Observation of New Charmless Decays of Bottom Hadrons

The MIT Faculty has made this article openly available. Please share how this access benefits you. Your story matters.

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>As Published</td>
<td><a href="http://dx.doi.org/10.1103/PhysRevLett.103.031801">http://dx.doi.org/10.1103/PhysRevLett.103.031801</a></td>
</tr>
<tr>
<td>Publisher</td>
<td>American Physical Society</td>
</tr>
<tr>
<td>Version</td>
<td>Final published version</td>
</tr>
<tr>
<td>Accessed</td>
<td>Tue Aug 14 18:27:09 EDT 2018</td>
</tr>
<tr>
<td>Citable Link</td>
<td><a href="http://hdl.handle.net/1721.1/51899">http://hdl.handle.net/1721.1/51899</a></td>
</tr>
<tr>
<td>Terms of Use</td>
<td>Article is made available in accordance with the publisher's policy and may be subject to US copyright law. Please refer to the publisher's site for terms of use.</td>
</tr>
<tr>
<td>Detailed Terms</td>
<td></td>
</tr>
</tbody>
</table>
We search for new charmless decays of neutral $b$ hadrons to pairs of charged hadrons, using 1 fb$^{-1}$ of data collected by the CDF II detector at the Fermilab Tevatron. We report the first observation of the $B^0 \to K^- \pi^+$ decay and measure $\mathcal{B}(B^0 \to K^- \pi^+) = (5.0 \pm 0.7 \text{stat} \pm 0.8 \text{syst}) \times 10^{-6}$. We also report the first observation of charmless $b$-baryon decays, and measure $\mathcal{B}(\Lambda_b^0 \to p \pi^-) = (3.5 \pm 0.6 \text{stat} \pm 0.9 \text{syst}) \times 10^{-6}$ and $\mathcal{B}(\Lambda_b^0 \to pK^-) = (5.6 \pm 0.8 \text{stat} \pm 1.5 \text{syst}) \times 10^{-6}$. No evidence is found for other modes, and we set the limit $\mathcal{B}(B^0_s \to \pi^+\pi^-) < 1.2 \times 10^{-6}$ at 90% C.L.
Two-body nonleptonic charmless decays of $b$ hadrons are among the most widely studied processes in flavor physics. The variety of open channels involving similar final states provides crucial experimental information to improve the accuracy of effective models of strong interaction dynamics. The quark-level transition $b \rightarrow u$ makes decay amplitudes sensitive to $\gamma$, the least known angle of the quark-mixing (Cabibbo-Kobayashi-Maskawa, CKM) matrix. Significant contributions from higher-order ("penguin") transitions provide sensitivity to the possible presence of new physics in internal loops, if the observed decay rates are inconsistent with expectations.

Rich experimental data are currently available for $B^+$ and $B^0_s$ mesons, produced in large quantities in $Y(4S)$ decays [1], while much less is experimentally known about the charmless decay modes of the $B^0$, which are expected to exhibit an equally rich phenomenology. Information from $B^0$ decays is needed to better constrain the phenomenological models of hadronic amplitudes in heavy flavor decays. This would lead to increased precision in comparing data to predictions, allowing extraction of CKM parameters from non-tree-level amplitudes [2] and greater sensitivity to new physics contributions.

Of the possible $B^0_s$ decay modes into pairs of charmless pseudoscalar mesons, only $B^0_s \rightarrow K^+ K^-$ has been observed to date [3]. The $B^0_s \rightarrow K^- \pi^+$ mode is of particular interest, because its branching fraction is sensitive to the CKM angle $\gamma$ [4] and the current experimental bound [3] is lower than most predictions [5–7].

A measurement of the branching fraction of the $B^0_s \rightarrow \pi^- \pi^+$ mode, along with the $B^0 \rightarrow K^- K^-$ mode, would allow a determination of the strength of the penguin-annihilation amplitudes [8], which is currently poorly known and a source of significant uncertainty in many calculations [6]. The present search is sensitive to both modes. Two-body charmless decays are also expected from bottom baryons. The modes $\Lambda_b^0 \rightarrow p K^-$ and $\Lambda_b^0 \rightarrow p \pi^-$ are predicted to have measurable branching fractions, of order $10^{-6}$ [9], and, in addition to the interest in their observation, must be considered as a possible background to the rare $B^0_s$ and $B^0$ modes being investigated.

In this Letter we report the results of a search for rare decays of neutral bottom hadrons into a pair of charged charmless hadrons ($p$, $K$, or $\pi$), performed in 1 fb$^{-1}$ of $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV, collected by the upgraded Collider Detector (CDF II) at the Fermilab Tevatron. We report the first observation of modes $B^0_s \rightarrow K^- \pi^+$, $\Lambda_b^0 \rightarrow p K^-$, and $\Lambda_b^0 \rightarrow p \pi^-$, and measure their relative branching fractions [10].

