Observation of $B^0 \to p\bar{\Lambda}\pi^-$

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We report the first observation of the charmless hyperonic B decay, $B^0 \to p\bar{\Lambda}\pi^-$, using a 78 fb^{-1} data sample recorded on the $\Upsilon(4S)$ resonance with the Belle detector at KEKB. The measured branching fraction is $\mathcal{B}(B^0 \to p\bar{\Lambda}\pi^-) = (3.97^{+1.00}_{-0.80} \pm 0.56) \times 10^{-6}$. Searches for $B^0 \to p\bar{\Lambda}K^-$ and $p\bar{\Sigma}^0\pi^-$ yield no significant signals and we set 90% confidence-level upper limits of $\mathcal{B}(B^0 \to p\bar{\Lambda}K^-) < 8.2 \times 10^{-7}$ and $\mathcal{B}(B^0 \to p\bar{\Sigma}^0\pi^-) < 3.8 \times 10^{-6}$.

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The Belle Collaboration recently reported the observation of $B^+ \to p\bar{p}K^+$ [1], which is the first known example of B meson decay to charmless final states containing baryons. The three-body decay rate is larger than the rate for two-body decays (such as $B \to p\bar{p}$ [2]), and the observed $M_{p\bar{p}}$ spectrum peaks near threshold, in agreement with theoretical suggestions [3,4]. In this Letter we report the first observation of the related three-body decay $B^0 \to p\bar{\Lambda}\pi^-$, and a search for $B^0 \to p\bar{\Lambda}K^-$ and $p\bar{\Sigma}^0\pi^-$ modes. The rate for $B^0 \to p\bar{\Lambda}\pi^-$ is comparable to $B^+ \to p\bar{p}K^+$, and the observed $M_{p\bar{\Lambda}}$ spectrum again peaks toward threshold.

In the standard model, these decays proceed via $b \to u$ tree and $b \to s(d)$ penguin diagrams. They may be used to search for direct CP violation and test our theoretical understanding of rare decay processes involving baryons [3–7]. Modes involving hyperons, in particular, can probe the s quark chirality in B decay [8]; with sufficient statistics, they could provide a tool for probing T violation [3] via the self-analyzed Λ polarization information.

We use a 78 fb^{-1} data sample, consisting of $85.0 \pm 0.5 \times 10^6$ $B\bar{B}$ pairs, collected by the Belle detector at the KEKB asymmetric energy e^+e^- (3.5 on 8 GeV) collider. The Belle detector is a large-solid-angle magnetic spectrometer that consists of a three-layer 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 (TOF) scintillation counters, 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 detector is described in detail elsewhere [9].

Since the e^+e^- center-of-mass energy is set to match the $\Upsilon(4S)$ resonance, which decays into a $B\bar{B}$ pair, one can use the following two kinematic variables to identify the reconstructed B meson candidates [10]: the beam-energy constrained mass, $M_{\rm bc} = \sqrt{E_{\rm beam}^2 - p_B^2}$, and the energy difference, $\Delta E = E_B - E_{\rm beam}$, where $E_{\rm beam}$ is the beam energy, and p_B and E_B are, respectively, the momentum and the energy of the reconstructed B meson in the $\Upsilon(4S)$ rest frame. The candidate region is defined as $5.2\ \text{GeV}/c^2 < M_{\rm bc} < 5.29\ \text{GeV}/c^2$ and $|\Delta E| < 0.2$ GeV in this analysis.

The event selection criteria are based on the information obtained from the tracking system (SVD + CDC) and the hadron identification system (CDC + ACC + TOF) and are optimized using Monte Carlo (MC) simulated event samples.

All primary charged tracks are required to satisfy track quality criteria based on the track impact parameters relative to the interaction point (IP). The deviations from the IP position are required to be within ± 0.3 cm in the transverse (x-y) plane, and within ± 3 cm in the z direction, where the z axis is defined by the positron beam line. Primary proton candidates are selected based on $p/K/\pi$ likelihood functions obtained from the hadron identification system. We require $L_p/(L_p + L_K) > 0.3$ and $L_p/(L_p + L_\pi) > 0.6$, where $L_{p/K/\pi}$ stands for the proton/kaon/pion likelihood. For kaons (pions), we require the kaon (pion) K-π likelihood ratio to be greater than 0.6. Λ candidates are reconstructed via the $p\pi^-$ decay channel using the method described in Ref. [2]. Σ^0 candidates are reconstructed via the $\Lambda\gamma$ decay channel, where we use a 35 MeV/c^2 mass window around the nominal mass [11] and require the γ energy to be greater than 100 MeV.

