Observation of $B^+ \to \Xi_c^0 \Lambda_c^+$ and Evidence for $B^0 \to \Xi_c^- \Lambda_c^+$

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We report the first observation of the decay $B^+ \rightarrow \Xi^0 \Lambda^+_c$ with a significance of 8.7 σ and evidence for the decay $B^0 \rightarrow \Xi^0 \Lambda^+_c$ with a significance of 3.8 σ. The product $B(B^+ \rightarrow \Xi^0 \Lambda^+_c) \times B(\Xi^0 \rightarrow \Xi^- \pi^+)$ is measured to be $(4.8_{-0.9}^{+1.0} \pm 1.1 \pm 1.2) \times 10^{-5}$, and $B(B^0 \rightarrow \Xi^0 \Lambda^+_c) \times B(\Xi^0 \rightarrow \Xi^+ \pi^- \pi^0)$ is measured to be $(9.3_{-2.8}^{+3.7} \pm 1.9 \pm 2.4) \times 10^{-5}$. The errors are statistical, systematic and the error of the $\Lambda_c^- \rightarrow pK^- \pi^+$ branching fraction, respectively. The decay $B^+ \rightarrow \Xi^0 \Lambda^+_c$ is the first example of a two-body exclusive $B^+$ decay into two charmed baryons. The data used for this analysis was accumulated at the $\Upsilon(4S)$ resonance, using the Belle detector at the $e^+e^-$ asymmetric-energy collider KEKB. The integrated luminosity of the data sample is equal to 357 fb$^{-1}$, corresponding to $386 \times 10^6 BB$ pairs.

FIG. 1: The quark diagram for the $B^+ \rightarrow \Xi^0 \Lambda^+_c$ decay.

A number of $B$-meson decay modes to final states containing baryons have been observed, including $b \rightarrow c\bar{c}d$ decays with either one final-state charmed meson (e.g. $B^0 \rightarrow D^0\bar{p}$) or a charmed baryon (e.g. $B^+ \rightarrow \Lambda_c^+ p\pi^+$), and charmless baryonic decays that proceed via $b \rightarrow s$ or $b \rightarrow u$ transitions. Two-body baryonic decay modes are found to have lower branching fractions than multi-body modes and, in the latter, near-threshold enhancements are observed in the baryon-pair invariant mass spectra. Some theoretical models attribute these phenomena to baryonic form factors that are large for multi-body modes.

Recently, Belle reported examples of baryonic decays that proceed via $b \rightarrow c\bar{c}s$ transitions: $B^- \rightarrow J/\psi\bar{p}$ and $B \rightarrow \Lambda_c^+ \Lambda_c^- K$. To date, however, nothing is experimentally known about two-body exclusive $B$ decays to two charmed baryons, which would also proceed through $b \rightarrow c\bar{c}s$ transitions. An example of such a decay is $B^+ \rightarrow \Xi^0 \Lambda^+_c$, which would proceed via the quark-diagram shown in Fig. 1. This two-body $B$ decay mode, like $B \rightarrow \Lambda_c^+ \Lambda_c^- K$, would produce a “wrong-sign” $\Lambda_c^+$, in contrast to all other known $B$ decay modes that only have $\bar{\Lambda}_c^-$’s in the final state. Recently the BaBar collaboration has measured the inclusive yield of (wrong-sign) $\Lambda_c^+$’s from $B$ decays. It was suggested that this type of $B$ decay might be a substantial component of baryonic $b \rightarrow c\bar{c}s$ transitions and could have an important influence on the determination of the charm particle yield per $B$ decay.

For exclusive two-body baryonic modes, a theoretical model based on QCD sum rules predicts $B(B \rightarrow \Xi \Lambda^+_c) \sim 10^{-3}$. Experimental measurements of $B \rightarrow \Xi \Lambda^+_c$ test theoretical predictions and provide additional information on the dynamics of two-body baryonic $B$ decays.

In this Letter we report the first observation of $B^+ \rightarrow \Xi^0 \Lambda^+_c$ and evidence for $B^0 \rightarrow \Xi^0 \Lambda^+_c$ decays. Charge conjugation is implied here and throughout the paper. The analysis is performed using data collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider. The data sample consists of 357 fb$^{-1}$ collected at the $\Upsilon(4S)$ resonance, which corresponds to $386 \times 10^6 BB$ pairs.

