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Hadronic $b \to c$ decays at Belle

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We present the most precise measurement of the angle ϕ_3 of the unitarity triangle, using Dalitz plot analysis of three-body neutral D decays from the $B^+ \to D^{(*)}K^{(*)+}$ processes. The decays $B \to D^{(*)}K^{(*)}(D = D^0/\bar{D}^0)$ include a $b \to u$ transition and provide a direct access to the angle ϕ_3. An improved measurement of the branching fractions for the decays $B^0 \to D_s^{(*)+}\pi^-$ and $\bar{B}^0 \to D_s^{(*)+}K^-$ are reported. These measurements facilitate calculation of an essential input in the time dependent CP analysis of the $B^0 \to D^{(*)\mp}\pi^{\pm}$, which is an indirect method for the ϕ_3 estimation. We also report the first observation of the three-body baryonic decays of charged B, namely $B^- \to \bar{p}\Lambda D^{(*)0}$. The branching fractions as well as the differential branching fractions as a function of the mass of the $p\bar{\Lambda}$ system are presented. These results are compared with theoretical predictions based on the generalized factorization approach. All the results presented here, are based on a large sample consisting of 657×10^6 $B\bar{B}$ pairs, recorded at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB e^+e^- collider.

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1. Introduction

Hadronic decays - particularly, involving a $b \to c$ transition - not only provide access to the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements [1], but also avail tools to test various assumptions made in order to simplify theoretical calculations, which would be impossible to perform otherwise. The uncertainties introduced due to these assumptions, in turn, constitute the largest part of the theoretical uncertainties, deteriorating the estimation of many CKM elements.

As a result of large hadronic uncertainties, the angle ϕ_3 (also known as γ) of the CKM unitarity triangle has been estimated with an uncertainty of about 20%, as opposed to the other two angles, which are known with considerable accuracies. In section 2 an attempt to measure the ϕ_3 directly is discussed, while section 3 deals with an independent approach to access the same angle, ϕ_3, indirectly. We also report in section 4 a measurement of the branching fraction of the three body decay $B^- \to \bar{p}\Lambda D^0$, which provides a testing ground for the *generalized factorization* assumption used in many QCD calculations.

2. Dalitz analysis of $B^+ \to D^{(*)}K^+$ decays

Due to the absence of a neutral B decay into a CP eigenstate, with amplitude sensitive to the angle ϕ_3, this unitarity triangle element is the least-well constrained by direct measurements. The most sensitive technique for a direct ϕ_3 measurement utilizes the interference-relation between the CP eigenstates D^0_{CP}, decaying to three body final states and the $D^0(\bar{D}^0)$ decays to the same final state, in a $B \to DK$ family [2]. The amplitudes for the process $B^\pm \to (K^0_S\pi^+\pi^-)_D K^\pm$ as a function of the Dalitz plot variables $m^2_\pm = m^2_{K^0_S\pi^\pm}$ is given by

$$M_\pm = f(m^2_\pm, m^2_\mp) + r_\pm e^{\pm i\phi_3 + i\delta} f(m^2_\mp, m^2_\pm), \tag{2.1}$$

where the functions $f(m^2_\pm, m^2_\mp)$ are the amplitudes of the corresponding three body D decays and are determined using large sample of flavor-tagged $\bar{D}^0 \to K^0_S\pi^+\pi^-$ decays produced in continuum data, $r_\pm$ is the ratio of the magnitudes of the two interfering $B^\pm$ amplitudes and is expected to be about 10%, and δ is the strong phase difference between the amplitudes. The amplitudes $f(m^2_\pm, m^2_\mp)$ are extracted assuming the isobar model for the D decays and fitting the resonances to Breit-Wigner shapes, in this study [3]. However, it is possible to perform the same study in a model-independent way, where the Dalitz plot is to be divided into various momentum bins [2].

