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


(Belle Collaboration)

1Budker Institute of Nuclear Physics, Novosibirsk
2Chuo University, Tokyo
3University of Cincinnati, Cincinnati, Ohio 45221
4University of Hawaii, Honolulu, Hawaii 96822
5High Energy Accelerator Research Organization (KEK), Tsukuba
6Hiroshima Institute of Technology, Hiroshima
7Institute for High Energy Physics, Vienna
8Institute for Theoretical and Experimental Physics, Moscow
9J. Stefan Institute, Ljubljana
10Kanagawa University, Yokohama
11Korea University, Seoul
12Kyoto University, Kyoto
13Kyungpook National University, Taegu
14Institut de Physique des Hautes Energies, Université de Lausanne, Lausanne
15University of Ljubljana, Ljubljana
16University of Maribor, Maribor
17University of Melbourne, Victoria
18Nagoya University, Nagoya
19National Kaohsiung Normal University, Kaohsiung
20National Lien-Ho Institute of Technology, Miaoli
21Department of Physics, National Taiwan University, Taipei
22H. Niewodniczanski Institute of Nuclear Physics, Krakow
23Niho Dental College, Niigata
24Niigata University, Niigata
25Osaka City University, Osaka
26Osaka University, Osaka
27Panjab University, Chandigarh
28Peking University, Beijing
29Saga University, Saga
30University of Science and Technology of China, Hefei
31Seoul National University, Seoul
32Sungkyunkwan University, Suwon
We report the first observation of the charmless hyperonic $B$ decay, $B^0 \rightarrow p \Lambda \pi^-$, using a 78 fb$^{-1}$ data sample recorded on the $Y(4S)$ resonance with the Belle detector at KEKB. The measured branching fraction is $\mathcal{B}(B^0 \rightarrow p \Lambda \pi^-) = (3.97^{+1.00}_{-0.80} \pm 0.56) \times 10^{-6}$. Searches for $B^0 \rightarrow p \Lambda K^-$ and $p \Sigma^0 \pi^-$ yield no significant signals and we set 90% confidence-level upper limits of $\mathcal{B}(B^0 \rightarrow p \Lambda K^-) < 8.2 \times 10^{-7}$ and $\mathcal{B}(B^0 \rightarrow p \Sigma^0 \pi^-) < 3.8 \times 10^{-6}$.

We use a 78 fb$^{-1}$ data sample, consisting of $85.0 \pm 0.5 \times 10^6 \ BB$ 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 $Y(4S)$ resonance, which decays into a $BB$ pair, one can use the following two kinematic variables to identify the reconstructed $B$ meson candidates [10]: the beam-energy constrained mass, $M_{bc} = [E_{\text{beam}} - p_B^2]$; and the energy difference, $\Delta E = E_B - E_{\text{beam}}$, where $E_{\text{beam}}$ is the beam energy, and $p_B$ and $E_B$ are, respectively, the momentum and the energy of the reconstructed $B$ meson in the $Y(4S)$ rest frame. The candidate region is defined as $5.2 \text{ GeV}/c^2 < M_{bc} > 5.29 \text{ GeV}/c^2$ and $|\Delta E| < 0.2 \text{ GeV}$ 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 $\pm 0.3$ cm in the transverse ($x$-$y$) plane, and within $\pm 3$ 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/pon likelihood. For kaons (pions), we require the kaon (pion) $K/\pi$ likelihood ratio to be greater than 0.6. A candidates are reconstructed via the $p \pi^-$ decay channel using the method described in Ref. [2]. $\Sigma^0$ 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 $\gamma$ energy to be greater than 100 MeV.
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 $Y(4S)$, and an MC sample of $120 \times 10^6$ continuum events. In the $Y(4S)$ rest frame, continuum events are jetlike while $B\bar{B}$ 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 $M_{bc}$ and $\Delta E$. 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 $Y(4S)$ rest frame are combined to form the signal (background) likelihood $L_{SBG}$. We require the likelihood ratio $LR = L_S/(L_S + L_{BG})$ 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 $\Delta E$ distribution for selected $p\Lambda \pi^-$ candidates that have $M_{bc} > 5.27$ GeV/$c^2$; Fig. 1(b) shows the $M_{bc}$ 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 $M_{bc}$ while a double Gaussian is used for $\Delta E$. The Gaussian parameters are determined from MC simulation. Background shapes are studied using sideband events (0.1 GeV < $|\Delta E|$ < 0.2 GeV for the $M_{bc}$ study and 5.20 GeV/$c^2$ < $M_{bc}$ < 5.26 GeV/$c^2$ for $\Delta E$) and are checked with the continuum MC sample. We use the ARGUS function [14] to model the $M_{bc}$ background and a linear function for the $\Delta E$ background. The fit results are shown as curves in Fig. 1. The fit to the $\Delta E$ distribution yields $39.2^{+9.1}_{-8.4}$ candidates with a significance of 5.8 standard deviations. The fit to the $M_{bc}$ distribution yields $33.7^{+8.1}_{-7.4}$ candidates with a significance of 5.7 standard deviations. The smaller yield in the $M_{bc}$ fit is consistent with the $\Delta E$ 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 $\Delta E$ distribution rather than to $M_{bc}$ in order to minimize possible bias from $B\bar{B}$ background, which tends to peak in $M_{bc}$ but not in $\Delta E$.