The Belle detector is a large-solid-angle magnetic spectrometer that 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 (ECL) comprised of CsI(Tl) crystals 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 $K^0_L$ mesons and to identify muons (KLM). The detector is described in detail elsewhere. Two different inner detector configurations were used. For the first sample of 152 million $BB$ pairs (Set I), a 2.0 cm radius beampipe and a 3-layer silicon vertex detector were used; for the latter 234 million $BB$ pairs (Set II), a 1.5 cm ra-
The $\Delta E$ and $M_{bc}$ distributions for the $B^+ \rightarrow \Xi_c^0 \Lambda_c^+$ candidates are shown in Figs. 22(a) and (b), where the two $\Xi_c^0$ modes are combined. We require $M_{bc} > 5.272$ GeV/c$^2$ $(|\Delta E| < 0.025$ GeV) for the $\Delta E$ ($M_{bc}$) projection 18. The hatched histograms in Figs. 22(a) and (b) show the sum of normalized $\Lambda_c^+$ and $\Xi_c^0$ mass sidebands 19, where no peaking structures are evident. The superimposed curves are the results of a simultaneous two-dimensional binned maximum likelihood fit to the both $\Delta E$ versus $M_{bc}$ distributions (for the two $\Xi_c^0$ channels) with a common value of $B(B^+ \rightarrow \Xi_c^0 \Lambda_c^+) \times B(\Xi_c^0 \rightarrow \Xi_c^0 + \pi^0) \times B(\Lambda_c^+ \rightarrow pK^+\pi^-)$. For this fit, we constrain the ratio $B(\Xi_c^0 \rightarrow \Lambda K^-\pi^+ + \Lambda K^-\pi^0 + \Lambda K^+\pi^-)/B(\Xi_c^0 \rightarrow \Xi^+ + \pi^0)$ to the recent Belle measurement of $1.07 \pm 0.12 \pm 0.07$ 20. To describe the signal we use Gaussians with means and widths fixed to the values obtained from MC. The backgrounds in $\Delta E$ and $M_{bc}$ are parametrized by a first-order polynomial and an ARGUS function 21, respectively. The fit gives a statistical significance of 8.7σ for the signal, where the statistical significance is defined as $\sqrt{2\ln(L_0/L_{\text{max}})}$, where $L_0$ and $L_{\text{max}}$ are the likelihoods with the signal fixed at zero and at the fitted value, respectively. The region $\Delta E < -0.08$ GeV is excluded from the fit to avoid possible contributions from $B^{'+0} \rightarrow \Xi_c^0 \Lambda_c^{0(0)/-}$ and $B^{0(+)} \rightarrow \Xi_c^0 \Sigma_c^{0(0)/+}$, $\Sigma_c^{0(0)/+} \rightarrow \Lambda_c^+ \pi^-\pi^0$ decays, where the pion is undetected. The same fitting procedure applied separately for the two $\Xi_c^0$ modes gives $12.4_{-3.4}^{+4.8}$ (6.8 σ significance) and $16.9_{-4.6}^{+4.8}$ (5.9 σ significance) events for $B^+ \rightarrow \Xi_c^0 \Lambda_c^+$ followed by $\Xi_c^0 \rightarrow \Xi^- + \pi^+$ and $B^+ \rightarrow \Xi_c^0 \Lambda_c^+$ followed by $\Xi_c^0 \rightarrow \Lambda K^-\pi^-$, respectively.

As a cross-check of the $B^+ \rightarrow \Xi_c^0 \Lambda_c^+$ signal, we select events in the $B$-signal region of $|\Delta E| < 0.025$ GeV and $M_{bc} > 5.272$ GeV/c$^2$ for two $\Xi_c^0$ modes and examine the $\Lambda_c^+$ and $\Xi_c^0$ mass distributions (Fig. 22(c) and (d)). For the $\Lambda_c^+$ ($\Xi_c^0$) distribution we require $\Xi_c^0$ ($\Lambda_c^+$) to be within $\pm 15$ MeV/c$^2$ of the nominal mass. We then fit each distribution with two Gaussians for the signal and a first-order polynomial to describe the background. The widths and means of the Gaussians are fixed to the values obtained from data as described above. The fitted signal yields of $32.6 \pm 7.2$ events for the $\Lambda_c^+$ and $29.4 \pm 6.9$ events for the $\Xi_c^0$ are in good agreement with the total signal yield for $B^+ \rightarrow \Xi_c^0 \Lambda_c^+$, including the two $\Xi_c^0$ decay modes.

