Evidence for Charmed Baryons in B-Meson Decay

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(Received 28 April 1987)

We report on new measurements of the Λ and proton branching fractions and momentum spectra from B-meson decay. The large Λ-to-p ratio, the absence of $B \to \Lambda\bar{\Lambda}X$, and the presence of Λ-lepton charge correlations suggest that charmed baryons are produced in B decay. Under the assumption that all of the observed baryons are associated with charmed-baryon production, we find a B–to–charmed-baryon branching fraction of $(7.4 \pm 2.9)\%$.

PACS numbers: 13.25.+m

B-meson decay into charmed mesons is well established.[1] It is also possible, however, for B's to decay into charmed baryons. We previously measured the inclusive production of protons (p or $\bar{p}$) and lambdas (Λ or $\bar{\Lambda}$) in B decay, and found both $B(B \to pX)$ and $B(B \to \Lambda X)$ to be $\simeq 6\%$.[2] If these baryons were the result of a hadronization process (e.g., virtual W^- decay), we would expect the production of strange baryons to be suppressed relative to that of nonstrange baryons. One possible explanation for the high Λ-to-p ratio is the production of charmed baryons as an intermediate state. In this Letter we show evidence which suggests that the baryons observed in B decay are indeed associated with charmed-baryon production. We first report on improved measurements of the inclusive rates and momentum spectra of p's and Λ's from B decay. (Throughout this Letter, charge-conjugate modes are implied.)

The data used in this analysis correspond to a total integrated luminosity of 78 pb^{-1} at the $\Upsilon(4S)$ resonance and 36 pb^{-1} of continuum e^+e^- data at an energy just below the threshold for producing $B\bar{B}$ pairs. This data sample includes approximately 180000 B mesons. The data were collected with the CLEO detector at the Cornell Electron Storage Ring. The CLEO detector[3] and its recent improvements[4] have been described elsewhere. The results reported in this Letter rely on charged-particle momentum measurements in the central tracking chambers, and on particle identification from time-of-flight and specific-ionization (dE/dx) measurements from the central drift chamber and outer dE/dx chambers.

We detect the Λ via its decay to $p\pi^-$. A Λ candidate is a positive-negative track pair with a minimum total momentum of 0.4 GeV/c and a vertex at least 1 cm from the beam line. The net momentum vector of the two tracks is required to extrapolate back to the primary vertex. Tracks consistent with being secondaries of K_S^0 decays or photon conversions in the beam pipe are excluded. No charged-particle identification information is used for the inclusive Λ analysis. For the analyses involving Λ's in conjunction with other particles, we require that the p candidate be consistent with the proton hypothesis in the particle-identification devices.

To determine the number of Λ candidates, the data are partitioned into momentum bins; each $p\pi^-$ invariant-mass distribution is fitted by the sum of a polynomial background and a Gaussian centered at the Λ mass. A Monte Carlo simulation of the detector is used to determine the expected width of the mass peak as well as the Λ reconstruction efficiency. The predicted full width at half maximum is 4 MeV. The measured width of the total Λ sample is 3.9 ± 0.2 MeV. The reconstruction efficiency for $\Lambda \to p\pi^-$ varies from 15% at low momenta to 40% at high momenta. The $\Upsilon(4S)$ and continuum Λ production rates are determined separately and then subtracted; the continuum data are scaled to account both for the difference in total integrated luminosity and for the energy dependence of the total hadronic cross section. After this continuum subtraction, we find 1007 ± 146 candidates for $B \to \Lambda X$.

The efficiency-corrected momentum spectrum for Λ's from B-meson decay is shown in Fig. 1. To estimate $f_{\rm low}$, the fraction of the Λ's from B decay which have too low a momentum to be detected, we consider $V-A$ decays of the form $\bar{B} \to \Lambda_c \bar{N} W^-$, where the effective mass of the $\Lambda_c \bar{N}$ combination is varied from 3.25 to 3.80 GeV; the W^- is treated as a virtual particle which decays to $l^- \bar{\nu}$ or to $\bar{u}d$ quarks that subsequently fragment to form hadrons. The Λ momentum spectrum from this model is shown by the solid curve in Fig. 1 (the curve is normalized to the data). We estimate $f_{\rm low} = 0.15 \pm 0.05$, and find

$$R_\Lambda = \frac{(N_\Lambda + N_{\bar{\Lambda}})}{2N_{B\bar{B}}} = B(B \to \Lambda X) = (4.2 \pm 0.6 \pm 0.4)\%,$$

where $N_{B\bar{B}}$ is the number of $B\bar{B}$ pairs. The first error quoted is statistical; the second error is systematic and accounts for uncertainties in $f_{\rm low}$, the fitting procedure, and the detector acceptance.

