Observation of $B^+ \to p\bar{\Lambda}K^+K^-$ and $B^+ \to \bar{p}\Lambda K^+K^-$

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S. E. Vaehsen,17 C. Van Hulse,1 R. Van Tonder,95 G. Varner,17 A. Vinokurova,4,67
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Abstract

We report the study of $B^+ \to p\Lambda K^+K^−$ and $B^+ \to \bar{p}\Lambda K^+K^+$ using a $772 \times 10^6 B\bar{B}$ pair data sample recorded on the $\Upsilon(4S)$ resonance with the Belle detector at KEKB. These include the observations of decay modes with the corresponding branching fractions $\mathcal{B}(B^+ \to p\Lambda K^+K^−) = (4.22^{+0.45}_{-0.44} \pm 0.51) \times 10^{-6}$, $\mathcal{B}(B^+ \to \bar{p}\Lambda K^+K^+) = (3.81^{+0.39}_{-0.37} \pm 0.45) \times 10^{-6}$, $\mathcal{B}(\eta_c \to p\Lambda K^−) = (2.9^{+0.4}_{-0.3} \pm 0.4) \times 10^{-3}$ and $\mathcal{B}(B^+ \to p\Lambda\phi) = (0.818 \pm 0.215 \pm 0.078) \times 10^{-6}$, where $\mathcal{B}$ denotes the decay branching fraction and the intermediate resonance decays are excluded in the four-body decay measurements.

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Baryonic $B$ decays have been studied at the B-factories [1], and many intriguing features have been found. Baryon-antibaryon pairs are produced almost collinearly in most baryonic $B$ decays such that their masses peak near threshold. There seems to exist a hierarchical structure in the branching fractions of multi-body decays, e.g., $\mathcal{B}(B^0 \rightarrow p\Lambda_c^-\pi^+\pi^-) > \mathcal{B}(B^+ \rightarrow p\Lambda_c^-\pi^+) > \mathcal{B}(B^+ \rightarrow p\bar{\Lambda}_c^-)$ [2][3]. The angular distribution of the proton against the energetic meson ($K^+$ and $\pi^-$ for the following cases) in the dibaryon system of $B^+ \rightarrow p\bar{p}K^+$ and $B^0 \rightarrow p\bar{\Lambda}\pi^-$ show a trend opposite those predicted by theory [1]. These two decays occur presumably via the $b \rightarrow sg$ penguin process, where $g$ denotes a hard gluon. Although a generalized factorization picture [4] can qualitatively explain some of the above features, the predicted branching fraction may differ by a factor of ten from experimental measurements, e.g., $B^0 \rightarrow p\bar{\Lambda}D^{*-}$ [5]. Later theoretical predictions [6] better compare with data after using improved baryonic form factors. It is clear that further studies of $b \rightarrow sg$ processes are needed in order to improve their theoretical understanding. In this paper, we report measurements of $B^+ \rightarrow p\bar{\Lambda}K^+K^-$ and $B^+ \rightarrow p\Lambda K^+K^+$, for which theoretical predictions on $\mathcal{B}(B^+ \rightarrow p\bar{\Lambda}K^+K^-)$ [7] and $\mathcal{B}(B^+ \rightarrow p\bar{\Lambda}\phi)$ [8] are available.

The data sample used in this study corresponds to an integrated luminosity of 711 fb$^{-1}$, which contains $772 \times 10^6$ $B\bar{B}$ pairs produced at the $\Upsilon(4S)$ resonance. The Belle detector [9, 10] is located at the interaction point (IP) of the KEKB asymmetric-energy $e^+ (3.5$ GeV) $e^- (8$ GeV) collider [11, 12]. It is a large-solid-angle spectrometer comprising six specialized sub-detectors: the Silicon Vertex Detector, the 50-layer Central Drift Chamber (CDC), the Aerogel Cherenkov Counter (ACC), the Time-Of-Flight scintillation counter (TOF), the electromagnetic calorimeter (ECL), and the $K^0_L$ and muon detector (KLM). A superconducting solenoid surrounding all but the KLM produces a 1.5 T magnetic field.