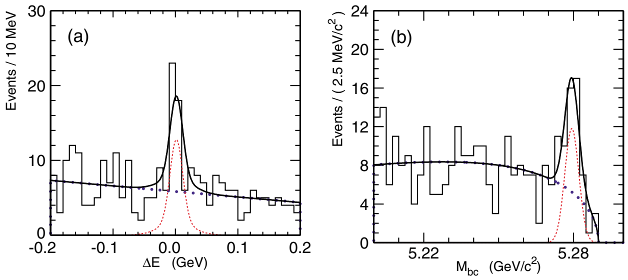

FIG. 1 (color online). (a) The ΔE and (b) $M_{\rm bc}$ distributions for $B^0 \to p\bar{\Lambda}\pi^-$ candidates. The solid, dotted, and dashed lines represent the combined fit result, fitted background, and fitted signal, respectively.

The dominant background for the rare decay modes reported here is from the continuum $e^+e^- \to q\bar{q}$ process. The background from B decays is much smaller. This is confirmed with an off-resonance data set (8.8 fb^{-1}) accumulated at an energy that is 60 MeV below the $\Upsilon(4S)$, and an MC sample of 120×10^6 continuum events. In the $\Upsilon(4S)$ rest frame, continuum events are jetlike while $B\overline{B}$ events are spherical. We follow the scheme defined in Ref. [12] and combine seven shape variables to form a Fisher discriminant [13] that is used to optimize continuum background suppression. The variables chosen have almost no correlation with $M_{\rm bc}$ and ΔE. Probability density functions (PDF's) for the Fisher discriminant and the cosine of the angle between the B flight direction and the e^- beam direction in the $\Upsilon(4S)$ rest frame are combined to form the signal (background) likelihood $\mathcal{L}_{\rm S(BG)}$. We require the likelihood ratio $\mathcal{LR} = \mathcal{L}_{\rm S}/(\mathcal{L}_{\rm S} + \mathcal{L}_{\rm BG})$ to be greater than 0.8, which suppresses about 94% of the background while retaining 66% of the signal. The signal and background PDF's are obtained from MC simulation studies.

Figure 1(a) shows the ΔE distribution for selected $p\bar{\Lambda}\pi^-$ candidates that have $M_{\rm bc} > 5.27\ {\rm GeV}/c^2$; Fig. 1(b) shows the $M_{\rm bc}$ distribution for events with $|\Delta E| < 0.03$ GeV. With the current statistics, no intermediate resonances are evident in the Dalitz plot for this channel. We use a binned likelihood fit to estimate the signal yield. A Gaussian is used to parametrize the signal in $M_{\rm bc}$ while a double Gaussian is used for ΔE. The Gaussian parameters are determined from MC simulation. Background shapes are studied using sideband events ($0.1\ {\rm GeV} < |\Delta E| < 0.2$ GeV for the $M_{\rm bc}$ study and $5.20\ {\rm GeV}/c^2 < M_{\rm bc} < 5.26\ {\rm GeV}/c^2$ for ΔE) and are checked with the continuum MC sample. We use the ARGUS function [14] to model the $M_{\rm bc}$ background and a linear function for the ΔE background. The fit results are shown as curves in Fig. 1. The fit to the ΔE distribution yields $39.2^{+9.1}_{-8.4}$ candidates with a significance of 5.8 standard deviations. The fit to the $M_{\rm bc}$ distribution yields $33.7^{+8.1}_{-7.4}$ candidates with a significance of 5.7 standard deviations. The smaller yield in the $M_{\rm bc}$ fit is consistent with the ΔE fit result after taking into account the efficiency of the $|\Delta E| < 0.03$ GeV selection. The signal yields and the branching fractions are determined from fits to the ΔE distribution rather than to $M_{\rm bc}$ in order to minimize possible bias from $B\bar{B}$ background, which tends to peak in $M_{\rm bc}$ but not in ΔE.

