Observation of $B^+ \to \Lambda_c^+ \Lambda_c^- K^+$ and $B^0 \to \Lambda_c^+ \Lambda_c^- K^0$ Decays

N. Gabyshev,[1] K. Abe,[6] K. Abe,[37] I. Adachi,[6] H. Aihara,[39] Y. Asano,[42] V. Aulchenko,[1] T. Aushev,[10] S. Bahinipati,[3] A. M. Bakich,[34] V. Balagura,[10] E. Barberio,[17] W. Bartel,[4] A. Bay,[14] I. Bedny,[1] U. Bitenc,[11] I. Bizjak,[11] A. Bondar,[1] A. Bozek,[23] M. Bračko,[6,16,11] T. E. Browder,[5] A. Chen,[20] W. T. Chen,[20] B. G. Cheon,[2] R. Chistov,[10] Y. Choi,[33] A. Chuvikov,[29] S. Cole,[34] J. Dalseno,[17] M. Danilov,[10] M. Dash,[43] A. Drutskoy,[3] S. Eidelman,[1] A. Garmash,[29] T. Gershon,[6] G. Gokhroo,[35] B. Golob,[15,11] J. Haba,[6] K. Hayasaka,[18] H. Hayashii,[19] M. Hazumi,[6] T. Hokuue,[18] Y. Hoshi,[37] S. Hou,[20] W.-S. Hou,[22] Y. B. Hsiung,[22] K. Ikado,[18] A. Imoto,[19] K. Inami,[18] R. Itoh,[6] M. Iwasaki,[39] Y. Iwasaki,[6] J. H. Kang,[44] T. Kawasaki,[24] H. R. Khan,[40] H. Kichimi,[6] S. M. Kim,[33] S. Korpar,[16,11] P. Krokovny,[1] R. Kulasiri,[3] C. C. Kuo,[20] A. Kuzmin,[1] Y.-J. Kwon,[44] G. Leder,[9] T. Lesiak,[23] S.-W. Lin,[22] D. Liventsev,[10] G. Majumder,[35] T. Matsumoto,[41] W. Mitaroff,[9] K. Miyabayashi,[19] H. Miyata,[24] Y. Miyazaki,[18] R. Mizuk,[10] E. Nakano,[26] M. Nakao,[6] Z. Natkaniec,[23] S. Nishida,[6] S. Ogawa,[36] T. Ohshima,[18] T. Okabe,[18] S. Okuno,[12] S. L. Olsen,[5] H. Ozaki,[6] H. Palka,[23] C. W. Park,[33] K. S. Park,[33] R. Pestotnik,[11] L. E. Piilonen,[43] Y. Sakai,[6] N. Sato,[18] N. Satoyama,[32] T. Schietinger,[14] O. Schneider,[14] C. Schwanda,[9] R. Seidl,[30] K. Senyo,[18] M. E. Sevior,[17] M. Shapkin,[8] H. Shibuya,[36] A. Somov,[3] N. Soni,[27] R. Stamen,[6] S. Stanič,[25] M. Starič,[11] T. Sumiyoshi,[41] K. Tamai,[6] N. Tamura,[24] M. Tanaka,[6] G. N. Taylor,[17] Y. Teramoto,[26] X. C. Tian,[28] T. Tsukamoto,[6] S. Uehara,[6] T. Uglov,[10] K. Ueno,[22] S. Uno,[6] P. Urquijo,[17] G. Varner,[5] K. E. Varvell,[34] S. Villa,[14] C. C. Wang,[22] C. H. Wang,[21] Y. Watanabe,[40] E. Won,[13] Q. L. Xie,[7] A. Yamaguchi,[38] M. Yamauchi,[6] J. Ying,[28] and Z. P. Zhang[31]

(Belle Collaboration)

