Recent Belle results related to $\pi - K$ interactions

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We report the recent results related to $\pi - K$ interactions based on the data collected by the Belle experiment at the KEKB collider. This includes the branching fraction and $CP$ asymmetry measurements of $B^+ \to K^+ K^- \pi^+$ decay, search for the $A^+_{c} \to \phi p\pi^0$, $A^+_c \to P^+_s \pi^0$ decays, branching fraction measurement of $A^+_c \to K^- \pi^+ p\pi^0$, first observation of doubly Cabibbo-suppressed decay $A^+_c \to K^- \pi^+ \pi^-$, and the measurement of CKM angle $\phi_3 (\gamma)$ with a model-independent Dalitz plot analysis of $B^+ \to D K^\pm$, $D \to K_S^0 \pi^+ \pi^-$ decay, where the quoted uncertainties are statistical and systematic, respectively.

To investigate the localized $CP$ asymmetry in the low $K^+ K^-$ invariant mass region, we perform the 2D fit (described above) to extract the signal yield and $A_{CP}$ in bins of $M_{K^+ K^-}$. The fitted results are shown in Fig. 1 and Table I. We confirm the excess and local $A_{CP}$ in the low $M_{K^+ K^-}$ region, as reported by the LHCb, and quantify the differential branching fraction in each $K^+ K^-$ invariant mass bin. We find a $4.8\sigma$ evidence for a negative $CP$ asymmetry in the region $M_{K^+ K^-} < 1.1$ GeV/$c^2$. To understand the origin of the low-mass dynamics, a full Dalitz analysis from experiments with a sizeable data set, such as LHCb and Belle II, will be needed in the future.

INTRODUCTION

In this report, we present some recent results related to $\pi - K$ interactions based on the data, collected by the Belle experiment at the KEKB $e^+e^-$ asymmetric-energy collider [1]. (Throughout this paper charge-conjugate modes are implied.) The experiment took data at center-of-mass energies corresponding to several $\Upsilon(nS)$ resonances; the total data sample recorded exceeds 1 ab$^{-1}$.

The Belle detector is a large-solid-angle magnetic spectrometer which consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic 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 $K_L^0$ mesons and to identify muons (KLM). The detector is described in detail elsewhere [2-3].

$CP$ ASYMMETRY IN $B^+ \to K^+ K^- \pi^+$ DECAYS

In the recent years, an unidentified structure has been observed by BaBar [4] and LHCb experiments [5, 6] in the low $K^+ K^-$ invariant mass spectrum of the $B^+ \to K^+ K^- \pi^+$ decays. The LHCb reported a nonzero inclusive $CP$ asymmetry of $-0.123 \pm 0.017 \pm 0.012 \pm 0.007$ and a large unquantified local $CP$ asymmetry in the same mass region. These results suggest that final-state interactions may contribute to $CP$ violation [7-8]. In this analysis, we attempt to quantify the $CP$ asymmetry and branching fraction as a function of the $K^+ K^-$ invariant mass, using 711 fb$^{-1}$ of data, collected at $\Upsilon(4S)$ resonance [9].

The signal yield is extracted by performing a two-dimensional unbinned maximum likelihood fit to the variables: the beam-energy constrained mass $M_{bc}$ and the energy difference $\Delta E$. The resulting branching fraction and $CP$ asymmetry are

$$B(B^+ \to K^+ K^- \pi^+) = (5.38 \pm 0.40 \pm 0.35) \times 10^{-6},$$

$$A_{CP} = -0.170 \pm 0.073 \pm 0.017,$$

where the quoted uncertainties are statistical and systematic, respectively.

FIG. 1: Differential branching fractions (left) and measured $A_{CP}$ (right) as a function of $M_{K^+ K^-}$. Each point is obtained from a two-dimensional fit with systematic uncertainty included. Red squares with error bars in the left figure show the expected signal distribution in a three-body phase space MC. Note that the phase space hypothesis is rescaled to the total observed $K^+ K^- \pi^+$ signal yield.