We use two methods to identify protons. At low momenta (0.2 to 0.9 GeV/c), protons are identified by their specific ionization (dE/dx) as measured in the central drift chamber. At higher momenta (0.7 to 1.7 GeV/c), the time-of-flight system is used to distinguish protons from other particles. Protons from Λ decay are used to measure the identification efficiency of these devices. Since the number of protons is very small compared to the total number of tracks, it is important to estimate how often other particles will be misidentified as protons. A sample of pions from K_S^0 decay is used to determine the probability that a pion will fake a proton. The contribution from misidentified kaons is more difficult to estimate. At low momenta, the time-of-flight and the outer dE/dx systems are used to select a sample of kaons from which we determine the kaon rejection efficiency for the central-drift-chamber dE/dx system. At high momenta, where the time-of-flight system is used, we assume that the rejection efficiency is only a function of the flight-time difference. We can therefore relate the kaon rejection efficiency to that determined for pions. The momentum region common to both particle-identification methods (0.7 to 0.9 GeV/c) is used to estimate the systematic error in our identification and fake probabilities. The track reconstruction efficiency, including the effect of absorption in the beam pipe, is determined from Monte Carlo simulation.

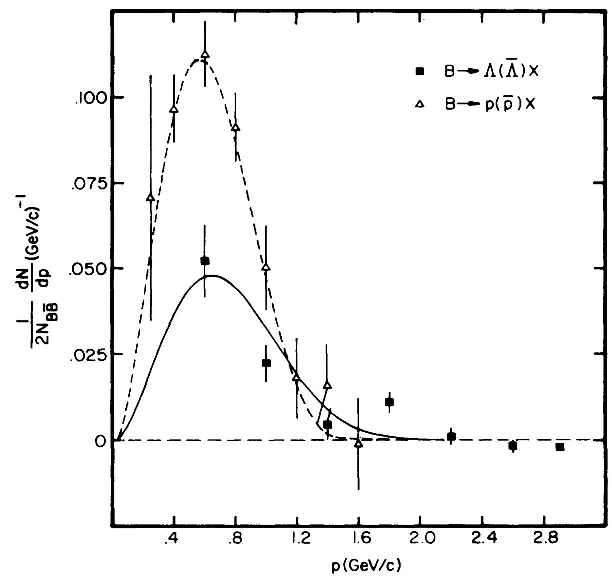

FIG. 1. Momentum spectra for Λ's and p's from B-meson decay. The Λ spectrum is corrected for Λ's which do not decay to $p\pi^-$. Protons from Λ decay are included in the proton sample. The curves represent the model used to estimate $f_{\rm low}$.

At low momenta (less than 0.9 GeV/c), we use only antiprotons to determine $B(B \to pX)$ because the proton sample contains a large background from beam gas events and from protons resulting from secondary interactions in the beam pipe. After subtracting the continuum and fake-proton contributions, and correcting for efficiency, we find 15044 ± 1261 p's and $\bar{p}$'s with 0.2 GeV/$c < P <$ 1.7 GeV/c [5]; the momentum spectrum is shown in Fig. 1. Using a model similar to that used in the inclusive Λ analysis, we estimate the fraction of the p momentum spectrum below 0.2 GeV/c to be $f_{\rm low} = 0.04 \pm 0.02$, and find

$$B'(B \to pX) = (N_p + N_{\bar{p}})/2N_{B\bar{B}} = (8.8 \pm 0.7 \pm 1.0)\%.$$

Note that this branching fraction includes protons from Λ decay. After subtracting this contribution, we find

$$R_p = B(B \to pX) = (6.1 \pm 0.8 \pm 1.0)\%.$$

If the Λ's in B decay were produced via the creation of $s\bar{s}$ pairs from the vacuum, we might expect to observe the decay $B \to \Lambda\bar{\Lambda}X$. We find only 5 ± 13 candidates for $B \to \Lambda\bar{\Lambda}X$, and set a limit of $B(B \to \Lambda\bar{\Lambda}X)/B(B \to \Lambda X) < 0.12$ at 90% confidence level. If the decay $B \to \Lambda\bar{\Lambda}X$ were the source of all Λ's in B decay, this ratio would be 0.5.

