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Study of $B \to X_c \Lambda^0 K_S/K$ with recoil mass approach

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In this study we search for decays $B^0 \to X_c^- \Lambda^0 K^+$ and $B^0 \to \overline{X}_c^0 \Lambda^0 K_S^0$ using Belle simulation, where X_c represents a charm baryon. Belle collected data at a center-of-mass energy close to $\Upsilon(4S)$ resonance, which decays to two B mesons almost every time. We follow a recoil approach where the other B meson is reconstructed in various hadronic modes, and the charm baryon is looked for in the recoil of the accompanying Λ^0 and K^+/K_S^0 coming from the signal B meson. This study will provide a comprehensive insight into baryonic B decays and the impact of $s\bar{s}$ quark pair production on their branching fractions.

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1. Introduction

The inclusive baryonic modes contribute about 6.8% of all B meson decays, as reported by ARGUS [1]. In contrast, the cumulative percentage for the known exclusive baryonic modes in B meson decays is approximately ∼1% [2]. The decay mechanism for B mesons predominantly involves $b \to cW$ transitions, particularly leading to the creation of charm mesons or baryons. While charm meson modes have been extensively studied, so far the examination of charm baryon modes has been concentrated towards Λ_c only, such as $B \to \Lambda_c p(n)\pi$ (n =1,2,3,4) [3, 4] and $B \to \Lambda_c \Xi_c$ [5]. Notably, these decays either proceed via $b \to c$ transitions with $u\bar{u}$, $d\bar{d}$ production or $b \to s$ transitions. Decays involving $b \to c$ with $s\bar{s}$ production have received less attention. We focus on $B \to \overline{\text{Baryon}}_c$ Baryon$_s$ Meson$_s$ (where the subscripts refer to the flavors namely, c for charm and s for strange), requiring at least one $s\bar{s}$ production coupled with a $b \to c$ transition. This exploration aims to shed light on how $s\bar{s}$ production can influence the branching fraction ($\mathcal{B}$) of these decays.

The analysis is conducted using Belle simulation, which involves $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ and $e^+e^- \to q\bar{q}(q = u, d, s, c)$. The Belle detector [6], which operated at the KEKB asymmetric-energy e^+e^- collider [7], collected data at a center-of-mass energy close to the $\Upsilon(4S)$ resonance from 1999 to 2010. Our analysis builds upon the inherent characteristic observed in $e^+e{-}B$ factory, where the $\Upsilon(4S)$ decays a pair of B mesons almost every time. The two B mesons undergo a back-to-back decay when viewed in the rest frame of the $\Upsilon(4S)$. It implies that they carry equal momentum in opposite directions and that knowing one of their kinematics gives access to the properties of other B meson without reconstructing it. Utilizing this property, we reconstruct one B meson (B_{tag}) via several hadronic modes and search for the accompanying particles of the charm baryon, i.e., Λ^0 and K/K^0_S, which are necessarily coming from the second B (B_{sig}). The charm baryon is considered as a missing (recoiling) particle and its four momentum is calculated from the known kinematics. With heavier and excited charm baryons, the exclusive reconstruction becomes challenging for their complicated decay processes, and that is where the recoil method helps.

2. Event Selection

For $B \to X_c^- \Lambda^0 K^+$, X_c can be Λ_c/Σ_c or any excited state of these baryons. Similarly, for $B \to X_c^0 \Lambda^0 K^0_S$, X_c can be Σ_c or other higher resonances of Σ_c. Determining the kinematic quantities requires reconstructing B_{tag} through fully hadronic modes. The reconstruction is done by an FEI (Full Event Reconstruction)[8] algorithm. To maximize the probability of getting a correct B_{tag}, its beam-constrained mass $M_{bc}(= \sqrt{E^2_{\text{beam}} - \vec{p}^{*2}_B})$ must be greater than 5.27 GeV/c^2 and the absolute value of the energy difference $\Delta E(= E^*_B - E_{\text{beam}})$ must be smaller than 0.05 GeV (E_{beam}, $\vec{p}_B$, E^*_B are the beam energy, momentum and energy of B meson calculated in rest frame of $\Upsilon(4S)$ respectively). The classifier output, $\mathcal{P}_{\text{FEI}}$, must be larger than 0.01 to enhance the purity. Whenever more than one B_{tag} candidate is present in an event, the one with the highest $\mathcal{P}_{\text{FEI}}$ value is retained for the analysis. Following the B_{tag} reconstruction, the subsequent step entails the reconstruction of a Λ^0 and a K/K^0_S candidate.

The Λ^0 candidates are reconstructed from their decay $\Lambda^0 \to p^+\pi^-$. Due to its long lifetime, Λ^0 particles travel a substantial distance before decaying. So, displaced vertices associated with two oppositely charged tracks are searched for. Selection criteria are also applied based on momentum, flight distance, and daughter-particle characteristics. Applying these criteria allows a considerable background of mis-reconstructed Λ^0 candidates to be suppressed. For the final selection of Λ^0 candidates, we require the $p\pi$ invariant mass to be within [1.113, 1.118] GeV/c^2, about three times the mass resolution. The K_S^0 candidates are reconstructed in the decay $K_S^0 \to \pi^+\pi^-$. The selection is similar to Λ^0, while the $\pi^+\pi^-$ invariant mass must lie within [0.490,0.505] GeV/c^2. The selection of the kaon track constraints on the impact parameters in the transverse plane and along the z axis to be smaller than 1 cm and 3 cm, respectively. These requirements effectively pinpoint the trajectory of the kaon track relative to the interaction point. Furthermore, particle identification criteria distinguish the kaon from other particle species.