[1]*Budker Institute of Nuclear Physics, Novosibirsk*
[2]*Chonnam National University, Kwangju*
[3]*University of Cincinnati, Cincinnati, Ohio 45221*
[4]*Deutsches Elektronen-Synchrotron, Hamburg*
[5]*University of Hawaii, Honolulu, Hawaii 96822*
[6]*High Energy Accelerator Research Organization (KEK), Tsukuba*
[7]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing*
[8]*Institute of High Energy Physics, Protvino*
[9]*Institute of High Energy Physics, Vienna*
[10]*Institute for Theoretical and Experimental Physics, Moscow*
[11]*J. Stefan Institute, Ljubljana*
[12]*Kanagawa University, Yokohama*
[13]*Korea University, Seoul*
[14]*Swiss Federal Institute of Technology of Lausanne, EPFL, Lausanne*
[15]*University of Ljubljana, Ljubljana*
[16]*University of Maribor, Maribor*
[17]*University of Melbourne, Victoria*
[18]*Nagoya University, Nagoya*
[19]*Nara Women's University, Nara*
[20]*National Central University, Chung-li*
[21]*National United University, Miao Li*
[22]*Department of Physics, National Taiwan University, Taipei*
[23]*H. Niewodniczanski Institute of Nuclear Physics, Krakow*
[24]*Niigata University, Niigata*
[25]*Nova Gorica Polytechnic, Nova Gorica*
[26]*Osaka City University, Osaka*
[27]*Panjab University, Chandigarh*
[28]*Peking University, Beijing*
[29]*Princeton University, Princeton, New Jersey 08544*
[30]*RIKEN BNL Research Center, Upton, New York 11973*
[31]*University of Science and Technology of China, Hefei*
[32]*Shinshu University, Nagano*
[33]*Sungkyunkwan University, Suwon*
[34]*University of Sydney, Sydney NSW*
[35]*Tata Institute of Fundamental Research, Bombay*

[36]*Toho University, Funabashi*
[37]*Tohoku Gakuin University, Tagajo*
[38]*Tohoku University, Sendai*
[39]*Department of Physics, University of Tokyo, Tokyo*
[40]*Tokyo Institute of Technology, Tokyo*
[41]*Tokyo Metropolitan University, Tokyo*
[42]*University of Tsukuba, Tsukuba*
[43]*Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061*
[44]*Yonsei University, Seoul*
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We report the first measurements of the doubly charmed baryonic B decays $B \to \Lambda_c^+ \Lambda_c^- K$. The $B^+ \to \Lambda_c^+ \Lambda_c^- K^+$ decay is observed with a branching fraction of $(6.5^{+1.0}_{-0.9} \pm 1.1 \pm 3.4) \times 10^{-4}$ and a statistical significance of 15.4σ. The $B^0 \to \Lambda_c^+ \Lambda_c^- K^0$ decay is observed with a branching fraction of $(7.9^{+2.9}_{-2.3} \pm 1.2 \pm 4.1) \times 10^{-4}$ and a statistical significance of 6.6σ. The branching fraction errors are statistical, systematic, and the error resulting from the uncertainty of the $\Lambda_c^+ \to pK^-\pi^+$ decay branching fraction. The analysis is based on 357 fb^{-1} of data accumulated at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider.

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Recently, a number of studies of single charmed baryon production in B decays have been reported [1–4]. The measured branching fractions of the two-body single charmed baryon decays $\bar{B}^0 \to \Lambda_c^+ \bar{p}$ [3] and $B^- \to \Sigma_c^0(2455)\bar{p}$ [4] are significantly smaller than theoretical expectations [5–8]. The multibody single charmed baryon decays $\bar{B} \to \Lambda_c^+ \bar{p}\pi(\pi)$ were found to have branching fractions about 1 order of magnitude larger than the corresponding two-body decays but still below theoretical predictions. While single charm production proceeds via a $b \to c\bar{u}d$ quark transition, production of two charmed particles occurs via a $b \to c\bar{c}s$ transition. In contrast to the single charmed baryon production, the two-body doubly charmed baryon B decay $B^+ \to \bar{\Xi}_c^0 \Lambda_c^+$ [9] recently observed at Belle has a branching fraction comparable to theoretical predictions [5]. It would be interesting to check whether theory can describe multibody double charmed decays. In this Letter, we report the first observation of the $B^+ \to \Lambda_c^+ \Lambda_c^- K^+$ and $B^0 \to \Lambda_c^+ \Lambda_c^- K^0$ decays, which are three-body decays that proceed via a $b \to c\bar{c}s$ transition. Inclusion of charge conjugate states is implicit unless otherwise stated. The analysis is based on a data sample of 357 fb^{-1} accumulated at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy collider corresponding to 386×10^6 $B\bar{B}$ 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 Čerenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter 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_L^0 mesons and to identify muons. The Belle detector is described in detail elsewhere [10]. Two different inner detector configurations were used. For the first sample of 152×10^6 $B\bar{B}$ pairs, a 2.0 cm radius beam pipe and a 3-layer silicon vertex detector were used; for the latter 234×10^6 $B\bar{B}$ pairs, a 1.5 cm radius beam pipe, a 4-layer silicon detector, and a small-cell inner drift chamber were used [11]. We use a GEANT-based Monte Carlo (MC) simulation to model the response of the detector and determine its acceptance [12].