CDF II is a multipurpose magnetic spectrometer surrounded by calorimeters and muon detectors [11,12]. The resolution on transverse momentum of charged particles is $\sigma_{p_T}/p_T^3 \sim 0.15\%/(\text{GeV}/c^2)$, corresponding to a typical mass resolution of 22 MeV/$c^2$ for our signals. The specific ionization energy loss ($dE/dx$) of charged particles can be measured from the charge collected by the drift chamber (COT), and provides a 1.5σ separation between kaons and pions with momenta greater than 2 GeV/$c$. The data were collected by a three-level trigger system [13], using a set of requirements specifically aimed at selecting two-pronged $B$ decays [3]. Two opposite-charge particles are required, with reconstructed transverse momenta $p_{T1}, p_{T2} > 2$ GeV/$c$, the scalar sum $p_{T1} + p_{T2} > 5.5$ GeV/$c$, and an azimuthal opening angle $\Delta \phi < 135^\circ$. The impact parameter $d$ (distance of closest approach to the beam line) of the two tracks is required to be $0.1 < d < 1.0$ mm, reducing the light-quark background by 2 orders of magnitude while preserving about half of the signal. An opening-angle requirement $20^\circ < \Delta \phi < 135^\circ$, preferentially selects two-body $B$ decays over multibody decays with 97% efficiency and further reduces background.

The offline selection is based on a more accurate determination of the same quantities used in the trigger, with the addition of two further observables: the isolation ($I_B$) of the $B$ candidate [14], and the quality of the three-dimensional fit ($\chi^2$ with 1 d.o.f.) of the decay vertex of the $B$ candidate. Requiring a large value of $I_B$ reduces the background from light-quark jets, and a low $\chi^2$ reduces the background from decays of different long-lived particles within the event, owing to the good resolution of the SVX detector in the $z$ direction. The selection is optimized for detection of the $B^0_s \rightarrow K^- \pi^+$ mode. Maximal sensitivity for both discovery and limit setting is achieved with a single choice of selection requirements [15] by minimizing the variance of the estimate of the branching fraction in the absence of signal [16]. The variance is evaluated by performing the full measurement procedure on simulated samples containing background and all signals from the known modes, but no $B^0_s \rightarrow K^- \pi^+$ signal. The background fraction for each selection is determined from data by extrapolating the mass sidebands of the signal, and the signal yield is predicted by a detailed detector simulation. This procedure yields the final selection: $I_B > 0.525$, $\chi^2 < 5$, $d > 120$ $\mu$m, $d_B < 60$ $\mu$m, and $L_T > 350$ $\mu$m.

No more than one $B$ candidate per event is found after this selection, and a mass ($m_{\pi\pi}$) is assigned to each, using a charged pion mass assignment for both decay products. The resulting mass distribution is shown in Fig. 1. A large peak is visible, dominated by the overlapping contributions.
FIG. 1 (color online). Mass distribution of the 8286 reconstructed candidates. The charged pion mass is assigned to both tracks. The total projection and projections of each signal and background component of the likelihood fit are overlaid on the data distribution. Signals and multibody background components are shown stacked on the combinatorial background component.

of the $B^0 \rightarrow K^+\pi^-$, $B^0 \rightarrow \pi^+\pi^-$, and $B^0 \rightarrow K^+K^-$ modes as seen in Ref. [3]. A $B^0 \rightarrow K^+K^-$ signal would appear as an enhancement around 5.18 GeV/c^2, while signals for the other modes of this search are expected at masses higher than the main peak (5.33–5.55 GeV/c^2). Backgrounds include misreconstructed multibody $b$-hadron decays (physics background) and random pairs of charged particles (combinatorial background).

We used an unbinned likelihood fit, incorporating kinematic (kin) and particle identification (PID) information, to determine the fraction of each individual mode in our sample. The likelihood for the $i$th event is

$$L_i = (1 - b) \sum_j f_j L_j^{\text{kin}} L_j^{\text{PID}} + b f_p L_p^{\text{kin}} L_p^{\text{PID}} + (1 - f_p) L_c^{\text{kin}} L_c^{\text{PID}},$$

where the index $j$ runs over all signal modes, and the index "p" ("c") labels the physics (combinatorial) background terms. The $f_j$ are the signal fractions to be determined by the fit, together with the background fraction parameters $b$ and $f_p$.