The Dalitz analysis of the $B^+ \to D^{(*)}K^+$ decays is performed in two steps. To obtain the fractional contributions from various backgrounds, a two-dimensional unbinned maximum likelihood (UML) fit is performed in the beam-constrained B meson mass $M_{\rm bc} = \sqrt{E^2_{\rm beam} - (\sum \vec{p}_i)^2}$ and the center of mass (CM) energy difference $\Delta E = \sum E_i - E_{\rm beam}$, where $E_{\rm beam}$, E_i and $\vec{p}_i$ are the beam energy, the energy and momenta of the B candidate decay products in the CM frame, respectively. In case of a $B^+ \to D^*K^+$ decay, the D^* candidate is reconstructed in $D^* \to D\pi^0$ and $D^* \to D\gamma$ decays. Finally, these background fractions are used in the Dalitz plot to obtain the event-by-event signal-to-background ratio. A four-dimensional UML fit is performed to the distributions of variables $M_{\rm bc}$, ΔE, $\cos\theta_{\rm thr}$, and $\mathscr{F}$, where $\theta_{\rm thr}$ is the angle between the thrust axis of the B candidate daughters and that of the rest of the event, and $\mathscr{F}$ is the Fisher discriminant composed of 11 parameters [4].

In the second phase of the analysis, the Dalitz distributions of the B^+ and B^- samples are fitted separately, using Cartesian parameters $x_\pm = r_\pm \cos(\pm\phi_3 + \delta)$ and $y_\pm = r_\pm \sin(\pm\phi_3 + \delta)$. In order to improve the sensitivity, all the $B \to D^{(*)}K$ modes are combined, which yield an estimate of $\phi_3 = (78.4^{+10.8}_{-11.6}(\text{stat}) \pm 3.6(\text{syst}) \pm 8.9(\text{model}))^\circ$ [3]. It is evident that the model assumed for the three body D decays contributes to one of the major sources of uncertainties. An attempt is being made towards reducing the model uncertainties by adopting a model-independent approach, much along the directions given in [2].

3. Measurement of $B^0 \to D_s^{(*)+}\pi^-$ and $B^0 \to D_s^{(*)-}K^+$ decays

Time dependent CP analysis of the $B^0 \to D^{(*)\mp}\pi^\pm$ decays offers an indirect approach for estimating ϕ_3 [5] and plays a crucial role providing an independent alternative to direct approaches. In addition, these processes do not receive contributions from Penguin diagrams, constituting a theoretically clean system. The amplitudes for the processes $B^0 \to D^{(*)-}\pi^+$ and $B^0 \to \bar{B}^0 \to D^{(*)-}\pi^+$ can interfere yielding an interference term proportional to $R_{D^{(*)}\pi}\sin(2\phi_1 + \phi_3)$, where $R_{D^{(*)}\pi}$ is the ratio of the amplitudes for the $\bar{B}^0 \to D^{(*)-}\pi^+$ and $B^0 \to D^{(*)-}\pi^+$ decays and is expected to be about 2%. The former involves a $b \to u$ transition and is a doubly Cabibbo suppressed decay (DCSD), while the latter involves a Cabibbo favored $b \to c$ transition (CFD) and can overwhelm the former. As a result, it is impossible to extract $R_{D^{(*)}\pi}$ from this analysis with the currently available data and needs to be provided externally. The $B^0 \to D_s^{(*)+}\pi^-$ decay, which is predominantly a spectator $b \to u$ process can be related to the DCSD amplitude, using the SU(3) flavor symmetry between the two. Under the the SU(3) assumption, $R_{D^{(*)}\pi}$ is given by

$$R_{D^{(*)}\pi} = \tan\theta_C \left(\frac{f_{D^{(*)}}}{f_{D_s^{(*)}}}\right)\sqrt{\frac{\mathscr{B}(B^0 \to D_s^{(*)+}\pi^-)}{\mathscr{B}(B^0 \to D^{(*)-}\pi^+)}} \tag{3.1}$$

