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Rare and baryonic decays of charm hadrons at Belle and Belle II

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The Belle and Belle II experiments have collected a 1.5 ab^{-1} sample of e^+e^- collision data at centre-of-mass energies near the $\Upsilon(nS)$ resonances. These samples contain a large number of $e^+e^- \rightarrow c\bar{c}$ events that produce charmed mesons and baryons. We present searches for rare flavour-changing neutral current $c \rightarrow u\ell^+\ell^-$ processes in several decay modes. Further, we study several decays of the Λ_c and Ξ_c to determine branching fractions, as well as CP asymmetries in singly Cabibbo-suppressed decays.

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1. Introduction

The Belle experiment [1] was conducted at the KEK laboratory in Tsukuba, Japan, using the asymmetric-energy e^+e^- collider, KEKB, with beam collision energies at or near the $\Upsilon(4S)$ resonance. Belle II [2], the upgraded successor to Belle, is being performed with an upgraded detector at the SuperKEKB collider, which is designed to achieve an instantaneous luminosity 40 times higher than KEKB. As of 2024, Belle II has accumulated an integrated luminosity of 530 fb^{-1}, which, when combined with the Belle data, results in a total of 1.5 ab^{-1} of data. This large dataset enables a precise study of weak interactions, CP violation, and rare processes in the decays of beauty and charm hadrons.

In addition to the production of charm hadrons through $B\bar{B}$ pair decays, the continuum process $e^+e^- \rightarrow c\bar{c}$ also plays a crucial role due to its large cross-section of approximately 1.3 nb. This high production rate of charm hadrons facilitates comprehensive studies of charm physics, enabling precise measurements of charm lifetimes, branching fractions, and searches for rare or forbidden decays.

We present the latest Belle and Belle II results, including rare flavour-changing neutral current (FCNC) decays, baryon number violating (BNV) decays, and several measurements of branching fractions in charmed baryon decays.

2. Search for Rare Decays

2.1 Search for $D^0 \rightarrow h^-h^+e^+e^-$ decays in Belle

The decay $D^0 \rightarrow h^-h^+e^+e^-$ proceeds through two contributions: FCNC process $c \rightarrow u\ell^+\ell^-$, which is highly suppressed in the standard model (SM) and a long distance contribution enhanced by intermediate resonances [3]. Signals in the non-resonant region of $m_{e^+e^-}$ serve as sensitive probes for BSM physics, while in the resonance region, measurements of the branching fraction can test the SM.

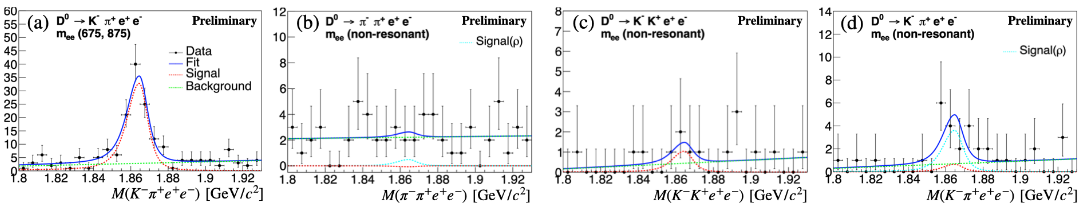

Figure 1: Invariant mass distribution of $D^0 \rightarrow h^-h^+e^+e^-$ candidates for $m_{e^+e^-}$ in resonance region (a) and non-resonant regions (b-d).

Using a dataset of 942 fb^{-1} collected by the Belle detector, we search for the decays $D^0 \rightarrow h^-h^+e^+e^-$ in both resonance and non-resonant regions as shown in Figure 1. In the mass range 675 MeV/c^2 < $m_{e^+e^-}$ < 875 MeV/c^2, we measure the branching fraction for $D^0 \rightarrow K^-\pi^+e^+e^-$ to be (39.6 ± 4.5 (stat.) ± 2.9 (syst.)) × 10^{-7}, which is consistent with the SM prediction and agrees with previous measurements from the BABAR experiment [4]. In non-resonant $m_{e^+e^-}$ regions, no significant signals were observed, and we set branching fraction upper limits at 90% confidence level (CL) in the range from 2×10^{-7} to 8×10^{-7}, which represent the most stringent limits to date for these decay modes.

2.2 Search for $\Xi_c^0 \to \Xi^0 \ell^+ \ell^-$ decays in Belle

In the SM, the weak current interaction exhibits Lepton Flavor Universality (LFU), meaning has identical coupling to all lepton generations. The LFU can be tested in semileptonic decays, such as $\Xi_c^0 \to \Xi^0 \ell^+ \ell^-$, where a comparison between the branching fractions for $\ell = e$ and $\ell = \mu$ serves as a probe for LFU.

