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Measurement of inclusive B meson decays into baryons

ARGUS Collaboration

H. Albrecht, P. Böckmann, R. Gläser, G. Harder, A. Krüger, A. Nippe, M. Reidenbach, M. Schäfer, W. Schmidt-Parzefall, H. Schröder, H.D. Schulz, F. Sefkow, J. Spengler, R. Wurth, A. Yagil
DESY, D-2000 Hamburg, Federal Republic of Germany

R.D. Appuhn, A. Drescher, C. Hast, D. Kamp, H. Kolanoski, A. Lindner, R. Mankel, U. Matthiesen [1], H. Scheck, G. Schweda, B. Spaan, A. Walther, D. Wegener
Institut für Physik [2], Universität, D-4600 Dortmund, Federal Republic of Germany

W. Funk, J.C. Gabriel, J. Stiewe, S. Werner
Institut für Hochenergiephysik [3], Universität, D-6900 Heidelberg, Federal Republic of Germany

K.W. Edwards [4], W.R. Frisken [5], H. Kapitzka [4], R. Kutschke [6], D.B. MacFarlane [7], K.W. McLean [7], A.W. Nilsson [7], R.S. Orr [6], J.A. Parsons [6], P.M. Patel [7], J.D. Prentice [6], S.C. Seidel [6], J.D. Swain [6], G. Tsipolitis [7], T.-S. Yoon [6]
Institute of Particle Physics [8], Canada

R. Ammar, S. Ball, D. Coppage, R. Davis, S. Kanekal, N. Kwak
University of Kansas [9], Lawrence, Kans., USA

T. Ruf, S. Schael, K.R. Schubert, K. Strahl, R. Waldi
Institut für Experimentelle Kernphysik [14], Universität, D-7500 Karlsruhe, Federal Republic of Germany

B. Boštjančič, G. Kernel, P. Križan, E. Križnič, M. Pleško
Institut J. Stefan and Oddelek za fiziko [11], Univerza v Ljubljani, Ljubljana, Yugoslavia

H.I. Cronström, L. Jönsson
Institute of Physics [12], University of Lund, Sweden

A. Babaev, M. Danilov, B. Fominykh, A. Golutvin, I. Gorelov, V. Lubimov, A. Rostovtsev, A. Semenov, S. Semenov, V. Shevchenko, V. Soloshenko, V. Tchistilin, I. Tichomirov, Yu. Zaitsev
Institute of Theoretical and Experimental Physics, Moscow, USSR

R. Childers, C.W. Darden, R.C. Fernholz
University of South Carolina [13], Columbia, SC, USA

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Abstract. The decay of B mesons into the baryons p, Λ and Ξ^- has been studied. The measured inclusive branching ratios for these decays are $\mathrm{Br}(B \to pX) = \left(8.2 \pm 0.5 ^{+1.3}_{-1.0}\right)\%$, $\mathrm{Br}(B \to \Lambda X) = (4.2 \pm 0.5 \pm 0.6)\%$ and $\mathrm{Br}(B \to \Xi^- X) < 0.51\%$ at the 90% confidence level. In addition investigations on $p\bar{p}$, $\Lambda\bar{p}$ and $\Lambda\bar{\Lambda}$ correlations were performed, yielding an approximately equal rate of protons and neutrons. From this one can derive a total baryonic branching ratio $\mathrm{Br}(B \to \text{baryons})$ of $(7.6 \pm 1.4)\%$.

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[3] Supported by the German Bundesministerium für Forschung und Technologie, under contract number 054HD24P
[4] Carleton University, Ottawa, Ontario, Canada
[5] York University, Downsview, Ontario, Canada
[6] University of Toronto, Toronto, Ontario, Canada
[7] McGill University, Montreal, Quebec, Canada
[8] Supported by the Natural Sciences and Engineering Research Council, Canada
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1 Introduction

B mesons offer the unique possibility to study baryon production in weak decays. Previous measurements on inclusive Λ_c^+ production in B decays have shown that baryonic B decays are dominated by $b \to c$ transitions leading to multiparticle final states [1]. Protons and Λ's are therefore expected to arise either from Λ_c^+ decays or from the fragmentation of the spectator quark. The investigation of inclusive proton and Λ production in B decays, for which only one measurement exists so far [2], represents an important check of the production mechanism and allows, in addition, a determination of Λ_c^+ branching ratios.

The data for the studies reported here were collected with the ARGUS detector at DORIS II storage ring at the energy of the $\Upsilon(4S)$ resonance and in the nearby continuum. The detector, its trigger and particle identification capabilities have been described elsewhere [3]. The event sample used in the analysis of the decays $B \to pX$ $(B \to \Lambda X)$* corresponds to an integrated luminosity of 83.3 pb^{-1} (95.4 pb^{-1}) on the $\Upsilon(4S)$ resonance and 25.3 pb^{-1} (42.2 pb^{-1}) in the continuum. The data sample for $B \to pX$ was restricted to those periods where the calibration of the time-of-flight and of the drift chamber systems was extremely stable.

2 Data analysis

2.1 Analysis of the decay $B \to \bar{p}X$

Only decays of B mesons into antiprotons were studied, which suffer less from background than protons. The separation of antiprotons from other charged particles was performed on a statistical basis. The expected time-of-flight and dE/dx distributions for electrons, charged π and K mesons and protons were derived directly from the data. K_s^0 mesons provide a clean $\pi^\pm$ sample, while Λ decays are a rich source of well-identified protons. The signal for electrons was derived from a sample of converted photons. A small sample of charged K mesons was selected from D^{*+} meson decays in the channel $D^{*+} \to D^0 \pi^+$, $D^0 \to K^- \pi^+$. Muons cannot be distinguished from pions by means of dE/dx and time-of-flight in the momentum range above 400 MeV/c and are not considered separately.