We detect the Λ_c^+ via the $\Lambda_c^+ \to pK^-\pi^+$, $p\bar{K}^0$, and $\Lambda\pi^+$ decay channels. When a Λ_c^+ and Λ_c^- are combined as B decay daughters, at least one of $\Lambda_c^{\pm}$ is required to have been reconstructed via the $pK^{\mp}\pi^{\pm}$ decay process. For each charged track, the particle identification (PID) information from the CDC, ACC, and TOF is used to construct likelihood functions L_p, L_K, and L_π for the proton, kaon, and pion assignments, respectively. Likelihood ratios $L_a/(L_a + L_b)$ are required to be greater than 0.6 to identify a particle as type a, where b denotes the other two possible hadron assignments from the three possiblities: proton, kaon, and pion. For the main mode $B^+ \to \Lambda_c^+ \Lambda_c^- K^+$, $\Lambda_c^+ \to pK^-\pi^+$, $\Lambda_c^- \to \bar{p}K^+\pi^-$, the PID efficiency for the primary K^+ is about 95%. Efficiencies for protons, kaons, and pions from Λ_c^+ decays are about 98%. The misidentification probability for pions (or kaons) to be identified as kaons (or pions) is less than 5%. The probability for pions or kaons to be identified as protons is less than 2%. Tracks consistent with an electron or muon hypothesis are rejected. A Λ_c^+ candidate is selected if the mass of its decay products is within 0.010 GeV/c^2 (2.5σ) of the nominal Λ_c^+ mass.

Neutral kaons are reconstructed in the $K_S^0 \to \pi^+\pi^-$ decay. Candidate Λ baryons are reconstructed in the decay $\Lambda \to p\pi^-$. We apply vertex and mass constrained fits for the K^0 and Λ candidates to improve the momentum resolution. The intersection point of the K^0 and Λ candidate daughter tracks must be displaced from the beam interaction point: The flight distance should be more than 0.5 mm.

A K^0 candidate is selected if the mass of its decay products is within 7.5 MeV/c^2 (3σ) of the K^0 mass. A Λ candidate is selected if the mass of its decay products is within 2.5 MeV/c^2 (2.5σ) of the Λ mass.

The B candidates are identified using the beam-energy-constrained mass $M_{\rm bc}$ and the mass difference ΔM_B. The beam-energy-constrained mass is defined as $M_{\rm bc} \equiv \sqrt{E_{\rm beam}^2 - (\sum \vec{p}_i)^2}$, where $E_{\rm beam}$ is the beam energy, and $\vec{p}_i$ are the three-momenta of the B meson decay products, all defined in the center-of-mass system (CMS) of the e^+e^- collision. The mass difference is defined as $\Delta M_B \equiv M(B) - m_B$, where $M(B)$ is the reconstructed mass of the B candidate and m_B is the world average B meson mass. The parameter ΔM_B is used instead of the energy difference $\Delta E = (\sum E_i) - E_{\rm beam}$, where E_i is the CMS energy of the B decay products, since ΔE shows a correlation with $M_{\rm bc}$, while ΔM_B does not [13]. $M(B) = \sqrt{E(B)^2 - (\sum \vec{p}_i)^2}$, where $E(B) = E(\Lambda_c^+) + E(\Lambda_c^-) + E(K)$, $E(\Lambda_c^+) = \sqrt{\vec{p}_{\Lambda_c^+}^2 + m_{\Lambda_c^+}^2}$, $\vec{p}_{\Lambda_c^+}$ is the Λ_c^+ momentum measured via its decay products, and $m_{\Lambda_c^+}$ is the value of the Λ_c^+ baryon mass [14]. We select events with $M_{\rm bc} > 5.20$ GeV/c^2 and $|\Delta M_B| < 0.20$ GeV/c^2. The prompt K^+ or the reconstructed K_S^0 trajectory and the Λ_c^+ or Λ_c^- trajectories are required to form a common B decay vertex. If there are multiple candidates in an event, the candidate with the best χ_B^2 for the B vertex fit is selected. The B vertex fit is performed without additional mass constraints for known particles.