where θ_C is the Cabibbo angle, $f_{D^{(*)}}$ and $f_{D_s^{(*)}}$ are the meson form factors, and the $\mathscr{B}$ represent the corresponding branching fractions. In addition to the absence of Penguin pollution, the $B^0 \to D_s^{(*)+}\pi^-$ process lack contributions from W-exchange diagrams, which are present in the $B^0 \to D^{(*)}\pi$ system. Hence, it is necessary to account for the neglected W-exchange processes in the numerator of $R_{D^{(*)}\pi}$. The $B^0 \to D_s^{(*)-}K^+$ decay proceeds only via a W-exchange diagram, which is SU(3) symmetric to that of CFD and can be used to estimate the size of the W-exchange contribution relative to the spectator diagrams. The branching fraction measurement of the $B^0 \to D_s^{(*)-}K^+$ decay can also supply indications towards possible re-scattering effects expected in this mode [6].

The events are reconstructed in three D_s^+ decay modes: $D_s^+ \to \phi\pi^+$, $D_s^+ \to \bar{K}^*(892)^0K^+$, and $D_s^+ \to K_S^0K^+$. In case of $B^0 \to D_s^+\pi^-$ decays, a two-dimensional UML fit to the distributions of the variables ΔE and $M_{D_s^+}$ is performed simultaneously to the samples in the three D_s^+ modes, where $M_{D_s^+}$ is the invariant mass of the D_s^+ candidates. The $B^0 \to D_s^+\pi^-$ and $B^0 \to D_s^-K^+$ decays cross-feed each other, due to the pion-kaon mis-identification and hence are fitted simultaneously. We obtain, $\mathscr{B}(B^0 \to D_s^+\pi^-) = (1.99 \pm 0.26 \pm 0.18) \times 10^{-5}$ and $\mathscr{B}(B^0 \to D_s^-K^+) = (1.91 \pm 0.24 \pm 0.17) \times 10^{-5}$, with a significance of 8.0 and 9.2 standard deviations, respectively [7]. This leads to a value of $R_{D\pi} = (1.71 \pm 0.11(\text{stat}) \pm 0.09(\text{syst}) \pm 0.02(\text{th}))\%$, which is consistent with its theoretical prediction.

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In case of $B^0 \to D_s^{*+}\pi^-$ decay, we constrain the $M_{D_s^+}$ to be within 3 standard deviations in the respective modes. The D_s^{*+} candidate is reconstructed in the $D_s^{*+} \to D_s^+\gamma$ decay. A one-dimensional UML fit is performed to the ΔE distributions in the six mutually exclusive samples simultaneously. In this case, we obtain $\mathscr{B}(B^0 \to D_s^{*+}\pi^-) = (1.75 \pm 0.34(\text{stat}) \pm 0.20(\text{syst})) \times 10^{-5}$ and $\mathscr{B}(B^0 \to D_s^{*-}K^+) = (2.02 \pm 0.33(\text{stat}) \pm 0.22(\text{syst})) \times 10^{-5}$, with a significance of 6.1 and 8.0 standard deviations, respectively [8]. The value determined of $R_{D^*\pi} = (1.58 \pm 0.15(\text{stat}) \pm 0.10(\text{syst}) \pm 0.03(\text{th}))\%$.

Both $R_{D^{(*)}\pi}$ values reported here are the most precise estimates, so far.

4. Measurement of $B^- \to \bar{p}\Lambda D$ decay

The vertex and the Penguin corrections to the hadronic matrix elements of four-quark operators can be absorbed in the effective Wilson coefficients , so that the momentum dependence is smeared out. Under such a factorization approximation - known as generalized factorization approximation - a baryonic three body B decay amplitude can be classified into three different categories: the current-type, transition-type, and hybrid of the two. In particular, the theoretical calculations based on this approximation predict a branching fraction of about 1.1×10^{-5} for the three body decay $B^- \to \bar{p}\Lambda D$, proceeding via an intermediate $\bar{p}\Lambda$ threshold.