Using the full dataset of 980 fb^{-1}, Belle reported the first search for the rare semileptonic decays $\Xi_c^0 \to \Xi^0 \ell^+ \ell^-$, where ℓ is either an electron or a muon [5]. As shown in Figure 2, no significant signal was observed in the invariant mass distributions of the $M(\Xi^0 \ell^+ \ell^-)$ candidates. As a result, we set the most stringent upper limits on the branching fractions at 90% CL: $\mathcal{B}(\Xi_c^0 \to \Xi^0 e^+ e^-) < 9.9 \times 10^{-5}$ and $\mathcal{B}(\Xi_c^0 \to \Xi^0 \mu^+ \mu^-) < 6.5 \times 10^{-5}$.

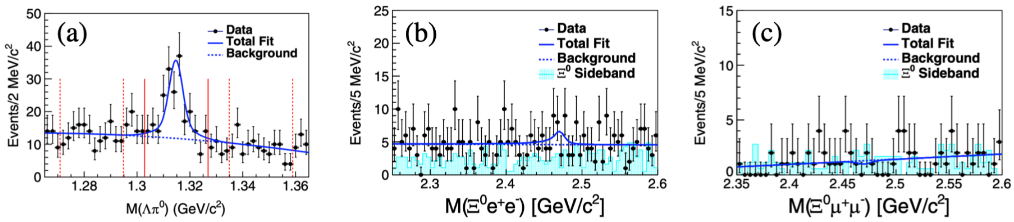

Figure 2: Invariant mass distribution of reconstructed $\Xi^0 \to \Lambda\pi^0$ candidates (a) and $\Xi_c^0 \to \Xi^0 \ell^+ \ell^-$ candidates (b and c).

2.3 Search for $D \to p\ell$ decays in Belle

BNV is a fundamental requirement to explain the matter-antimatter asymmetry observed in the universe. Several grand unified theories and BSM propose BNV processes of nucleons [6–10]. The $D \to p\ell$ decays, where D represents either a D^0 or $\bar{D}^0$ meson, and ℓ denotes either an electron or a muon, violate both baryon (B) and lepton (L) numbers. However, the difference between baryon and lepton numbers ($\Delta(B - L)$) remains conserved.

Recently, using the full dataset of 980 fb^{-1}, Belle reported the most stringent upper limits for the electron channels and the first-ever upper limits for the muon channels [11]. The upper limits range between $(5 - 8) \times 10^{-7}$, depending on the decay mode, as shown in Table 1.

Table 1: Reconstruction efficiency (ϵ), signal yield (N_S), signal significance (S), upper limit on the signal yield ($N_{p\ell}^{UL}$), and branching fraction ($\mathcal{B}$) at 90% CL for baryon number violating decay modes.

Decay mode	ϵ(%)	N_S	$S(\sigma)$	$N_{p\ell}^{UL}$	$\mathcal{B}$ (10^{-7})
$D^0 \to p e^-$	10.2	-6.4 ± 8.5	–	17.5	< 5.5
$\bar{D}^0 \to p e^-$	10.2	-18.4 ± 23.0	–	22.0	< 6.9
$D^0 \to \bar{p} e^+$	9.7	-4.7 ± 23.0	–	22.0	< 7.2
$\bar{D}^0 \to \bar{p} e^+$	9.6	7.1 ± 9.0	0.6	23.0	< 7.6
$D^0 \to p \mu^-$	10.7	11.0 ± 23.0	0.9	17.1	< 5.1
$\bar{D}^0 \to p \mu^-$	10.7	-10.8 ± 27.0	–	21.8	< 6.5
$D^0 \to \bar{p} \mu^+$	10.5	-4.5 ± 14.0	–	21.1	< 6.3
$\bar{D}^0 \to \bar{p} \mu^+$	10.4	16.7 ± 8.8	1.6	21.4	< 6.5

3. Intermediate structure of $\Lambda_c^+ \to pK_S^0\pi^0$ decay in Belle

Using the full dataset of 980 fb^{-1}, we investigate the intermediate structure of the $\Lambda_c^+ \to pK_S^0\pi^0$ decay. As shown in Figure 3 (a) and (b), a distinct peaking structure is observed in the $p\pi^0$ invariant mass distribution near the $p\eta$ mass threshold in the decay $\Lambda_c^+ \to pK_S^0\pi^0$. Furthermore, the same effect was observed in Figure 3 (c) [12]. This behavior is analogous to the threshold cusp observed at the $\eta\Lambda$ threshold in the $\Lambda_c^+ \to pK^-\pi^+$ decay, which was attributed to the $\Lambda(1670)$ resonance enhancing the threshold cusp effect[13, 14], suggesting that the peak near the $p\eta$ threshold can also be attributed to a threshold cusp enhanced by the $N(1535)^+$.