SEARCH FOR $A^+_c \to \phi p\pi^0$ AND BRANCHING FRACTION MEASUREMENT OF $A^+_c \to K^- \pi^+ P\pi^0$

The story of exotic hadron spectroscopy begins with the discovery of the $X(3872)$ by the Belle collaboration in 2003 [10]. Since then, many exotic $XYZ$ states have...
been reported by Belle and other experiments [11]. Recent observations of two hidden-charm pentaquark states \( P_c^+(4380) \) and \( P_c^+(4450) \) by the LHCb collaboration in the \( J/\psi p \) invariant mass spectrum of the \( \Lambda_b^0 \to J/\psi p K^- \) process [12] raises the question of whether a hidden-strangeness pentaquark \( P_s^+ \), where the \( c\bar{c} \) pair in \( P_c^+ \) is replaced by an \( s\bar{s} \) pair, exists [13–15]. The strangeness pentaquark \( \bar{P} \) state also holds for \( \Lambda \) decays. We obtain a forward-angle bump structure in \( \Lambda_c^+ \to \phi p \pi^0 \) production \((\gamma p \to \phi p)\), a forward-angle bump structure at \( \sqrt{s} = 2.0 \) GeV has been observed by the LEPS [10] and CLAS collaborations [17]. However, this structure appears only at the most forward angles, which is not expected for the decay of a resonance [18].

![FIG. 2: Feynman diagram for the decay (a) \( \Lambda_c^+ \to \phi p\pi^0 \) and (b) \( \Lambda_c^+ \to P_s^+\pi^0 \).](image)

Previously, the decay \( \Lambda_c^+ \to \phi p\pi^0 \) has not been studied by any experiment. Here, we report a search for this decay, using 915 fb\(^{-1}\) of data [19]. In addition, we search for the nonresonant decay \( \Lambda_c^+ \to K^+K^-\pi^0 \) and measure the branching fraction of the Cabibbo-favored decay \( \Lambda_c^+ \to K^-\pi^+\pi^0 \).

In order to extract the signal yield, we perform a two-dimensional (2D) unbinned extended maximum likelihood fit to the variables \( m(K^+K^-\pi^0) \) and \( m(K^+K^-) \). Projections of the fit result are shown in Fig. 3. From the fit, we extract 148.4 ± 61.8 signal events, 75.9 ± 84.8 nonresonant events, and 7158.4 ± 36.4 combinatorial background events. The statistical significances are found to be 2.4 and 1.0 standard deviations for \( \Lambda_c^+ \to \phi p\pi^0 \) and nonresonant \( \Lambda_c^+ \to K^+K^-\pi^0 \) decays, respectively. We use the well-established decay \( \Lambda_c^+ \to pK^-\pi^+ \) [11] as the normalization channel for the branching fraction measurements.

Since the significances are below 3.0 standard deviations both for \( \phi p\pi^0 \) signal and \( K^+K^-\pi^0 \) nonresonant decays, we set upper limits on their branching fractions at 90% confidence level (CL) using a Bayesian approach. The results are

\[
\begin{align*}
B(\Lambda_c^+ \to \phi p\pi^0) &< 15.3 \times 10^{-5}, \\
B(\Lambda_c^+ \to K^+K^-\pi^0)_{\text{NR}} &< 6.3 \times 10^{-5},
\end{align*}
\]

which are the first limits on these branching fractions.

To search for a putative \( P_s^+ \to \phi p \) decay, we select \( \Lambda_c^+ \to K^+K^-\pi^0 \) candidates in which \( m(K^+K^-) \) is within 0.020 GeV/c\(^2\) of the \( \phi \) meson mass [11] and plot the background-subtracted \( m(\phi p) \) distribution (Fig. 4). This distribution is obtained by performing 2D fits as discussed above in bins of \( m(\phi p) \). The data shows no clear evidence for a \( P_s^+ \) state. We set an upper limit on the product branching fraction \( B(\Lambda_c^+ \to P_s^+\pi^0) \times B(P_s^+ \to \phi p) \) by fitting the distribution of Fig. 4 to the sum of a RBW function and a phase space distribution determined from a sample of simulated \( \Lambda_c^+ \to \phi p\pi^0 \) decays. We obtain 77.6 ± 28.1 \( P_s^+ \) events from the fit, which gives an upper limit of

\[
B(\Lambda_c^+ \to P_s^+\pi^0) \times B(P_s^+ \to \phi p) < 8.3 \times 10^{-5}
\]

at 90% CL. From the fit, we also obtain, \( M_{P_s^+} = (2.025 \pm 0.005) \) GeV/c\(^2\) and \( \Gamma_{P_s^+} = (0.022 \pm 0.012) \) GeV, where the uncertainties are statistical only.