We report the first observation of this three body decay at Belle. The Λ candidates are reconstructed in the $\Lambda \to p\pi$ decay process and the selection is optimized based on the Λ decay topology. The D mesons are reconstructed in $D \to K\pi$ and $D \to K\pi\pi^0$ decays. A two-dimensional UML fit is performed to the M_{bc}-ΔE distributions of each of the two D data-samples separately. Fig. 1 shows results of the two-dimensional fits. We obtained, $\mathscr{B}(B^- \to \bar{p}\Lambda D^0) =$

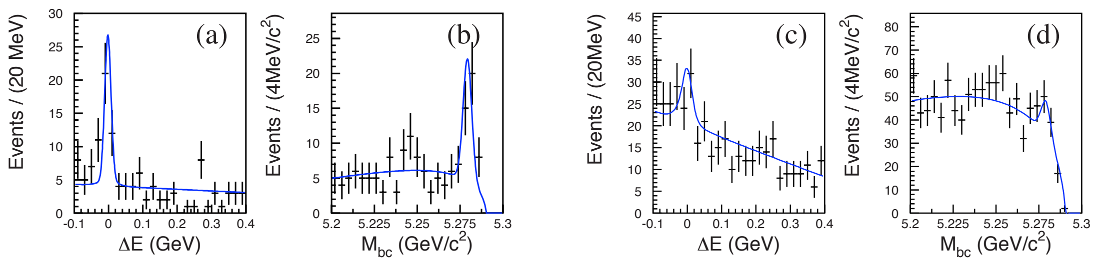

Figure 1: The two-dimensional fit to the ΔE ((a), (c)) and M_{bc} ((b), (d)) distributions of the $D \to K\pi$ (left) and $D \to K\pi\pi^0$ (right) data samples.

$(1.43^{+0.34}_{-0.30} \pm 0.14) \times 10^{-5}((1.35^{+0.44}_{-0.40} \pm 0.18) \times 10^{-5})$ in the $D^0 \to K\pi$ ($D^0 \to K\pi\pi^0$) mode. Here, the first uncertainty is statistical, while the second is systematic. The combined branching fraction is $(1.40^{+0.27}_{-0.24} \pm 0.16) \times 10^{-5}$, with a significance of 8.61 standard deviations. We also observe an enhancement in the yield near the $\bar{p}\Lambda$ threshold region, i.e. at 2 GeV/c^2, as shown in Fig. 2. These observations are consistent with the theoretical expectations based on the generalized factorization approximation.

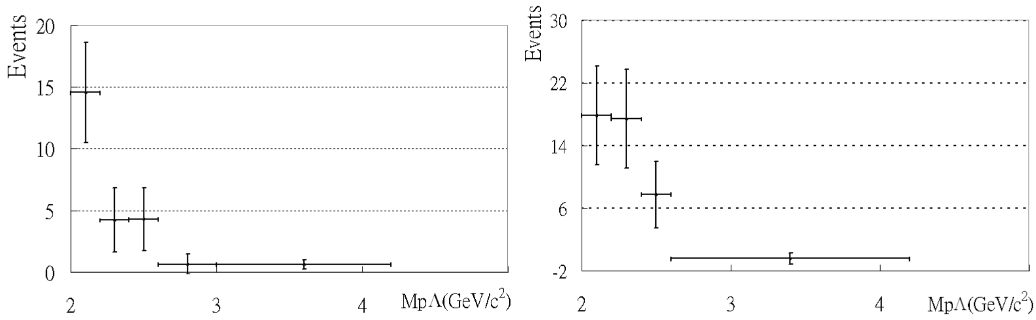

Figure 2: Yield as a function of the $\bar{p}\Lambda$ invariant mass. An enhancement in the $\bar{p}\Lambda$ threshold region, near 2 GeV/c^2 is seen in $D^0 \to K\pi$ (left) as well as $D^0 \to K\pi\pi^0$ (right) data samples.

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