In this analysis, we combine $p\Lambda K^+K^-(\bar{p}\Lambda K^+K^+)$ to form $B^+$ candidates. We require charged particles (tracks from $\Lambda$ are excluded) to originate near the IP, less than 1.0 cm away along the positron beam direction and less than 0.2 cm away in the transverse plane. To identify a kaon or a proton track, we use the likelihood information from the charged-hadron identification system (CDC, ACC, TOF) [13] and apply the same selection criteria as in Ref. [14]. We use information from ECL and KLM to reject charged particles resembling electrons and muons. We require $\Lambda(p\pi^-)$ candidates to have a displaced vertex that is consistent with a long-lived particle originating from the IP and a mass between 1.111 and 1.121 GeV/c$^2$. 


We use the following two variables, \( \Delta E \equiv E_{\text{recon}} - E_{\text{beam}} \) and \( M_{bc} \equiv \sqrt{(E_{\text{beam}}/c^2)^2 - (P_{\text{recon}}/c)^2} \), to identify signal, where \( E_{\text{recon}}/P_{\text{recon}} \) and \( E_{\text{beam}} \) are the reconstructed \( B \) energy/momentum and beam energy measured in the \( \Upsilon(4S) \) rest frame, respectively. We define \( 5.24 < M_{bc} < 5.29 \, \text{GeV}/c^2 \) and \( |\Delta E| < 0.2 \, \text{GeV} \) as the fit region; \( 5.27 < M_{bc} < 5.29 \, \text{GeV}/c^2 \) and \( |\Delta E| < 0.03 \, \text{GeV} \) as the signal region.

The dominant background is from the continuum process \( (e^+e^- \rightarrow q\bar{q}, \, q = u, d, s, c) \). We generate phase space \( B^+ \rightarrow p\bar{\Lambda}K^+K^- \) and \( B^+ \rightarrow p\Lambda K^+K^- \) signal events and continuum background using EvtGen \[15\] and later process them with a GEANT3-based detector simulation program that provides the detector-level information \[16\]. These Monte Carlo (MC) samples are used to optimize the signal selection criteria. We use a neural network package, Neurobayes \[17\], for background suppression. There are 21 input variables for the training of Neurobayes: 17 modified Fox-Wolfram moments treating the information of particles involved in the signal \( B \) candidate separately from those in the rest of the event \[18, 19\], to distinguish spherical \( BB \) events from the jet-like \( q\bar{q} \) events; the missing mass of each event; the vertex difference between the \( B^+ \) candidate and the accompanying \( B \); the angle between \( B^+ \) flight direction and the beam axis in the \( \Upsilon(4S) \) rest frame; the tagging information for the accompanying \( B \) \[20\]. The output value of Neurobayes is between +1 (\( BB \)-like) and −1 (\( q\bar{q} \)-like). The optimized selection and its related systematic uncertainty contribution is mode dependent.

We consider at most one \( B^+ \) candidate in each event: if there are multiple candidates, we select the one with the smallest \( \chi^2_{B^+ \text{vtx}} + \chi^2_{\Lambda \text{vtx}} \), where \( \chi^2_{B(\Lambda) \text{vtx}} \) represents the \( \chi^2 \) value of \( B(\Lambda) \) vertex fit. The probability to have multiple \( B \) candidates is less than 6% and the success rate of this selection is larger than 92% according to MC study.

In the investigation of possible intermediate states in \( B^+ \rightarrow p\bar{\Lambda}K^+K^-/B^+ \rightarrow p\Lambda K^+K^- \), we check the mass spectra from combinations of various final state particles in and near the signal region. We find many intermediate resonances: \( \eta_c \), \( J/\psi \) and \( \chi_{c1} \) in \( M(p\bar{\Lambda}K^-) \); \( \phi \) in \( M(K^+K^-) \); \( \Lambda(1520) \) in \( M(pK^-) \). After removing events in the mass windows of resonances: \( 2.92 < M(p\bar{\Lambda}K^-) < 3.11 \, \text{GeV}/c^2 \) for \( \eta_c \) and \( J/\psi \), \( 3.49 < M(p\bar{\Lambda}K^-) < 3.53 \, \text{GeV}/c^2 \) for \( \chi_{c1} \), \( 1.01 < M(K^+K^-) < 1.03 \, \text{GeV}/c^2 \) for \( \phi \), and \( 1.46 < M(pK^-) < 1.58 \, \text{GeV}/c^2 \) for \( \Lambda(1520) \), we still observe a large number of signal events. We attribute them to genuine four-body decays. Note that there is no significant \( D^0 \) peak found. We also find a threshold peak mixed with phase space distribution in the \( p\bar{\Lambda} \) mass spectrum. Therefore, we generate signal MC
samples with this feature to mimic data. This mixing ratio is mode dependent in order to match with data.