The high statistics decay \( \Lambda_c^+ \to K^-\pi^+\pi^0 \) is used to adjust the data-MC differences in the \( \phi p\pi^0 \) signal and \( K^+K^-\pi^0 \) nonresonant decays. For the \( \Lambda_c^+ \to K^-\pi^+\pi^0 \) sample, the mass distribution is plotted in Fig. 5. We fit this distribution to obtain the signal yield. We find 242.039 ± 2342 signal candidates and 472.729 ± 467 background candidates. We measure the ratio of branching fractions,

\[
\frac{B(\Lambda_c^+ \to K^-\pi^+\pi^0)}{B(\Lambda_c^+ \to K^-\pi^+p)} = (0.685 \pm 0.007 \pm 0.018),\]

| \( M_{K^+K^-} \) | \( \text{d}B/\text{d}M \times 10^{-7} \) | \( A_{CP} \) |
|---|---|---|
| 0.8–1.1 | 14.0 ± 2.7 ± 0.8 | -0.90 ± 0.17 ± 0.04 |
| 1.1–1.5 | 37.8 ± 3.8 ± 1.9 | -0.16 ± 0.10 ± 0.01 |
| 1.5–2.5 | 10.0 ± 2.3 ± 1.7 | -0.15 ± 0.23 ± 0.03 |
| 2.5–3.5 | 10.0 ± 1.6 ± 0.6 | -0.09 ± 0.16 ± 0.01 |
| 3.5–5.3 | 8.1 ± 1.2 ± 0.5 | -0.05 ± 0.15 ± 0.01 |
Several doubly Cabibbo-suppressed (DCS) decays of charmed mesons have been observed [11]. Their measured branching ratios with respect to the corresponding Cabibbo-favored (CF) decays play an important role in constraining models of the decay of charmed hadrons and in the study of flavor- SU(3) symmetry [22, 23]. On the other hand, because of the smaller production cross-sections for charmed baryons, DCS decays of charmed baryons have not yet been observed, and only an upper limit, \( \frac{B(\Lambda_c^+ \to pK^+\pi^-)}{B(\Lambda_c^+ \to pK^-\pi^+)} < 0.46\% \) at 90\% CL, has been reported by the FOCUS Collaboration [24]. Here we present the first observation of the DCS decay \( \Lambda_c^+ \to pK^+\pi^- \) and the measurement of its branching ratio with respect to the CF decay \( \Lambda_c^+ \to pK^-\pi^+ \), using 980 fb\(^{-1}\) of data [25].

Figure 5 shows the invariant mass distributions of (a) \( pK^-\pi^+ \) (CF) and (b) \( pK^+\pi^- \) (DCS) combinations. DCS decay events are clearly observed in \( M(pK^+\pi^-) \). In order to obtain the signal yield, a binned least-\( \chi^2 \) fit is performed. From the mass fit, we extract (1.452\pm0.015)\times10^6 \( \Lambda_c^+ \to pK^-\pi^+ \) events and 3587\pm380 \( \Lambda_c^+ \to pK^+\pi^- \) events. The latter has a peaking background from the single Cabibbo-suppressed (SCS) decay \( \Lambda_c^+ \to \Lambda(p\pi^-)K^+ \), which has the same final-state topology. After subtracting the SCS contribution, we have 3379\pm380\pm78 DCS events, where the first uncertainty is statistical and the second is systematic due to SCS subtraction. The corresponding statistical significance is 9.4 standard deviations. We measure the branching ratio,

\[
\frac{B(\Lambda_c^+ \to pK^+\pi^-)}{B(\Lambda_c^+ \to pK^-\pi^+)} = (2.35 \pm 0.27 \pm 0.21) \times 10^{-3},
\]