If the Λ's in $\bar{B}$ decay ($\bar{B}$ mesons contain the b quark) were associated with charmed baryons Θ_c, they would be produced through the reaction $\bar{B} \to \Theta_c \bar{N} X$,[6] where the Θ_c decays to a Λ. In this reaction, protons and neutrons would arise from charmed-baryon decay and antiprotons and antineutrons would arise from the need to conserve baryon number. Since it is unlikely that a $\bar{\Lambda} K$ pair would be produced to conserve baryon number, $\bar{B}$ mesons would decay to Λ's and not to $\bar{\Lambda}$'s. A $\bar{B}$ which decays to a baryon-antibaryon pair cannot produce a high-momentum lepton because there is not enough energy. Therefore, a high-momentum lepton in an $\Upsilon(4S) \to B\bar{B}$ event must come from the B which does not decay to a Λ. Since a B meson decays into positively charged leptons, $\Upsilon(4S)$ decays in which the $\bar{B}$ decays into a charmed baryon would produce Λl^+ pairs, but would not produce Λl^- pairs. Other mechanisms would allow mesons containing a b quark to decay to equal numbers of Λ's and $\bar{\Lambda}$'s, and thus would not result in a Λl charge correlation.

To search for Λ-lepton candidate events, we consider electrons and muons with momentum greater than 1.4 GeV/c and less than 2.4 GeV/c.[7] The lower momentum cut greatly reduces the background from sources of leptons other than direct decay from the B which does not produce a Λ.[8] The upper momentum cut is the maximum observed momentum of leptons from B decay.[9] We also require $0.4 < P_\Lambda < 2.0$ GeV/c, since all of the observed $B \to \Lambda X$ signal occurs in this momentum interval.[10] Figure 2(a) shows the $p\pi^-$ invariant-mass distribution for events with Λl^+ candidates after continuum subtraction; Figure 2(b) shows the same plot for Λl^- candidates. A clear signal is observed in the Λl^+ plot, while no signal is seen in the Λl^- plot. The Λl^+ signal has a mass and width consistent with that found in the inclusive Λ sample. Fitting the data with the mass and width fixed to these values, we find 26.6 ± 7.9 Λl^+ candidates and 3.3 ± 4.8 Λl^- events.[11,12] Statistically, there is a 99% probability that we have observed a Λ-lepton charge correlation. This result suggests that charmed baryons are the dominant source of Λ's in B decay.[13]

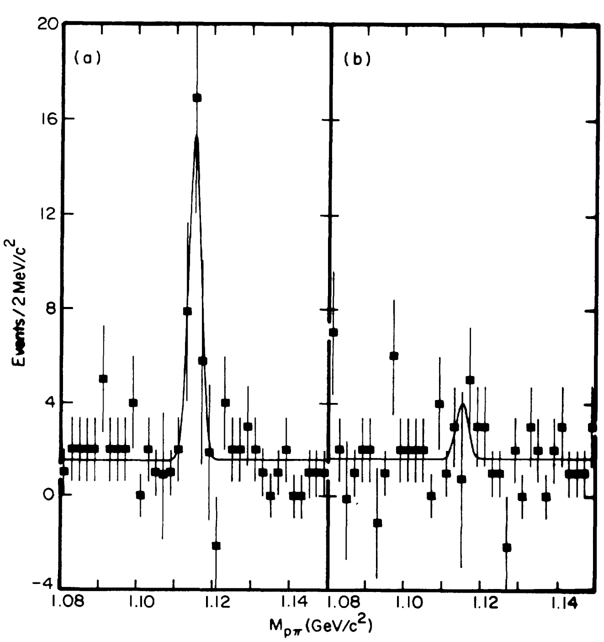

FIG. 2. $p\pi^-$ invariant mass for (a) $\Upsilon(4S) \to \Lambda l^+ (\bar{\Lambda} l^-) X$ and (b) $\Upsilon(4S) \to \Lambda l^- (\bar{\Lambda} l^+) X$ candidates; the data have been continuum subtracted.