We use an extended unbinned maximum likelihood fit to extract signal yields of genuine $B^+ \to p\bar{\Lambda}K^+K^-$ and $B^+ \to \bar{p}\Lambda K^+K^+$ four-body decays. The generic $B$ ($b \to c$) and continuum background form no peak in the fit region. Thus, we use Gaussian functions to model the signal shapes in both $\Delta E$ and $M_{bc}$, a second-order polynomial function for the background $\Delta E$ distribution and an ARGUS function [21] for the background $M_{bc}$ distribution. The fit results are displayed in Fig. 1. We apply the same fitting procedure in bins of $M_{p\bar{\Lambda}/\bar{p}\Lambda}$ to determine the signal yields. The corresponding normalized and efficiency-corrected signal yield distributions are shown in Fig 2. Clear threshold peaks are observed.

Since the signal yield is significant enough, we fix the signal shapes in a similar likelihood fit to extract the signal yields with intermediate resonances $\eta_c$, $J/\psi$, $\chi_{c1}$ and $\phi$. In addition to $\Delta E$ and $M_{bc}$, we include the invariant mass of an intermediate resonance as a third variable in our fit. We use the world average mass and width values of these resonances to generate MC samples [2]. For $\eta_c$ and $\phi$, we use a Breit-Wigner function convolved with a Gaussian function; for $J/\psi$ and $\chi_{c1}$, we use the sum of two Gaussian functions in order to fit the corresponding MC mass distributions. The obtained signal shapes are fixed in the later data fit. We use a 2nd-order polynomial function to model the background shape in the resonance mass spectrum. The different components of the fit function are the resonance signal (peaking in all spectra), genuine four-body signal (only peaking in $\Delta E$ and $M_{bc}$), background with resonances produced by other processes (only peaking in $M_{res}$) and non-peaking background. In contrast to fixed peaking shapes, all non-peaking shapes are floated and determined from the fit. Figure 3 shows the fit results for $B^+ \to \eta_c K^+(\eta_c \to p\bar{\Lambda}K^-)$ and $B^+ \to J/\psi K^+(J/\psi \to p\bar{\Lambda}K^-)$; Fig. 4 shows the fit result of $B^+ \to p\bar{\Lambda}\phi$.

The value of the fit significance is defined by $\sqrt{-2 \times \ln(L_0/L_\sigma)}(\sigma)$, where $L_0$ is the likelihood with null signal yield and $L_\sigma$ is the likelihood with measured yield. In the above calculation, we have used the likelihood function which is smeared by considering the additive systematic uncertainties that would affect the fitted yield.

The systematic uncertainty is mode-dependent. We consider tracking uncertainty per track for charged particles (0.35% for each charged particle and 0.49% for $\Lambda$). The uncertainty of the estimated number of $B\bar{B}$ pairs is 1.4%. The uncertainty in proton/antiproton identification is determined by using the study of $\Lambda/\bar{\Lambda}$ (0.38% to 0.53%) in data, while the un-
FIG. 1. Projection plots of $\Delta E (5.27 < M_{bc} < 5.29 \text{ GeV}/c^2)$ and $M_{bc} (|\Delta E| < 0.03 \text{ GeV})$ of genuine four-body decay. The top plots are for the final state $p\bar{\Lambda}K^+K^-$, the bottom plots are for $\bar{p}\Lambda K^+K^-$. Points with error bars are data, the dotted line is signal, the hatched region is background, the solid black curve is the total distribution of all components.

Certainty in kaon identification is determined from the study of $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ in data (2.0% to 3.7%). We generate two kinds of signal MC; one considering a threshold enhancement in the dibaryonic system, the other with only phase space decays, and we mix the two samples to mimic the real data. The MC modeling uncertainty is set to be the larger difference in reconstruction efficiency between the threshold enhancement MC and phase space MC (0.52% to 9.3%). The smallest value, 0.52%, is for $B^+ \to \eta_cK^+$ due to limited phase space. The uncertainty from fixed signal probability density function (PDF) is obtained by varying all of the shape variables by one sigma and refitting (2.7% to 3.3%). The statistical uncertainty of the MC reconstruction efficiency is 0.31% to 0.47%. The
FIG. 2. Normalized and efficiency-corrected signal yield distributions of $M(p\bar{\Lambda})$ and $M(\bar{p}\Lambda)$ for four-body decay of the final states $p\bar{\Lambda}K^+K^+$ (top) and $\bar{p}\Lambda K^+K^+$ (bottom).