3. Background Suppression

After all the selections, we look into the recoil mass (M_{recoil}) distribution, where the background due to $e^+e^- \to q\bar{q}$ light quark production (aka continuum) makes up nearly 54% of the total background. This background is suppressed with a boosted decision tree (BDT). A classifier is trained with several event-shape variables that discriminate the isotropic decays of B meson from the jet-like topology of continuum events. We retain events satisfying the BDT criterion that yields the maximum figure of merit, $\frac{S}{\sqrt{S+B}}$,(where S and B represent the number of signal and background events, respectively).

4. Signal Yield Estimation

After all the selections, the signal yield is estimated with a maximum likelihood fit to the unbinned distribution of M_{recoil}. The signal shapes are modeled with a sum of two Gaussians with a common mean, and an exponential function describes the backgrounds. The statistical significance obtained for $B^0 \to X_c^-\Lambda^0K^+$ is 5.8σ, and that for $B^0 \to X_c^0\Lambda^0K_S^0$ is 2.5σ. The significance is calculated using $\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{\max})}$ where $\mathcal{L}_0$ represents the likelihood without signal hypothesis and $\mathcal{L}_{\max}$ is the likelihood with a signal component.

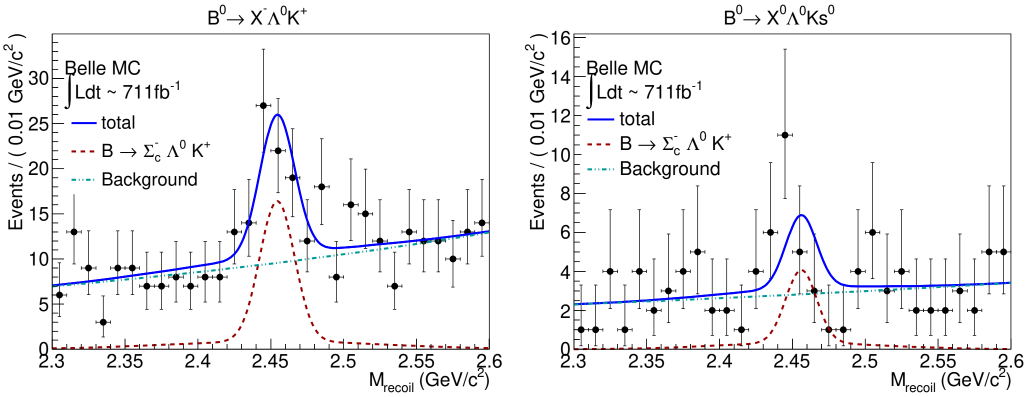

Figure 1: fit to the distribution of M_{recoil} of (left)$B^0 \to X_c^-\Lambda^0K^+$ and (right)$B^0 \to X_c^0\Lambda^0K_S^0$.

5. Result and Discussion

The obtained signal yield, N_{sig}, is used to calculate the decay branching fraction as

$$\mathcal{B} = \frac{N_{\text{sig}}}{N_{B\overline{B}} \times \epsilon \times \mathcal{B}_i}$$

Where $N_{B\overline{B}}$ represents the number of $B\bar{B}$ events, ϵ is the signal efficiency, and $\mathcal{B}_i$ is the product of branching fractions of the intermediate particle decays,(i.e. for $B^0 \to \Sigma_c^- \Lambda^0 K^+$, $\mathcal{B}_i$ is $\mathcal{B}(\Lambda^0 \to p^+\pi^-)$, and for $B^0 \to X_c^0 \Lambda^0 K_S^0$ it will be $\mathcal{B}(\Lambda^0 \to p^+\pi^-) \times \mathcal{B}(K_S^0 \to \pi^+\pi^-)$). The efficiencies are calculated from dedicated simulated samples of $B^0 \to \Sigma_c^- \Lambda^0 K^+$ and $B^0 \to \bar{\Sigma}_c^0 \Lambda^0 K_S^0$.

The obtained signal efficiencies and branching fractions are listed in Table 1. The calculated branching fractions are found to be consistent with the generated values coming from PYTHIA. Looking ahead, we will analyze the Belle(II) data, where the underlying mechanism might show a new picture. While the excited states of baryons are not simulated, their presence in data may direct towards new unknown modes.

Decay	$\epsilon(10^{-4})$	Yield	$\mathcal{B}(10^{-4})$
$B^0 \to \Sigma_c^- \Lambda^0 K^+$	6.16±0.25	62±13	2.02± 0.43
$B^0 \to \bar{\Sigma}_c^0 \Lambda^0 K_S^0$	1.89±0.14	17±7	2.4±0.95

Table 1: Summary of efficiency, signal yield, $\mathcal{B}$ for $B^0 \to \Sigma_c^- \Lambda^0 K^+$ and $B^0 \to \bar{\Sigma}_c^0 \Lambda^0 K_S^0$

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