Since the decay is not uniform in phase space, we fit the $\Delta E$ signal yield in bins of $M_{p\Lambda}$ 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 $p\Lambda$ 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 $p\Lambda$ mass, similar to that observed for $B^+ \to p\bar{K}^+$ decays [1]. The results of the fits, along with the efficiencies and partial branching fractions for each $M_{p\Lambda}$ bin, are given in Table I. We sum the partial branching fractions in Table I to obtain

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

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

<table>
<thead>
<tr>
<th>$M_{p\Lambda}$ (GeV/$c^2$)</th>
<th>Signal yield</th>
<th>Efficiency (%)</th>
<th>$B (10^{-6})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;2.2</td>
<td>11.4$^{+9.0}_{-8.4}$</td>
<td>12.5</td>
<td>1.08$^{+0.37}_{-0.33}$</td>
</tr>
<tr>
<td>2.2–2.4</td>
<td>11.2$^{+4.4}_{-3.7}$</td>
<td>11.7</td>
<td>1.12$^{+0.37}_{-0.34}$</td>
</tr>
<tr>
<td>2.4–2.6</td>
<td>2.4$^{+2.7}_{-2.0}$</td>
<td>11.1</td>
<td>0.25$^{+0.29}_{-0.23}$</td>
</tr>
<tr>
<td>2.6–2.8</td>
<td>2.4$^{+2.6}_{-2.0}$</td>
<td>9.9</td>
<td>0.28$^{+0.31}_{-0.22}$</td>
</tr>
<tr>
<td>2.8–3.4</td>
<td>2.4$^{+2.9}_{-2.2}$</td>
<td>11.4</td>
<td>0.24$^{+0.30}_{-0.23}$</td>
</tr>
<tr>
<td>3.4–4.0</td>
<td>5.0$^{+3.6}_{-2.8}$</td>
<td>11.7</td>
<td>0.51$^{+0.36}_{-0.29}$</td>
</tr>
<tr>
<td>4.0–4.6</td>
<td>$3.3^{+2.3}_{-1.8}$</td>
<td>12.5</td>
<td>$-0.31^{+0.21}_{-0.17}$</td>
</tr>
<tr>
<td>&gt;4.6</td>
<td>7.0$^{+4.2}_{-3.5}$</td>
<td>10.4</td>
<td>0.79$^{+0.48}_{-0.39}$</td>
</tr>
</tbody>
</table>
Kaon/pion identification is studied with a kaon/pion identification requirement. We assign a 2% error for each track, 3% for additional uncertainty of off-IP tracks for trend. The systematic error is found to be 4%. The addition of the proper decay time distributions for data and PDF’s. We assign an error of 3% for this. The MC variation of the parameters of the signal and background determination. The error on the number of total bins contributes a 4% error in the branching fraction. We also search for the decay modes $B^0 \to p \Sigma^0 \pi^-$ and $B^0 \to p \pi^-$. 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 $B^0 \to p \Lambda \pi^-$, $p \Lambda \pi^-$, and $p \Sigma^- \pi^0$ with 85.0 $\pm$ 0.5 $\times$ 10$^6$ $B\bar{B}$ events. A clear signal is seen in the $p \Lambda \pi^-$ mode, and we measure a branching fraction of $B(B^0 \to p \Lambda \pi^-) = (3.97^{+1.00}_{-0.80} \pm 0.56) \times 10^{-6}$. The other two modes are not seen, and we set 90% confidence-level upper limits of $B(B^0 \to p \Lambda K^-) < 8.2 \times 10^{-7}$ and $B(B^0 \to p \Sigma^0 \pi^-) < 3.8 \times 10^{-6}$.

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*On leave from Fermi National Accelerator Laboratory, Batavia, IL 60510.
†On leave from Nova Gorica Polytechnic, Nova Gorica.

[10] Throughout this Letter, inclusion of charge conjugate mode is always implied unless otherwise stated.