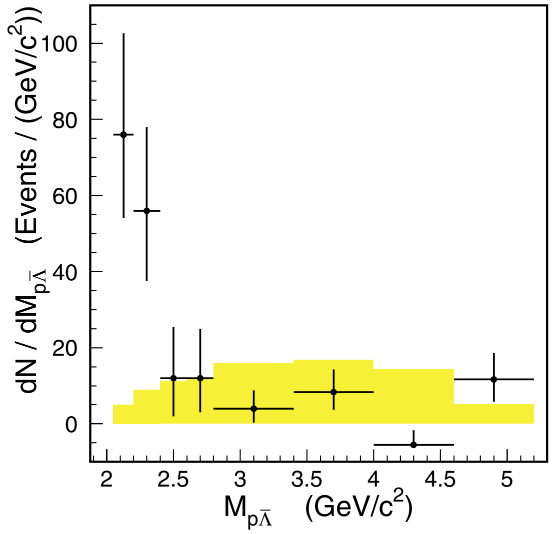

FIG. 2 (color online). The fitted yield divided by the bin size for $B^0 \to p\bar{\Lambda}\pi^-$ as a function of $M_{p\bar{\Lambda}}$. The shaded distribution is from a phase-space MC simulation with area normalized to signal yield.

Since the decay is not uniform in phase space, we fit the ΔE signal yield in bins of $M_{p\bar{\Lambda}}$ and correct for the MC-determined detection efficiency for each bin. This reduces the model dependence of the branching fraction determination. The signal yield as a function of $p\bar{\Lambda}$ mass is shown in Fig. 2. The distribution from a three-body phase space MC, normalized to the area of the signal, is superimposed. The observed mass distribution peaks at low $p\bar{\Lambda}$ mass, similar to that observed for $B^+ \to p\bar{p}K^+$ decays [1]. The results of the fits, along with the efficiencies and partial branching fractions for each $M_{p\bar{\Lambda}}$ bin, are given in Table I. We sum the partial branching fractions in Table I to obtain

TABLE I. The event yield, efficiency, and branching fraction ($\mathcal{B}$) for each $M_{p\bar{\Lambda}}$ bin.

$M_{p\bar{\Lambda}}$ (GeV/c^2)	Signal yield	Efficiency (%)	$\mathcal{B}$ (10^{-6})
<2.2	$11.4^{+4.0}_{-3.3}$	12.5	$1.08^{+0.37}_{-0.31}$
2.2–2.4	$11.2^{+4.4}_{-3.7}$	11.7	$1.12^{+0.44}_{-0.37}$
2.4–2.6	$2.4^{+2.7}_{-2.0}$	11.1	$0.25^{+0.29}_{-0.21}$
2.6–2.8	$2.4^{+2.6}_{-1.8}$	9.9	$0.28^{+0.31}_{-0.22}$
2.8–3.4	$2.4^{+2.9}_{-2.2}$	11.4	$0.24^{+0.30}_{-0.23}$
3.4–4.0	$5.0^{+3.6}_{-2.8}$	11.7	$0.51^{+0.36}_{-0.29}$
4.0–4.6	$-3.3^{+2.3}_{-1.8}$	12.5	$-0.31^{+0.21}_{-0.17}$
> 4.6	$7.0^{+4.2}_{-3.5}$	10.4	$0.79^{+0.48}_{-0.39}$

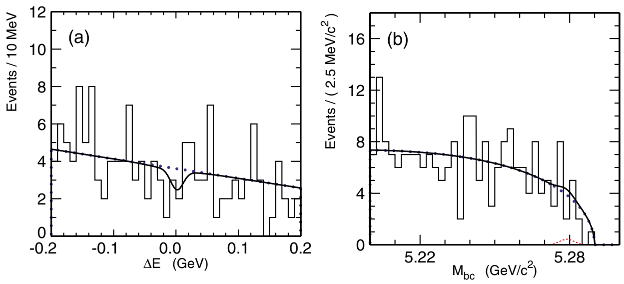

FIG. 3 (color online). (a) The ΔE and (b) M_{bc} distributions for $B^0 \to p\bar{\Lambda}K^-$ candidates. The solid line represents the fit results.

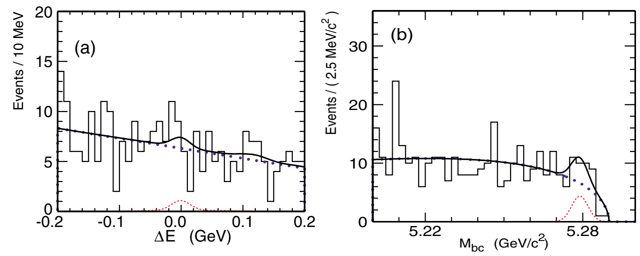

FIG. 4 (color online). (a) The ΔE and (b) M_{bc} distributions for $B^0 \to p\bar{\Sigma}^0\pi^-$ candidates. Note that events from $B^0 \to p\bar{\Lambda}\pi^-$ decay can feed into the high ΔE region (~ 0.1 GeV). The corresponding distribution is obtained from the $p\bar{\Lambda}\pi^-$ MC and included in the fit.

$$\mathcal{B}(B^0 \to p\bar{\Lambda}\pi^-) = [3.97^{+1.00}_{-0.80}(\text{stat}) \pm 0.56(\text{syst})] \times 10^{-6},$$

where the systematic uncertainty is described below.