The uncertainty of $q\bar{q}$ suppression is obtained from the reconstruction efficiency difference with and without the cut (0.50% to 5.0%). The $\Lambda$ selection uncertainty is determined by the difference of the flight-distance distribution between data and MC (3.0%). We apply the $D^0$ veto to redo the analysis and attribute the possible veto uncertainty 2.2% to 7.4%, where the statistical uncertainty from data is included. All the above uncertainties are combined in quadrature to obtain the total systematic uncertainties (5.9% to 12%).

Table II summarizes the fit yields, reconstruction efficiencies and corresponding systematic uncertainties of each mode. Note that the reconstruction efficiencies in Table II include the decay branching fraction 63.9% for the long-lived $\Lambda \to p\pi^-$ in the MC simulation and efficiencies have been corrected for the MC-data difference of the proton/kaon identification.

Assuming that $\Upsilon(4S)$ decays into neutral and charged $B\bar{B}$ pairs equally and using the world average values $[2]$ of $\mathcal{B}(B^+ \to \eta K^+)$, $\mathcal{B}(B^+ \to J/\psi K^+)$ and $\mathcal{B}(B^+ \to \chi_{c1} K^+)$, we obtain the results listed in Table III. The obtained branching fractions of four-body decay of $B^+ \to p\bar{\Lambda}K^+K^-$ and $B^+ \to p\bar{\Lambda}\phi$ are consistent with theoretical predictions $[7, 8]$. 

| Table I summarizes the fit yields, reconstruction efficiencies and corresponding systematic uncertainties of each mode. Note that the reconstruction efficiencies in Table II include the decay branching fraction 63.9% for the long-lived $\Lambda \to p\pi^-$ in the MC simulation and efficiencies have been corrected for the MC-data difference of the proton/kaon identification. |

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TABLE I. Signal yields \((N_s)\), reconstruction efficiencies \((\varepsilon_{\text{eff}})\), systematic uncertainties \((\text{sys})\) and significances \((\sigma)\) from extended unbinned maximum likelihood fits.

| Mode                     | \(N_s\) \(\pm\) \(\text{sys}\) (%) | \(\varepsilon_{\text{eff}}\) (%) | \(\text{sys}\) (%) | \(\sigma\) |
|--------------------------|--------------------------------------|----------------------------------|---------------------|---------|
| \(B^+ \to p\bar{\Lambda}K^+K^-\) | \(190.1^{+20.3}_{-19.6}\) | 5.84                           | 12.2                | 11.7    |
| \(B^+ \to \bar{p}\Lambda K^+K^-\) | \(188.0^{+19.2}_{-18.4}\) | 6.40                           | 11.8                | 12.7    |
| \((B^+ \to \eta c K^+)\) \(\times (\eta_c \to p\bar{\Lambda}K^-)\) | \(89.7^{+14.1}_{-13.3}\) | 7.19                           | 5.91                | 8.46    |
| \((B^+ \to \eta c K^+)\) \(\times (\eta_c \to \bar{p}\Lambda K^+)\) | \(67.0^{+14.1}_{-13.3}\) | 7.36                           | 7.55                | 5.63    |
| **Total significance of \(\eta_c\) mode** | \(10.2\) |                                 |                     |         |
| \((B^+ \to J/\psi K^+)\) \(\times (J/\psi \to p\bar{\Lambda}K^-)\) | \(19.0^{+5.7}_{-5.0}\) | 6.57                           | 7.83                | 4.92    |
| \((B^+ \to J/\psi K^+)\) \(\times (J/\psi \to \bar{p}\Lambda K^+)\) | \(25.5^{+6.6}_{-5.9}\) | 6.56                           | 5.90                | 5.50    |
| **Total significance of \(J/\psi\) mode** | \(7.38\) |                                 |                     |         |
| \((B^+ \to \chi_{c1} K^+)\) \(\times (\chi_{c1} \to p\bar{\Lambda}K^-)\) | \(10.2^{+4.0}_{-3.9}\) | 7.39                           | 11.9                | 3.18    |
| \((B^+ \to \chi_{c1} K^+)\) \(\times (\chi_{c1} \to \bar{p}\Lambda K^+)\) | \(13.4^{+5.0}_{-4.3}\) | 6.38                           | 10.5                | 3.79    |
| **Total significance of \(\chi_{c1}\) mode** | \(4.95\) |                                 |                     |         |
| \((B^+ \to p\bar{\Lambda}\phi)\) \(\times (\phi \to K^+K^-)\) | \(23.2\pm6.1\) | 7.52                           | 9.53                | 5.15    |