where the uncertainties are statistical and systematic, respectively. This measured branching ratio corresponds to \((0.82 \pm 0.21)\tan^4\theta_c\), where the uncertainty is the total, which is consistent within 1.5 standard deviations with the naive expectation \((\sim \tan^4\theta_c) [24]\). LHCb’s recent measurement of \( \frac{B(\Lambda_c^+ \to pK^+\pi^-)}{B(\Lambda_c^+ \to pK^-\pi^+)} = (1.65 \pm 0.15 \pm 0.05) \times 10^{-3} [20] \) is lower than our ratio at the 2.0\sigma level. Multiplying this ratio with the previously measured \( B(\Lambda_c^+ \to pK^-\pi^+) = (6.84 \pm 0.24^{+0.24}_{-0.21})\% \) by the Belle Collaboration [27], we obtain the absolute branching fraction of the DCS decay,

\[
B(\Lambda_c^+ \to pK^+\pi^-) = (1.61 \pm 0.23^{+0.07}_{-0.08}) \times 10^{-4},
\]

where the first uncertainty is due to the total uncertainty of the branching ratio and the second is uncertainty due to the branching fraction of the CF decay. After subtracting the contributions of \( \Lambda^*(1520) \) and \( \Delta \) isobar intermediates, which contribute only to the CF decay, the revised
The CKM angle $\phi_3$ (also denoted as $\gamma$) is one of the least constrained parameters of the CKM Unitary Triangle. Its determination is however theoretically clean due to absence of loop contributions; $\phi_3$ can be determined using tree-level processes only, exploiting the interference between $b \to ucs$ and $b \to cus$ transitions that occurs when a process involves a neutral $D$ meson reconstructed in a final state accessible to both $D^0$ and $\bar{D}^0$ decays (see Fig. 7). Therefore, the angle $\phi_3$ provides a SM benchmark, and its precise measurement is crucial in order to disentangle non-SM contributions to other processes, via global CKM fits. The size of the interference also depends on the ratio ($r_B$) of the magnitudes of the two tree diagrams involved and $\delta_B$, the strong phase difference between them. Those hadronic parameters will be extracted from data together with the angle $\phi_3$.

The measurement is performed in three different ways: (a) by utilizing decays of $D$ mesons to $CP$ eigenstates, such as $\pi^+\pi^-$, $K^+K^-$ ($CP$ even) or $K_{S}^{0}\pi^0$, $\phi K_{S}^{0}$ ($CP$ odd), proposed by M. Gronau, D. London, and D. Wyler (and called the GLW method [28, 29]) by making use of DCS decays of $D$ mesons, e.g., $D^0 \to K^+\pi^-$, proposed by D. Atwood, I. Dunietz, and A. Soni (and called the ADS method [30]) and (c) by exploiting the interference pattern in the Dalitz plot of the $D$ decays such as $D^0 \to K_{S}^{0}\pi^+\pi^-$, proposed by A. Giri, Y. Grossman, A. Soffer, and J. Zupanc (and called the GGSZ method [31]).

Using a model-dependent Dalitz plot method, Belle’s earlier measurement [32] based on a data sample of 605 fb$^{-1}$ integrated luminosity yielded $\phi_3 = (78.4_{-11.6}^{+10.8} \pm 3.6 \pm 8.9)^\circ$ and $r_B = 0.160_{-0.038}^{+0.040} \pm 0.011_{-0.010}^{+0.050}$, where the uncertainties are statistical, systematic and Dalitz model dependence, respectively. Although with more data one can squeeze on the statistical part, the result will still remain limited by the model uncertainty.

In a bid to circumvent this problem, Belle has carried out a model-independent analysis [33], using GGSZ method [31], that is further extended in a latter work [34]. The analysis is based on the 711 fb$^{-1}$ of data, collected at the $T(4S)$ resonance. In contrast to the conventional Dalitz method, where the $D^0 \to K_{S}^{0}\pi^+\pi^-$ amplitudes are parameterized as a coherent sum of several quasi-two-body amplitudes as well as a nonresonant term, the model-independent approach invokes study of a binned Dalitz plot. In this approach, the expected number of events in the $i^{th}$ bin of the Dalitz plan for the $D$ mesons from $B^\pm \to DK^\pm$ is given by

$$N_i = h_B[K_{+} + r_B^2 K_{+}] + 2\sqrt{K_{i}K_{i}}(x_i c_i + y_i s_i),$$  \hspace{1cm} (1)$$