The $B^0 \rightarrow \Xi_c^- \Lambda_c^+$ mode is an isospin partner of the $B^+ \rightarrow \Xi_c^0 \Lambda_c^+$ mode. Therefore their branching fractions are expected to be of the same order of magnitude. The $\Delta E$ and $M_{bc}$ distributions for the $B^0 \rightarrow \Xi_c^- \Lambda_c^+$ candidates are shown in Figs. 23(a) and (b). The superimposed curves are the results of a two-dimensional binned maximum likelihood fit to the $\Delta E$ versus $M_{bc}$ distribution. The fit gives $8.3_{-3.3}^{+3.3}$ signal events. The signal significance is 3.8σ, taking into account the systematic uncertainty from the signal and background parameterization. The hatched histogram shows the sum of the normalized $\Lambda_c^+$ and $\Xi_c^-$ mass sidebands. We apply the same procedure...
TABLE I: Summary of the fit results, efficiencies, products of branching fractions and statistical significances. For the $B^+$ for two $\Xi^0_b$ modes the product of branching fractions is $B(B^+ \rightarrow \Xi^0_b \Lambda^+_c) \times B(\Xi^0_b \rightarrow \Xi^- \pi^+)$ since for $\Xi^0_b \rightarrow \Lambda K^- \pi^+$ we use the ratio $B(\Xi^0_b \rightarrow \Lambda K^- \pi^+)/B(\Xi^0_b \rightarrow \Xi^- \pi^+)$ mentioned in the text. The uncertainties in the products of the branching ratios are statistical, systematic and the uncertainty of the $\Lambda^+_c \rightarrow p K^- \pi^+$ branching fraction.

| Decay Mode |
|------------|
| $B^+ \rightarrow \Xi^0_b \Lambda^+_c$, $\Xi^0_c \rightarrow \Xi^- \pi^+$ | 12.4$^{+2.4}_{-2.3}$ | 1.14 | 5.6$^{+1.5}_{-1.3}$ ± 1.1 ± 1.5 | 6.8$e$ |
| $B^+ \rightarrow \Xi^0_b \Lambda^+_c$, $\Xi^0_c \rightarrow \bar{\Lambda} K^+ \pi^-$ | 16.9$^{+4.8}_{-4.0}$ | 2.04 | 4.0$^{+1.1}_{-0.9}$ ± 0.9 ± 1.0 | 5.9$e$ |
| $B^+ \rightarrow \Xi^0_b \Lambda^+_c$, simultaneous fit | 4.8$^{+1.1}_{-0.9}$ ± 1.1 ± 1.2 | 8.7$e$ |
| $B^0 \rightarrow \Xi^0_c \Lambda^+_c$, $\Xi^0_c \rightarrow \Xi^- \pi^-$ | 8.3$^{+2.4}_{-2.5}$ | 0.46 | 9.3$^{+1.0}_{-2.5}$ ± 1.9 ± 2.4 | 3.8$e$ |

![Figure 2](image2.png)

FIG. 2: a) and b): The $\Delta E$(a)) and $M_{bc}$(b)) distributions for the $B^+ \rightarrow \Xi^0_b \Lambda^+_c$ candidates. The hatched histograms show the combined $\Xi^0_b$ and $\Lambda^+_c$ mass sidebands normalized to the signal region. The excess around $\Delta E = -0.150$ GeV may be due to the contributions from $B^{+}/0 \rightarrow \Xi^0_b \Lambda^+_c \pi^0/-$ and $B^{0}/+ \rightarrow \Xi^0_b \Sigma^0/+, \Sigma^0/+ \rightarrow \Lambda^+_c \pi^-/0$ decays, where the pion is undetected. Therefore, we exclude this region from the fit. c) and d): The $\Xi^0_c$ (c)) and $\Lambda^+_c$ (d)) mass distributions for the $B^+ \rightarrow \Xi^0_b \Lambda^+_c$ candidates taken from the B-signal region of $|\Delta E| < 0.025$ GeV and $M_{bc} > 5.272$ GeV/$c^2$. For the $\Xi^0_b$ ($\Lambda^+_c$) distribution we require $\Lambda^+_c$ ($\Xi^0_b$) to be within $\pm 15$ MeV/$c^2$ of the nominal mass. The overlaid curves are the fit results (see the text).