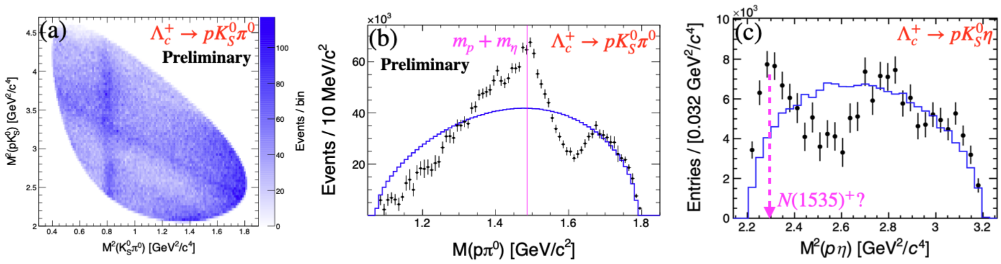

Figure 3: Dalitz plot (a) and efficiency-corrected mass projections of $M(p\pi^0)$ in the $\Lambda_c^+ \to pK_S^0\pi^0$ (b) and $M^2(p\eta)$ in the $\Lambda_c^+ \to pK_S^0\eta$ (c).

4. Branching Fractions of Charmed Baryon Decays

The weak decays of charmed baryons provide a unique platform for studying Quantum Chromodynamics (QCD) and the interplay between factorizable and non-factorizable effects in decay amplitudes. These decays are excellent probes of both strong and weak interactions, offering valuable insights into the dynamics of hadronic systems. Recent experimental results from Belle and Belle II have significantly improved the precision of branching fraction measurements, particularly for previously unmeasured decay modes.

For the first time in the charm sector, the combined Belle and Belle II datasets of 1.4 ab^{-1} have been used to measure the branching fractions of the decays of the charmed baryon Ξ_c^0 to the final states involving π^0, η, and η'. Figure 4 shows invariant mass distributions of Ξ_c^0 candidates decaying into $\Xi^0 h^0$. We reported the first measurement of three branching fractions [15]:

$$B(\Xi_c^0 \to \Xi^0\pi^0) = (6.9 \pm 0.3\ (\text{stat.}) \pm 0.5\ (\text{syst.}) \pm 1.3\ (\text{norm.})) \times 10^{-3}, \quad (1)$$

$$B(\Xi_c^0 \to \Xi^0\eta) = (1.6 \pm 0.2\ (\text{stat.}) \pm 0.2\ (\text{syst.}) \pm 0.3\ (\text{norm.})) \times 10^{-3}, \quad (2)$$

$$B(\Xi_c^0 \to \Xi^0\eta') = (1.2 \pm 0.3\ (\text{stat.}) \pm 0.1\ (\text{syst.}) \pm 0.2\ (\text{norm.})) \times 10^{-3}. \quad (3)$$

In addition, recent Belle results, using the full Belle dataset of 980 fb^{-1}, have reported precise measurements of the decays of the Λ_c^+ baryon, including both Cabibbo-Favored (CF) and Singly Cabibbo-Suppressed (SCS) decays [12, 16, 17]. The invariant mass distributions of Λ_c^+ candidates are shown in Figure 5. The measured branching fractions for CF decays include:

$$B(\Lambda_c^+ \to \Sigma^+\eta) = (3.14 \pm 0.35\ (\text{stat.}) \pm 0.17\ (\text{syst.}) \pm 0.25\ (\text{norm.})) \times 10^{-3}, \quad (4)$$

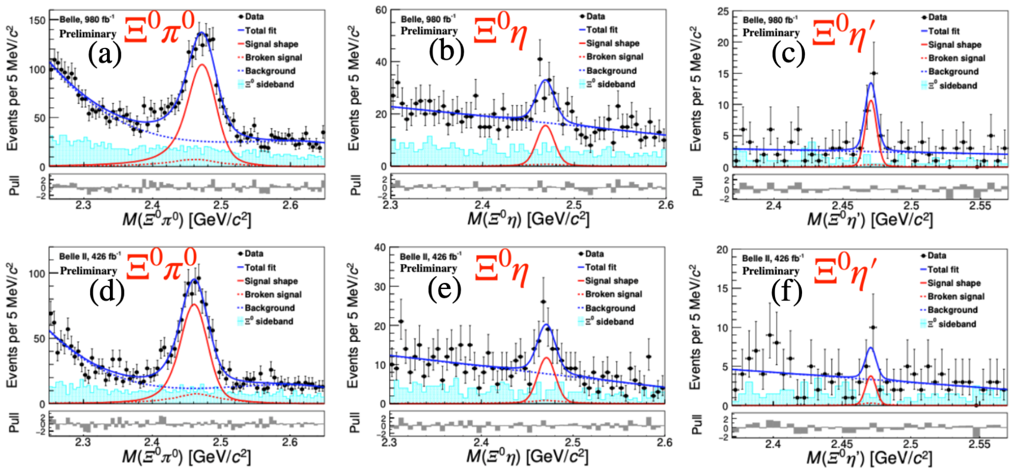

Figure 4: Invariant mass distributions and fit results of $\Xi_c^0 \to \Xi^0 h^0$ decays for Belle (upper) and Belle II (lower).