Figure 1 shows ΔM_B and $M_{\rm bc}$ projections for selected $B^+ \to \Lambda_c^+ \Lambda_c^- K^+$ and $B^0 \to \Lambda_c^+ \Lambda_c^- K^0$ decay events. The ΔM_B projection is shown for $M_{\rm bc} > 5.27$ GeV/c^2, and the $M_{\rm bc}$ projection is shown for $|\Delta M_B| < 0.015$ GeV/c^2. The widths determined from single Gaussian fits to MC-generated events are 2.7 and 3.3 MeV/c^2 for $M_{\rm bc}$ and ΔM_B, respectively. A two-dimensional binned maximum likelihood fit is performed to determine the signal yield. The ΔM_B distribution is approximated by a Gaussian for the signal plus a first order polynomial for the background, and the $M_{\rm bc}$ distribution is represented by a single Gaussian for the signal plus an ARGUS function [15] for the background. The signal shape parameters are fixed to the values obtained from a fit to a MC simulation. All yields and background shape parameters are allowed to float.

From the fit, we obtain signal yields of $48.5^{+7.5}_{-6.8}$ and $10.5^{+3.8}_{-3.1}$ events with statistical significances of 15.4σ and 6.6σ, for $B^+ \to \Lambda_c^+ \Lambda_c^- K^+$ and $B^0 \to \Lambda_c^+ \Lambda_c^- K^0$, respectively. The significance is calculated as $\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{\rm max})}$, where $\mathcal{L}_{\rm max}$ and $\mathcal{L}_0$ denote the maximum likelihoods with the fitted signal yield and with the yield fixed at zero, respectively.

The branching fraction $\mathcal{B}_{ij}$ for the ith Λ_c^+ decay and the jth Λ_c^- decay mode are calculated as $\mathcal{B}_{ij} = N_{ij}/[N_{B\bar{B}}\varepsilon_{ij}\mathcal{B}_i(\Lambda_c^+)\mathcal{B}_j(\Lambda_c^-)]$, where N_{ij} is the B signal yield. The detection efficiencies ε_{ij} are determined from MC simulation. The Λ_c^+ decay branching fractions $\mathcal{B}_i(\Lambda_c^+)$ are converted to the product $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)\Gamma_i/\Gamma(pK^-\pi^+)$ to isolate the common uncertainty from the branching fraction of $\Lambda_c^+ \to pK^-\pi^+$. The values of $\Gamma_i/\Gamma(pK^-\pi^+)$ are (0.47 ± 0.04) and (0.180 ± 0.032) for the pK^0 and $\Lambda\pi^+$ modes, respectively [16]. The overall detection efficiency ε for the total signal yield N is calculated as $\sum \varepsilon_{ij}[\Gamma_i/\Gamma(pK^-\pi^+)][\Gamma_j/\Gamma(pK^-\pi^+)]$. The overall branching fraction is calculated as