The kinematic information is summarized by three loosely correlated observables: (a) the mass $m_{\pi\pi}$; (b) the signed momentum imbalance $\alpha = (1 - p_1/p_2)q_1$, where $p_1$ ($p_2$) is the lower (higher) of the particle momenta, and $q_1$ is the sign of the charge of the particle of momentum $p_1$; (c) the scalar sum of particle momenta $p_\text{tot} = p_1 + p_2$. The above variables allow evaluation of the invariant mass $m_{12}$ of a candidate for any mass assignment of the decay products ($m_1$, $m_2$), using the equation

$$m_{12}^2 = m_{\pi\pi}^2 - 2m_x^2 + m_{x1}^2 + m_{x2}^2 - 2\sqrt{p_1^2 + m_x^2} \sqrt{p_2^2 + m_x^2},$$

where $p_1 = \frac{1 + \alpha}{2}\sqrt{m_1}$, $p_2 = \frac{1 - \alpha}{2}\sqrt{m_2}$.

We used the mass sidebands in data ($m_{\pi\pi} \in [5.00, 5.12] \cup [5.6, 6.2]$ GeV/c^2) to obtain the kinematic distributions of backgrounds [16]. The mass distribution of the combinatorial background is parametrized by an exponential function, while the physics background is modeled by an ARGUS function [17] convoluted with a Gaussian resolution function. In order to ensure the reliability of the search for small signals in the vicinity of larger peaks, the shapes of the mass distributions assigned to each signal have been modeled in detail, including momentum dependence and non-Gaussian resolution tails from a full detector simulation, and the effects of soft photon radiation in the final state [16,18]. This resolution model describes very accurately the observed shape of the $D^0 \rightarrow K^-\pi^+$ signal in a sample of $1.5 \times 10^6$ $D^{*+} \rightarrow D^0\pi^+$ decays, collected with a similar trigger selection. The $D^{*+} \rightarrow D^0\pi^+$ sample was also used to calibrate the $dE/dx$ response of the drift chamber to kaons and pions, using the charge of the pion from $D^{*+}$ decay to identify the $D^0$ decay products. The $dE/dx$ response of protons was determined from a sample of about 124 000 $\Lambda^0 \rightarrow p\pi^-$ decays. The model of the background allows for pion, kaon, proton, and electron components, whose fractions are determined by the fit. Muons are indistinguishable from pions with the available 10% fractional $dE/dx$ resolution and are therefore incorporated into the pion component.

From the signal fractions returned by the likelihood fit we calculate the signal yields shown in Table I. The significance of each signal is evaluated as the ratio of the yield observed in data, and its total uncertainty (statistical and systematic) as determined from a simulation where the size of that signal is set to zero. This evaluation assumes a Gaussian distribution of yield estimates, supported by the results obtained from repeated fits to simulated samples. We obtain significant signals for the $B^0 \rightarrow K^-\pi^+$ mode (8.2$\sigma$), and for the $\Lambda^0 \rightarrow p\pi^-$ (6.0$\sigma$) and $\Lambda^0 \rightarrow pK^-$