$$B(\Lambda_c^+ \to \Sigma^+\eta') = (4.16 \pm 0.75\,(\text{stat.}) \pm 0.17\,(\text{syst.}) \pm 0.25\,(\text{norm.})) \times 10^{-3}, \tag{5}$$

$$B(\Lambda_c^+ \to pK_S^0\eta) = (4.35 \pm 0.10\,(\text{stat.}) \pm 0.20\,(\text{syst.}) \pm 0.22\,(\text{norm.})) \times 10^{-3}. \tag{6}$$

$$B(\Lambda_c^+ \to pK_S^0\pi^0) = (2.12 \pm 0.01\,(\text{stat.}) \pm 0.05\,(\text{syst.}) \pm 0.10\,(\text{norm.})) \times 10^{-2}, \tag{7}$$

The branching fractions for the SCS decays of Λ_c^+ baryons include:

$$B(\Lambda_c^+ \to pK_S^0K_S^0) = (2.35 \pm 0.12\,(\text{stat.}) \pm 0.07\,(\text{syst.}) \pm 0.04\,(\text{norm.})) \times 10^{-4}, \tag{8}$$

$$B(\Lambda_c^+ \to \Lambda K^+) = (6.57 \pm 0.17\,(\text{stat.}) \pm 0.11\,(\text{syst.}) \pm 0.35\,(\text{norm.})) \times 10^{-4}, \tag{9}$$

$$B(\Lambda_c^+ \to \Sigma^0 K^+) = (3.58 \pm 0.19\,(\text{stat.}) \pm 0.06\,(\text{syst.}) \pm 0.19\,(\text{norm.})) \times 10^{-4}. \tag{10}$$

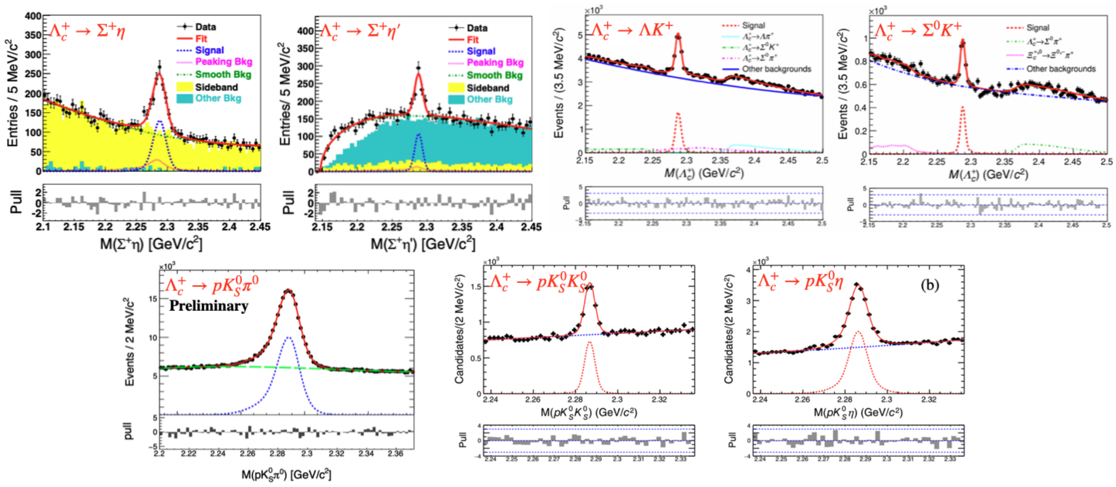

Figure 5: Invariant mass distributions and fit results of Λ_c^+ decays.

These results are either the first or the most accurate to date, highlighting Belle II's significant contributions to charmed baryon decays.

5. Conclusion

The Belle experiment, even though its data-taking ended nearly 15 years ago, continues to yield fruitful results in charm physics. Through its large dataset, we reported significant advancements in rare decays including $c \to u\ell\ell$ and baryon number violating processes. Additionally, extensive data of Belle allowed us to explore the intermediate structure of multibody decays.

Furthermore, we reported several branching fractions of charmed baryon decays, including the first-ever combined analysis of Belle and Belle II datasets in charm physics. With Belle II now joining the effort, its higher luminosity and advanced detectors will further enhance precision measurements, offering great potential for breakthroughs in charm physics.

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