In summary, using a sample of \(772 \times 10^6\) \(B\bar{B}\) pair events, we measure the branching fractions of the four-body decays \(B^+ \to p\bar{\Lambda}K^+K^-\) and \(B^+ \to \bar{p}\Lambda K^+K^-\) with intermediate resonance modes being excluded. The feature of a threshold enhancement of the dibaryon system persists, but with non-negligible phase space contribution. We also observe the three-body decay of \(\eta_c \to p\bar{\Lambda}K^-\). The measured \(B(J/\psi \to p\bar{\Lambda}K^-)\) is in good agreement with the world average \([2]\). We also confirm the observation of \(\chi_{c1} \to p\bar{\Lambda}K^-\). These decay amplitudes can be useful for a better understanding of the charmonium system. We observe the charmless decay \(B^+ \to p\bar{\Lambda}\phi\) with a smaller branching fraction than that of the four-body
FIG. 3. Projection plots of $\Delta E$ (5.27 < $M_{bc}$ < 5.29 GeV/$c^2$ and 2.75 < $M_{p\bar{\Lambda}K^-}$ < 3.2 GeV/$c^2$), $M_{bc}$ ($|\Delta E| < 0.03$ GeV and 2.75 < $M_{p\bar{\Lambda}K^-}$ < 3.2 GeV/$c^2$) and $M_{p\bar{\Lambda}K^-}$ ($|\Delta E| < 0.03$ GeV and 5.27 < $M_{bc}$ < 5.29 GeV/$c^2$) of $B^+ \rightarrow \eta_c K^+$ and $B^+ \rightarrow J/\psi K^+$. The top plots are for the final state $p\bar{\Lambda}K^+K^-$, the bottom plots are for $\bar{p}\Lambda K^+K^-$. Points with error bars are data, the cross-hatched region covering the whole bottom is background, the dotted/darker-hatched line on the bottom is $\eta_c/J/\psi$ signals, the horizontal-line region accumulating on background is a contribution of four-body decay, the solid black curve is the total distribution of all components. In this fit, the feed-down of background of resonances is negligible.

decay. Its signal yield is not significant enough to perform an angular analysis.

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FIG. 4. Projection plots of $\Delta E$ ($5.27 < M_{bc} < 5.29 \text{ GeV}/c^2$ and $1.00 < M_{K^+K^-} < 1.08 \text{ GeV}/c^2$), $M_{bc}$ ($|\Delta E| < 0.03 \text{ GeV}$ and $1.00 < M_{K^+K^-} < 1.08 \text{ GeV}/c^2$) and $M_{K^+K^-}$ ($|\Delta E| < 0.03 \text{ GeV}$ and $5.27 < M_{bc} < 5.29 \text{ GeV}/c^2$) of $B^+ \rightarrow p\bar{\Lambda}\phi$. Points with error bars are data, the dotted line is signal, the cross-hatched region covering the whole bottom is background, the horizontal-line region accumulating on background is contributions of four-body decay, the solid black curve is the total distribution of all components.

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TABLE II. Summary of measured branching fractions. The listed four-body modes exclude any intermediate resonance.

| Mode                        | Branching fraction                                      |
|-----------------------------|---------------------------------------------------------|
| $B^+ \rightarrow p\bar{\Lambda}K^+K^-$ | $(4.22^{+0.45}_{-0.44} \pm 0.51) \times 10^{-6}$       |
| $B^+ \rightarrow \bar{p}\Lambda K^+K^+$  | $(3.81^{+0.39}_{-0.37} \pm 0.45) \times 10^{-6}$       |
| $B^+ \rightarrow p\bar{\Lambda}\phi$    | $(0.818 \pm 0.215 \pm 0.078) \times 10^{-6}$           |
| $\eta_c \rightarrow p\bar{\Lambda}K^-$  | $(2.9^{+0.4}_{-0.3} \pm 0.3) \times 10^{-3}$           |
| $J/\psi \rightarrow p\bar{\Lambda}K^-$  | $(8.57^{+1.68}_{-1.49} \pm 0.48) \times 10^{-4}$       |
| $\chi_{c1} \rightarrow p\bar{\Lambda}K^-$| $(9.42^{+2.71}_{-2.32} \pm 0.87) \times 10^{-4}$       |

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