The systematic uncertainty in particle selection is studied mainly using high statistics control samples. Proton identification is studied with a $\Lambda \to p\pi^-$ sample. Kaon/pion identification is studied with a $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ sample. Tracking efficiency is studied with $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$ samples. Based on these studies, we assign a 2% error for each track, 3% for each proton identification requirement, and 2% for each kaon/pion identification requirement.

We study the $\mathcal{LR}$ continuum suppression by varying the $\mathcal{LR}$ cut value from 0 to 0.9 to check the systematic trend. The systematic error is found to be 4%. The additional uncertainty of off-IP tracks for Λ reconstruction is estimated to be 6%, which is determined from the difference of the proper decay time distributions for data and MC simulation.

The systematic uncertainty in the fit yield is studied by varying the parameters of the signal and background PDF's. We assign an error of 3% for this. The MC statistical uncertainty and modeling with eight $M_{p\bar{\Lambda}}$ bins contributes a 4% error in the branching fraction determination. The error on the number of total $B\bar{B}$ pairs is determined to be 1%. The error of the branching fraction for $\Lambda \to p\pi^-$ is 0.8% [11].

The tracking systematic error is estimated to be 8% by summing the correlated errors of 2% per charged track. The particle identification error is estimated to be 8% by summing the correlated errors of 3% per proton identification and 2% for the primary pion identification. Then we combine them in quadrature along with other uncorrelated errors to determine a total systematic error of 14%.

We also search for the decay modes $B^0 \to p\bar{\Lambda}K^-$ and $B^0 \to p\bar{\Sigma}^0\pi^-$. The M_{bc} and ΔE distributions with fit projections are shown in Figs. 3 and 4. With the signal region extended to $|\Delta E| < 0.04$ GeV and $M_{bc} > 5.27$ GeV$/c^2$, no significant signal is found. We use the fit results to estimate the expected background and compare this with the observed number of events in the signal region in order to set the upper limit on the yield at the 90% confidence level [15–17]. This procedure takes systematic uncertainties into account. The estimated backgrounds are 28.9 ± 2.6 and 50.5 ± 4.0, the numbers of observed events are 26 and 56, the systematic uncertainties are 14% and 28%, and the upper limit yields are 8.3 and 22.4 for $p\bar{\Lambda}K^-$ and $p\bar{\Sigma}^0\pi^-$, respectively. We estimate the efficiencies from a phase space MC sample. The 90% confidence-level upper limits for the branching fractions are $\mathcal{B}(B^0 \to p\bar{\Lambda}K^-) < 8.2 \times 10^{-7}$ and $\mathcal{B}(B^0 \to p\bar{\Sigma}^0\pi^-) < 3.8 \times 10^{-6}$.

Following our observation of the $B^+ \to p\bar{p}K^+$ mode, some authors [6,7] predicted a much smaller branching fraction ($< 10^{-6}$) for the $B^0 \to p\bar{\Lambda}\pi^-$ mode, but a relatively sizable $B^0 \to p\bar{\Sigma}^0\pi^-$. Although the predicted rates are not borne out by our present findings, the threshold peaking behavior shown in Fig. 2 was anticipated [3,4,7].

In summary, we have performed a search for the rare baryonic decays $B^0 \to p\bar{\Lambda}\pi^-$, $p\bar{\Lambda}K^-$, and $p\bar{\Sigma}^0\pi^-$ with $85.0 \pm 0.5 \times 10^6$ $B\bar{B}$ events. A clear signal is seen in the $p\bar{\Lambda}\pi^-$ mode, and we measure a branching fraction of $\mathcal{B}(B^0 \to p\bar{\Lambda}\pi^-) = (3.97^{+1.00}_{-0.80} \pm 0.56) \times 10^{-6}$. The other two modes are not seen, and we set 90% confidence-level upper limits of $\mathcal{B}(B^0 \to p\bar{\Lambda}K^-) < 8.2 \times 10^{-7}$ and $\mathcal{B}(B^0 \to p\bar{\Sigma}^0\pi^-) < 3.8 \times 10^{-6}$.

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