.

FIG. 5: $A_{CP}(\bar{K}^0\pi^\pm)$ in each data sub-sample. The horizontal line and hatched area show the central value and the 1σ statistical error of the $A_{CP}(\bar{K}^0\pi^\pm)$ result reported here. The solid points with the statistical error bars represent the $A_{CP}(\bar{K}^0\pi^\pm)$ result obtained for each data sub-sample; the open points show $A_{CP}(D^\pm \to K_S^0\pi^\pm)$. The sum of the three left-most points corresponds to the 29 fb$^{-1}$ data sample used in our previous measurement.