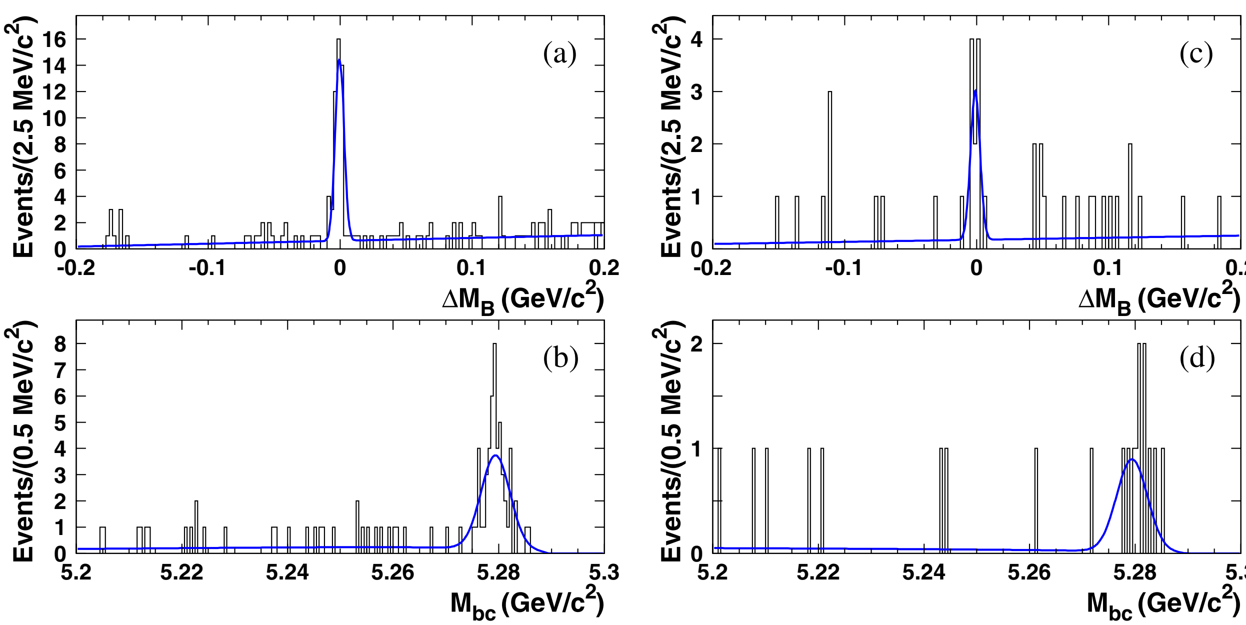

FIG. 1 (color online). Candidate (a),(b) $B^+ \to \Lambda_c^+ \Lambda_c^- K^+$ and (c),(d) $B^0 \to \Lambda_c^+ \Lambda_c^- K^0$ decay events: (a),(c) ΔM_B distribution for $M_{\rm bc} > 5.27$ GeV/c^2 and (b),(d) $M_{\rm bc}$ distribution for $|\Delta M_B| < 0.015$ GeV/c^2. Curves indicate the fit results.

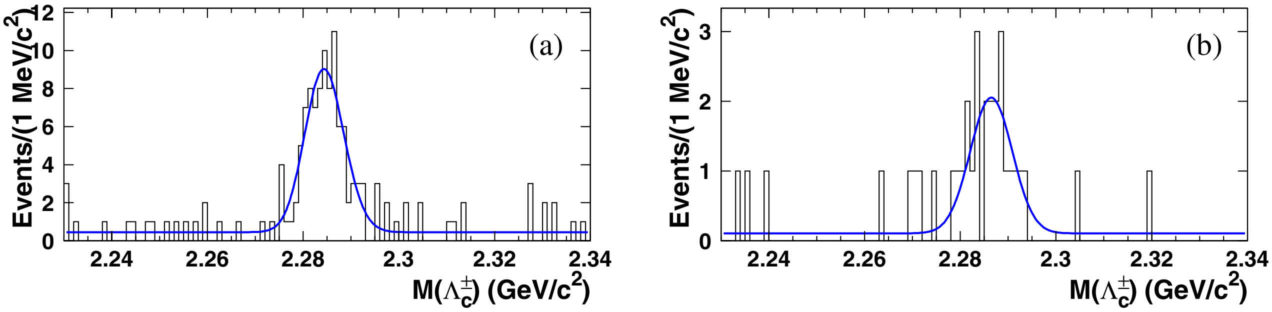

FIG. 2 (color online). $M(\Lambda_c^\pm)$ mass distributions for (a) $B^+ \to \Lambda_c^+ \Lambda_c^- K^+$ and (b) $B^0 \to \Lambda_c^+ \Lambda_c^- K^0$ decay candidates in the B signal region. Curves indicate the fit results.