In what follows we assume that all baryons from B decay are produced from or in conjunction with charmed baryons. Using this assumption and our measured inclusive p and Λ yields, we can obtain a maximum value for $B_{\Theta_c} = B(B \to \Theta_c X)$, as well as an estimate of $B_\Lambda = B(\Theta_c \to \Lambda X)$. We make the following definitions:

$$B_p = B(\Theta_c \to pX), \quad B_n = B(\Theta_c \to nX),$$

$$f_p = B(B \to \Theta_c \bar{p} X)/B_{\Theta_c},$$

$$f_n = 1 - f_p = B(B \to \Theta_c \bar{n} X)/B_{\Theta_c}.$$

The two measured branching ratios may be written as

$$R_p = B(B \to pX) = B_{\Theta_c} f_p + B_{\Theta_c} B_p, \qquad (1)$$

$$R_\Lambda = B(B \to \Lambda X) = B_{\Theta_c} B_\Lambda. \qquad (2)$$

(R_p, B_p, and B_n do not include decay products of Λ's.) Since $B_\Lambda + B_p + B_n = 1$, we can solve Eqs. (1) and (2) for B_{Θ_c} in terms of R_p, R_Λ, f_p, and B_n/B_p:

$$B_{\Theta_c} = \frac{R_\Lambda + R_p(1 + B_n/B_p)}{1 + f_p(1 + B_n/B_p)}. \qquad (3)$$

With the assumption that Λ's arise only from Θ_c decay, $f_p = B(B \to \Lambda \bar{p} X)/B(B \to \Lambda X)$. To measure f_p, we repeat the inclusive Λ analysis for events with an identified antiproton. The number of Λp events is used to measure the fake contribution to $B(B \to \Lambda \bar{p} X)$. After all corrections, we have 405 ± 88 $B \to \Lambda \bar{p} X$ candidates, and find $f_p = 0.46 \pm 0.12$.

Since we are unable to detect neutrons, we cannot measure B_n/B_p. Simple models of Θ_c decay imply that if no quark pairs are popped, $B_n/B_p = 0$. If quark popping occurs, B_n/B_p can be as large as 1. Table I summarizes our measurements of B_{Θ_c} and B_Λ for this range of values.

To avoid assuming a value for B_n/B_p, we can measure B_{Θ_c} using a measurement of $B \to p\bar{p}X$, where we now include protons from Λ decay. The branching ratio can be written as

$$B_{p\bar{p}} = B(B \to p\bar{p}X) = B_{\Theta_c} B_p f_p + R_\Lambda f_p (0.64). \qquad (4)$$

The first term represents $p\bar{p}$ pairs from B decay where neither the p nor $\bar{p}$ comes from a Λ; the second term represents $p\bar{p}$ pairs including a p from Λ decay. The Λ to p branching fraction is 0.64.[14]

Since we do not expect any real pp or $\bar{p}\bar{p}$ pairs from B decay, we use the apparent number of pp and $\bar{p}\bar{p}$ pairs to measure the background from tracks misidentified as

TABLE I. Estimates of B-to-charmed-baryon branching fraction. (Θ_c represents whatever mixture of charmed baryons is produced in B decay.)

B_n/B_p	$B(B\to\Theta_c X)$ (%)	$B(\Theta_c\to\Lambda X)$ (%)
0	7.1 ± 1.0	59 ± 12
$\frac{1}{2}$	7.9 ± 1.4	53 ± 13
1	8.5 ± 1.6	49 ± 13

protons. After subtracting fake p's and making a small correction ($\simeq 10\%$) for events in which both B's produce protons, we find 1030 ± 75 $p\bar{p}$ pairs with each particle having $0.4\ \text{GeV}/c<P<1.0\ \text{GeV}/c$. Correcting for the protons outside this momentum range, we find $B_{p\bar{p}}=(2.4\pm0.4)\%$. Solving Eqs. (1) and (4) simultaneously gives

$$B_{\Theta_c}=\frac{R_p f_p - B_{p\bar{p}} + R_\Lambda f_p(0.64)}{f_p^2}=(7.4\pm2.9)\%. \quad (5)$$

This result is in good agreement with our earlier measurement using Eq. (3). Both methods assume that all baryons are associated with charmed-baryon production, and that all Λ's come from charmed-baryon decay.

We have also searched for a direct B to Λ_c signal in several Λ_c decay modes. The high combinatoric backgrounds, however, make it difficult to extract convincing signals. We find the following limits at 90% confidence level:

$$B(B\to\Lambda_c X)B(\Lambda_c\to pK^+\pi^-)<0.23\%,$$

$$B(B\to\Lambda_c X)B(\Lambda_c\to pK^0)<0.62\%,$$

$$B(B\to\Lambda_c X)B(\Lambda_c\to\Lambda\pi^+\pi^+\pi^-)<0.36\%.$$

These limits are consistent with the measured Λ_c branching fractions[14] and the $B\to\Theta_c$ branching ratio estimated above. The high uncertainty in the Λ_c branching fractions would preclude the use of this method to measure $B(B\to\Lambda_c X)$ even if clear signals were observed.