<table>
<thead>
<tr>
<th>Mode</th>
<th>$N_s$</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow K^-\pi^+$</td>
<td>230 ± 34 ± 16</td>
<td>8.2$\sigma$</td>
</tr>
<tr>
<td>$B^0 \rightarrow \pi^+\pi^-$</td>
<td>26 ± 16 ± 14</td>
<td>&lt;3$\sigma$</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^+K^-$</td>
<td>61 ± 25 ± 35</td>
<td>&lt;3$\sigma$</td>
</tr>
<tr>
<td>$\Lambda^0 \rightarrow p\pi^-$</td>
<td>156 ± 20 ± 11</td>
<td>11.5$\sigma$</td>
</tr>
<tr>
<td>$\Lambda^0 \rightarrow pK^-$</td>
<td>110 ± 18 ± 16</td>
<td>6.0$\sigma$</td>
</tr>
</tbody>
</table>
TABLE II. Measured relative branching fractions of rare modes. The ratio $f_{\Lambda}/f_{d}$ is $p_T$ dependent [19], and is defined here as $f_{\Lambda}/f_{d} = \sigma(p\bar{p} \rightarrow X; p_T > 6 \text{ GeV}/c; \eta < 1)/\sigma(p\bar{p} \rightarrow B^{0}\pi^{-}; p_T > 6 \text{ GeV}/c; \eta < 1)$. Absolute branching fractions were derived by normalizing to the current world-average value $\mathcal{B}(B^0 \rightarrow K^- \pi^+) = (19.4 \pm 0.6) \times 10^{-6}$, and assuming the average values at high energy for the production fractions: $f_{\Lambda}/f_{d} = 0.276 \pm 0.034$, and $f_{\Lambda}/f_{d} = 0.230 \pm 0.052$ [20]. The first quoted uncertainty is statistical, the second is systematic.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Relative $\mathcal{B}$</th>
<th>Absolute $\mathcal{B}(10^{-6})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0_s \rightarrow K^- \pi^+$</td>
<td>$f_{\Delta} \frac{B^0_s \rightarrow K^- \pi^+}{f_{d} B^0 \rightarrow K^- \pi^+}$</td>
<td>$0.071 \pm 0.010 \pm 0.007$</td>
</tr>
<tr>
<td>$B^0_s \rightarrow \pi^+ \pi^-$</td>
<td>$f_{\Delta} \frac{B^0_s \rightarrow \pi^+ \pi^-}{f_{d} B^0 \rightarrow K^- \pi^+}$</td>
<td>$0.007 \pm 0.004 \pm 0.005$</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^+ K^-$</td>
<td>$f_{\Delta} \frac{B^0 \rightarrow K^+ K^-}{f_{d} B^0 \rightarrow K^- \pi^+}$</td>
<td>$0.020 \pm 0.008 \pm 0.006$</td>
</tr>
<tr>
<td>$\Lambda^0_b \rightarrow p K^-$</td>
<td>$f_{\Delta} \frac{\Lambda^0_b \rightarrow p K^-}{f_{d} B^0 \rightarrow K^- \pi^+}$</td>
<td>$0.066 \pm 0.009 \pm 0.008$</td>
</tr>
<tr>
<td>$\Lambda^0_b \rightarrow p \pi^-$</td>
<td>$f_{\Delta} \frac{\Lambda^0_b \rightarrow p \pi^-}{f_{d} B^0 \rightarrow K^- \pi^+}$</td>
<td>$0.042 \pm 0.007 \pm 0.006$</td>
</tr>
</tbody>
</table>

(Table II continued)
Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Science and Technology Facilities Council and the Royal Society, U.K.; the Institut National de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; and the Academy of Finland.

aDeceased.
bVisitor from University of Massachusetts Amherst, Amherst, MA 01003, USA.
cVisitor from Universiteit Antwerpen, B-2610 Antwerp, Belgium.
dVisitor from University of Bristol, Bristol BS8 1TL, United Kingdom.
eVisitor from Chinese Academy of Sciences, Beijing 100864, China.
fVisitor from Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, 09042 Monserrato (Cagliari), Italy.
gVisitor from University of California Irvine, Irvine, CA 92697, USA.
hVisitor from University of California, Santa Cruz, Santa Cruz, CA 95064, USA.
iVisitor from Cornell University, Ithaca, NY 14853, USA.
jVisitor from University of Cyprus, Nicosia CY-1678, Cyprus.
kVisitor from University College Dublin, Dublin 4, Ireland.
lVisitor from University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom.
mVisitor from Universidad Iberoamericana, Mexico D.F., Mexico.
nVisitor from Queen Mary, University of London, London, E1 4NS, United Kingdom.
oVisitor from University of Manchester, Manchester M13 9PL, United Kingdom.
pVisitor from Nagasaki Institute of Applied Science, Nagasaki, Japan.
qVisitor from University of Notre Dame, Notre Dame, IN 46556, USA.
rVisitor from University de Oviedo, E-33007 Oviedo, Spain.
sVisitor from Texas Tech University, Lubbock, TX 79409, USA.
tVisitor from IFIC (CSIC-Universitat de Valencia), 46071 Valencia, Spain.
uVisitor from University of Virginia, Charlottesville, VA 22904, USA.
vVisitor from Bergische Universität Wuppertal, 42097 Wuppertal, Germany.
wOn leave from J. Stefan Institute, Ljubljana, Slovenia.

Throughout this Letter, C conjugate modes are implied and branching fractions indicate CP averages.


CDF II uses a cylindrical coordinate system in which φ is the azimuthal angle, r is the radius from the nominal beam line, and z points in the proton beam direction, with the origin at the center of the detector. The transverse plane is the plane perpendicular to the z axis.


Isolation is defined as $I_B = p_T(B)/(p_T(B) + \sum p_T)$, where $p_T(B)$ is the transverse momentum of the $B$ candidate, and the sum runs over all other tracks within a cone of radius 1, in η-φ space around the $B$ flight direction.


Defined as $m_{\pi\pi}e^{-c_\Delta(m_{\pi\pi}/m_\Delta)^2}\sqrt{1 - (m_{\pi\pi}/m_\Delta)^2}$, for $m_{\pi\pi} < m_\Delta$. The cutoff $m_\Delta$ and the coefficient $c_\Delta$ were free parameters in our fit. See H. Albrecht et al. (ARGUS Collaboration), Phys. Lett. B 241, 278 (1990).