$N_S/[N_{B\bar{B}} \varepsilon \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)^2]$, using the overall signal yield N_S and the decay branching fraction $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = (5.0 \pm 1.3)\%$ [16]. The detection efficiencies are calculated to be 7.79% for the $B^+ \to \Lambda_c^+ \Lambda_c^- K^+$ decay and 1.38% for the $B^0 \to \Lambda_c^+ \Lambda_c^- K^0$ decay.

The number of $B\bar{B}$ pairs $N_{B\bar{B}}$ is $(386 \pm 4) \times 10^6$. The fractions of charged and neutral B mesons are assumed to be equal. We obtain branching fractions of

$$\mathcal{B}(B^+ \to \Lambda_c^+ \Lambda_c^- K^+) = (6.5^{+1.0}_{-0.9} \pm 1.1 \pm 3.4) \times 10^{-4}$$

and $$\mathcal{B}(B^0 \to \Lambda_c^+ \Lambda_c^- K^0) = (7.9^{+2.9}_{-2.3} \pm 1.2 \pm 4.1) \times 10^{-4},$$

where the first and the second errors are statistical and systematic, respectively. The last error is due to the 52% uncertainty in the absolute branching fraction $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$.

Systematic uncertainties in the detection efficiencies arise from the track reconstruction efficiency (8%–10% depending on the process, assuming a correlated systematic error of about 1% per charged track), the PID efficiency (9%–10% assuming a correlated systematic error of 2% per proton and 1% per pion or kaon), three-body decay model uncertainty (11% for the $B^+ \to \Lambda_c^+ \Lambda_c^- K^+$ decay and 5% for the $B^0 \to \Lambda_c^+ \Lambda_c^- K^0$ decay), and MC statistics (1%–2%). The other uncertainties are associated with $\Gamma(\Lambda_c^+)/\Gamma(pK^-\pi^+)$ (2%–3%) and the number of $N_{B\bar{B}}$ events (1%). The total systematic error is 17% for $B^+ \to \Lambda_c^+ \Lambda_c^- K^+$ and 15% for $B^+ \to \Lambda_c^+ \Lambda_c^- K^0$.

Figure 2 shows the mass distributions $M(\Lambda_c^\pm)$ for B candidates in the signal region $|\Delta M_B| < 0.015$ GeV/c^2 and $M_{\rm bc} > 5.27$ GeV/c^2. The $M(\Lambda_c^\pm)$ mass distributions are shown for $|M(\Lambda_c^\mp) - m_{\Lambda_c^+}| < 0.010$ GeV/c^2. The curves show the results of a fit with the sum of a Gaussian and a linear background. The means and widths of the Gaussians are fixed to values obtained from fits to MC samples. For $B^+ \to \Lambda_c^+ \Lambda_c^- K^+$ decay, we obtain a Λ_c^+ yield of $39.5^{+7.3}_{-6.5}$ events and a Λ_c^- yield of $48.2^{+7.7}_{-7.0}$ events. For $B^0 \to \Lambda_c^+ \Lambda_c^- K^0$, yields of $11.4^{+3.8}_{-3.2}$ and $10.0^{+3.8}_{-3.1}$ events are obtained from the Λ_c^+ and Λ_c^- distributions, respectively. These values are consistent with the B signal yields given above.