where $h_B$ is the overall normalization and $K_i$ is the number of events in the $i^{th}$ Dalitz bin of the flavor-tagged (whether $D^0$ or $\bar{D}^0$) $D^0 \to K_{S}^{0}\pi^+\pi^-$ decays, accessible via the charge of the slow pion in $D^{*\pm} \to D^{\pm}\pi^\pm$. The terms $c_i$ and $s_i$ contain information about the strong-phase difference between the symmetric Dalitz points [$m^2(K_{S}^{0}\pi^+)$, $m^2(K_{S}^{0}\pi^-)$] and [$m^2(K_{S}^{0}\pi^+)$]; they are the external inputs obtained from quantum correlated $D^0\bar{D}^0$ decays at the $\psi(3770)$ resonance in CLEO [35, 36]. Finally $x_{\pm} = r_B \cos(\delta_B \pm \phi_3)$ and $y_{\pm} = r_B \sin(\delta_B \pm \phi_3)$, where $\delta_B$ is the strong-phase difference between $B^\pm \to D^0K^\pm$ and $B^\pm \to D^0\bar{K}^\mp$.

We perform a combined likelihood fit to four signal selection variables in all Dalitz bins (16 bins in our case) for the $B^\pm \to DK^\pm$ signal and Cabibbo-favored $B^\pm \to D\pi^\pm$ control samples; the free parameters of the fit are $x_{\pm}$, $y_{\pm}$, overall normalization (see Eq. 1) and background fraction. Table [1] summarizes the results obtained for $B^\pm \to DK^\pm$ decays. From these results, we obtain $\phi_3 = (77.3_{-14.9}^{+15.1} \pm 4.1 \pm 4.3)^\circ$ and $r_B = 0.145 \pm 0.030 \pm 0.010 \pm 0.011$, where the first error is

![FIG. 6: Distributions of (a) $M(pK^-\pi^+)$ and (b) $M(pK^+\pi^-)$ and residuals of data with respect to the fitted combinatorial background. The solid curves indicate the full fit model and the dashed curves the combinatorial background.](image)

![FIG. 7: Feynman diagram for $B^- \to D^0K^-$ and $B^- \to \bar{D}^0K^-$.](image)
TABLE II: Results of the $x$, $y$ parameters and their statistical correlation for $B^+ \rightarrow DK^+$ decays. The quoted uncertainties are statistical, systematic, and precision on $c_i$, $s_i$, respectively.

| Parameter | $x_+$ | $y_+$ | $\text{corr}(x_+, y_+)$ | $x_-$ | $y_-$ | $\text{corr}(x_-, y_-)$ |
|-----------|-------|-------|------------------------|-------|-------|------------------------|
|           | $+0.095 \pm 0.045 \pm 0.014 \pm 0.010$ | $+0.135^{+0.053}_{-0.057} \pm 0.015 \pm 0.023$ | $-0.315$ | $-0.110 \pm 0.043 \pm 0.014 \pm 0.007$ | $-0.050^{+0.052}_{-0.055} \pm 0.011 \pm 0.017$ | $+0.059$ |

is statistical, the second is systematic, and the last error is due to limited precision on $c_i$ and $s_i$. Although $\phi_3$ has a mirror solution at $\phi_3 = 180^\circ$, we retain the value consistent with $0^\circ < \phi_3 < 180^\circ$. We report evidence for direct $CP$ violation, the fact that $\phi_3$ is nonzero, at the 2.7 standard deviations level. Compared to results of the model-dependent Dalitz method, this measurement has somewhat poorer statistical precision despite a larger data sample used. There are two factors responsible for lower statistical sensitivity: 1) the statistical error for the same statistics is inversely proportional to the $r_B$ value, and the central value of $r_B$ in this analysis is smaller, and 2) the binned approach is expected to have the statistical precision that is, on average, 10–20% poorer than the unbinned one. On the positive side, however, the large model uncertainty for the model-dependent study ($8.9^\circ$) is now replaced by a purely statistical uncertainty due to limited size of the $\psi(3770)$ data sample available at CLEO (4.3$^\circ$). With the use of BES-III data, this error will decrease to 1$^\circ$ or less.

The model-independent approach therefore offers an ideal avenue for Belle II and LHCb in their pursuits of $\phi_3$. We expect that the statistical error of the $\phi_3$ measurement using the statistics of a 50 ab$^{-1}$ data sample that will be available at Belle II will reach $1 - 2$$. We also expect that the experimental systematic error can be kept at the level below 1$, since most of its sources are limited by the statistics of the control channels.

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