![Figure 3](image3.png)

FIG. 3: a) and b): The $\Delta E$(a)) and $M_{bc}$(b)) distributions for the $B^0 \rightarrow \Xi^- \Lambda^+_c$ candidates. The hatched histograms show the combined $\Xi^0_c$ and $\Lambda^+_c$ mass sidebands normalized to the signal region. c) and d): The $\Xi^- (c))$ and $\Lambda^+_c (d))$ mass distributions for the $B^0 \rightarrow \Xi^- \Lambda^+_c$ candidates taken from the B-signal region of $|\Delta E| < 0.025$ GeV and $M_{bc} > 5.272$ GeV/$c^2$. For the $\Xi^- (\Lambda^+_c)$ distribution we require $\Lambda^+_c (\Xi^-)$ to be within $\pm 15$ MeV/$c^2$ of the nominal mass. The overlaid curves are the fit results (see the text).

![Image](image.png)

used for $B^+ \rightarrow \Xi^0_b \Lambda^+_c$ to check the $\Lambda^+_c$ and $\Xi^-_c$ signals as shown in Figs. (c) and (d). The fit gives $9.0 \pm 3.0$ events for the $\Lambda^+_c$ and $8.4 \pm 2.8$ events for the $\Xi^-_c$. Both are in agreement with the $B^0 \rightarrow \Xi^-_c \Lambda^+_c$ signal yield.

Table summarizes the results of the fits for the $B^+$ and $B^0$ decays, the reconstruction efficiencies including the $B(\Lambda \rightarrow p \pi^-)$, statistical significance of the signals and extracted products of branching fractions. Here we use $B(\Lambda^+_c \rightarrow p K^- \pi^+) = (5.0 \pm 1.3)%$ and assume equal fractions of charged and neutral $B$ mesons produced in $\Upsilon(4S)$ decays.

The major sources of systematic error are the uncertainties in the tracking efficiency of 7% (1% per track), 11% in charged particle identification efficiency (1% for pion, 2% for kaon and 3% for proton), 5% in $\Lambda$ finding, 6% in efficiency estimation due to MC statistics, 10% in the signal and background parameterization, and 13% in $B(\Xi^0_b \rightarrow \Lambda K^- \pi^+)/B(\Xi^0_b \rightarrow \Xi^- \pi^+)$.

Added in quadrature, these correspond to a total systematic error of 23% for $B^+ \rightarrow \Xi^0_b \Lambda^+_c$ and 20% for $B^0 \rightarrow \Xi^-_c \Lambda^+_c$. 
In summary, we report the first observation of the $B^+ \rightarrow \Xi_c^0 \Lambda_c^+$ decay mode and the first evidence for the $B^0 \rightarrow \Xi_c^- \Lambda_c^+$ decay mode. The products of branching fractions $B(B^+ \rightarrow \Xi_c^0 \Lambda_c^+) \times B(\Xi_c^0 \rightarrow \Xi^+ \pi^-) = (4.8^{+1.0}_{-0.9}\pm 1.1\pm 1.2) \times 10^{-5}$ and $B(B^0 \rightarrow \Xi_c^- \Lambda_c^+) \times B(\Xi_c^- \rightarrow \Xi^+ \pi^- \pi^-) = (9.3^{+3.7}_{-2.8}\pm 1.9\pm 2.4) \times 10^{-5}$ are measured with $8.7 \sigma$ and $3.8 \sigma$ significance, respectively. These results and Belle’s recent observation of $B \rightarrow \Lambda_c^+ \Lambda_c^- K^+$ decays are the first examples of $B$ decays into two charmed baryons. The branching fraction obtained for $B^+ \rightarrow \Xi_c^0 \Lambda_c^+$ together with the theoretical predictions for $B(\Xi_c^0 \rightarrow \Xi^+ \pi^-)$ of $\sim (0.9 - 2)\%$ result in $B(B^+ \rightarrow \Xi_c^0 \Lambda_c^+) \sim (2.4 - 5.3) \times 10^{-3}$. This can be compared with the theoretical prediction of $10^{-3}$.

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