In conclusion, we have made improved measurements of the inclusive yields and momentum distributions of protons and Λ's from B decay. The lack of $B\to\Lambda\bar{\Lambda}X$ events and the observed Λl^+ correlation are evidence that charmed baryons are produced in B decay. Statistically, the chance that none of the Λ's observed in B decay are from charmed baryons is 1%. Assuming that all baryon production in B decay is associated with charmed-baryon production, we use Eq. (5) to find $B(B\to\text{charmed baryon}+X)=(7.4\pm2.9)\%$. If other mechanisms produce baryons, the actual branching ratio will be lower. Therefore, we find a model-independent upper limit of $B(B\to\text{charmed baryon}+X)<11.2\%$ at 90% confidence level.

We gratefully acknowledge the efforts of the Cornell Electron Storage Ring staff which made this work possible. Two of us (H.K. and R. Kass) thank the Outstanding Junior Investigator program of the U.S. Department of Energy. One of us (K.K.) thanks the Bunting Institute for support. This research was conducted with use of the Cornell National Supercomputer Facility, which is funded in part by the National Science Foundation, New York State, and IBM. This work was supported by the National Science Foundation and the U.S. Department of Energy.

[1]D. Bortoletto *et al.*, Phys. Rev. D **35**, 19 (1987); P. Hass *et al.*, Phys. Rev. Lett. **56**, 2781 (1986).

[2]M. S. Alam *et al.*, Phys. Rev. Lett. **51**, 1143 (1983).

[3]D. Andrews *et al.*, Nucl. Instr. Methods Phys. Res. **211**, 47 (1983).

[4]C. Bebek *et al.*, Phys. Rev. Lett. **56**, 1893 (1986).

[5]Below 0.9 GeV/c we assume that $N_p+N_{\bar{p}}=2N_{\bar{p}}$.

[6]The symbol Θ_c denotes whatever mixture of charmed baryons is produced in B decay. All charmed baryons ultimately decay to Λ's, p's, or n's.

[7]The techniques used to identify leptons in the CLEO detector are described in A. Chen *et al.*, Phys. Rev. Lett. **52**, 1084 (1984).

[8]The number of real Λl pairs from other sources is less than one event for both Λl^+ and Λl^-. The background from hadrons misidentified as leptons is approximately 5%.

[9]K. Chadwick *et al.*, Phys. Rev. D **27**, 475 (1983).

[10]Continuum processes produce $\Lambda l^\pm$ pairs in which the momenta of the lepton and Λ tend to be nearly aligned. From $\Upsilon(4S)$ decays there is no correlation between the two momenta if the Λ and lepton are decay products of different B mesons. Therefore, to suppress the continuum we require $-0.8<\cos\theta_{\Lambda l}<0.9$, where $\theta_{\Lambda l}$ is the angle between the Λ momentum and the lepton momentum. This requirement reduces the continuum signal by more than 75%, while reducing the signal from B decay by only 15%.

[11]As a check on the total number of Λl events ($N_{\Lambda l^+}+N_{\Lambda l^-}=29.9\pm9.2$), we estimate $N_{\Lambda l}$ from the inclusive Λ and lepton production rates. If the Λ and l come from different B's, the number of Λl pairs expected is

$$N_{\Lambda l}=(N_l/N_B)N_\Lambda\epsilon,$$

where N_l, N_Λ, and N_B are the detected numbers of leptons, Λ's, and B mesons, respectively, from the $\Upsilon(4S)$; ϵ is the efficiency of the $\cos\theta_{\Lambda l}$ requirement. We predict $N_{\Lambda l}=26\pm5$, which agrees with the sum $N_{\Lambda l^+}+N_{\Lambda l^-}$.

[12]Note that $B^0\bar{B}^0$ mixing would generate a signal in the Λl^- sample. If this mixing were 20%, as reported by the ARGUS Collaboration [H. Albrecht *et al.*, DESY Report No. 87-029, 1987 (to be published)], we would expect to observe four events from this mechanism.

[13]Λ's from "penguin" diagrams ($b\to s$) would be indistinguishable from Λ's from charged baryons according to this test. The penguin mechanism is expected to be strongly suppressed: J. F. Donoghue, Phys. Rev. D **30**, 1499 (1984); M. B. Gavela *et al.*, Phys. Lett. **148B**, 225 (1984); N. Bilic and B. Guberna, Z. Phys. C **27**, 399 (1985); T. N. Pham, Phys. Lett. **145B**, 113 (1984).

[14]M. Aguilar-Benitez *et al.* (Particle Data Group), Phys. Lett. **170B**, 1 (1986).