We consider possible contributions from other B decays, which could give a B signal in the ΔE and ΔM_B distributions but should produce a uniform distribution in the Λ_c^+ mass region. To assess this type of background, we analyze the Λ_c^+ sideband 0.015 GeV/$c^2 < |M(\Lambda_c^+) - m_{\Lambda_c^+}| < 0.055$ GeV/c^2 and $|M(\Lambda_c^-) - m_{\Lambda_c^-}| < 0.010$ GeV/c^2 and the Λ_c^- sideband 0.015 GeV/$c^2 < |M(\Lambda_c^-) - m_{\Lambda_c^-}| < 0.055$ GeV/c^2 and $|M(\Lambda_c^+) - m_{\Lambda_c^+}| < 0.010$ GeV/c^2. We conclude that other B decays contribute less than 1.7 events at 90% C.L. in the $B^+ \to \Lambda_c^+ \Lambda_c^- K^+$ mode and less than 0.2 events at 90% C.L. in $B^0 \to \Lambda_c^+ \Lambda_c^- K^0$; both contributions are neglected.

Figure 3 shows the $M(\Lambda_c^+ \Lambda_c^-)$ mass distributions for (a) $B^+ \to \Lambda_c^+ \Lambda_c^- K^+$ decay candidates and (b) $B^0 \to \Lambda_c^+ \Lambda_c^- K^0$ decay candidates in the B signal region

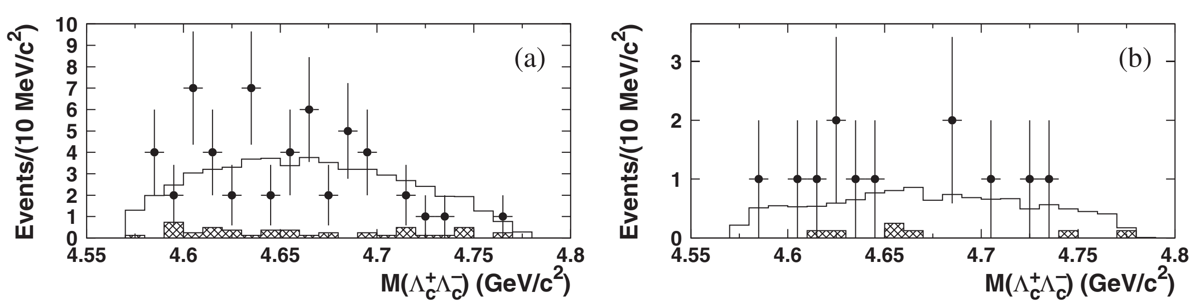

FIG. 3. $M(\Lambda_c^+ \Lambda_c^-)$ mass distributions for (a) $B^+ \to \Lambda_c^+ \Lambda_c^- K^+$ and (b) $B^0 \to \Lambda_c^+ \Lambda_c^- K^0$ decay candidates in the B signal region. Points with error bars are data. Open histograms—MC simulations for a uniform phase space distribution. Hatched histograms—normalized Λ_c^+ sideband data.

$|\Delta M_B| < 0.015\ \mathrm{GeV}/c^2$ and $M_{\mathrm{bc}} > 5.27\ \mathrm{GeV}/c^2$. No deviations from phase space distributions are evident.

In summary, we have reported the first measurement of the doubly charmed baryonic B decay $B^+ \to \Lambda_c^+ \Lambda_c^- K^+$ with a branching fraction of $(6.5^{+1.0}_{-0.9} \pm 1.1 \pm 3.4) \times 10^{-4}$ and a statistical significance of 15.4σ and the $B^0 \to \Lambda_c^+ \Lambda_c^- K^0$ decay with a branching fraction of $(7.9^{+2.9}_{-2.3} \pm 1.2 \pm 4.1) \times 10^{-4}$ and a statistical significance of 6.6σ. These three-body doubly charmed B decay branching fractions are about the same order of magnitude (or slightly smaller) than the branching fraction of the two-body doubly charmed decay $B^+ \to \bar{\Xi}_c^0 \Lambda_c^+$, which is due to the same $b \to c\bar{c}s$ quark transition, also observed by Belle [9]. The behavior of these $b \to c\bar{c}s$ decays is qualitatively different from single charmed baryon decays, where three-body decays have bigger branching fractions than two-body decays. The obtained branching fraction is by 5–6 orders of magnitude higher than expected from naive estimation for the $B \to \Lambda_c^+ \Lambda_c^- K$ decay with color suppression, which is also highly suppressed by phase space [17]. All of this needs further experimental and theoretical study.

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