The measured time-of-flight (T) and dE/dx resolutions are independent of the particle species, when determined as functions of

$$\mathcal{T} = T - T_{\text{calc}}$$

and

$$\mathcal{D} = \frac{dE}{dx} \bigg/ \left.\frac{dE}{dx}\right|_{\text{calc}}.$$

The index "calc" indicates the theoretically expected values for the specific particle type, calculated using the measured momentum and polar angle of the charged track.

The samples of uniquely identified particles were used to obtain corrections for deviations from the theoretically expected values. For the time-of-flight measurements these corrections depend on the polar angle θ, while for the dE/dx measurements they depend on the momentum and the charge of the particle. In both cases a slight time-dependence was also taken into account.

The $\mathcal{T}$ and $\mathcal{D}$ distributions of the uniquely identified tracks were used to determine the probability density distributions for the time-of-flight and dE/dx measurements. In Fig. 1a and b the distributions are plotted for the pion and proton samples. The width of the distributions reflect the resolution of the detector.

The $\mathcal{T}$ distribution was parametrized by fitting the sum of a gaussian plus an exponential in order to describe the tail:

$$f(\mathcal{T}) = A_1 \cdot \exp - \frac{(\mathcal{T} - t_0)^2}{2\sigma_t^2} + A_2 \cdot \exp \frac{|\mathcal{T} - t_0|}{a}.$$

For the $\mathcal{D}$ distribution, a gaussian in $\ln \mathcal{D}$ was used

$$g(\mathcal{D}) = A_3 \cdot \exp - \frac{(\ln \mathcal{D} - \ln d_0)^2}{2\sigma_d^2}.$$

The mean values t_0 and d_0, the resolutions σ and the quantities A_1, A_2, A_3 and a are free parameters of the fit and do not vary significantly with the particle's momentum. In order to obtain probability densities the integrals of $f(\mathcal{T})$ and $g(\mathcal{D})$ were normalized to 1.

To determine the numbers n_i ($i = e, \pi, K$ and p) of the different particle species in a given data sample, a set of likelihoods is calculated from the measured time-of-flight and dE/dx for each track j using:

$$l_{ij} = f(T - T_{\text{calc},i})_j \cdot g\left(\frac{dE}{dx} \bigg/ \left.\frac{dE}{dx}\right|_{\text{calc},j}\right)_j, \qquad i = e, \pi, K, p.$$

The overall likelihood for a track j is given by

$$L_j = \sum_i l_{ij} \cdot \frac{n_i}{N}, \qquad i = e, \pi, K, p$$

* Branching ratios are defined as $\text{Br}(B \to pX) = (N(p) + N(\bar{p}))/(N(B) + N(\bar{B}))$

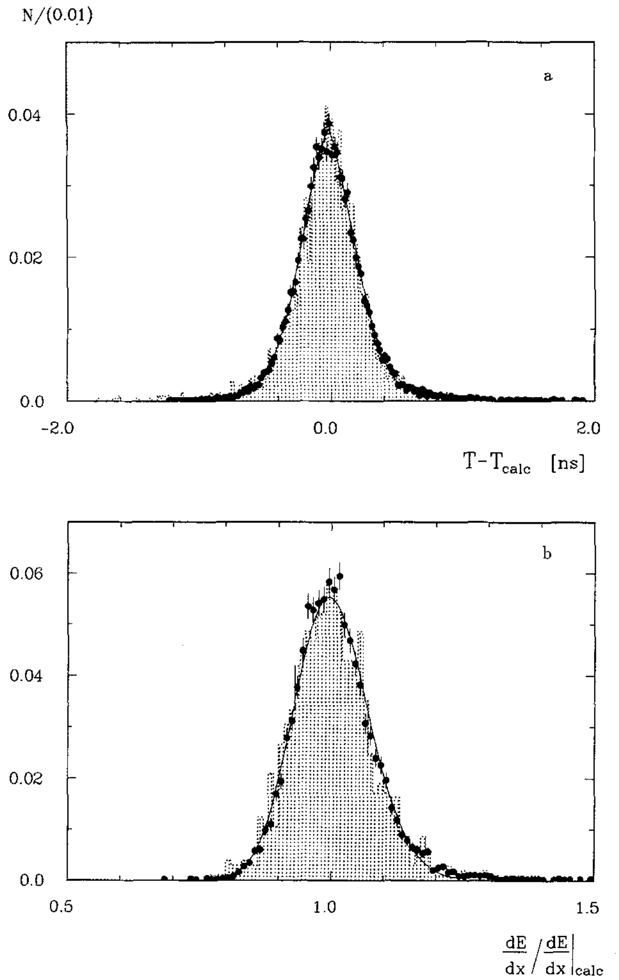

Fig. 1 a, b. Probability distributions for **a** time of flight and **b** specific energy loss $\left(\frac{dE}{dx}\right)$ for pions (dots) and protons (histogram). The full lines correspond to the fitted probability densities $f(\mathscr{T})$ and $g(\mathscr{D})$

with

$$N = n_e + n_\pi + n_K + n_p. \tag{1}$$

For the full data sample we finally calculate the likelihood

$$L = \prod_{j=1}^{N} L_j.$$

By maximizing L as a function of n_i, with the constraint (1), the numbers of the different particle species are obtained.

The systematic uncertainties of this method were studied by generating a large sample of particles, with approximately the same abundancies as observed in the data and the expected $\mathscr{D}$ and $\mathscr{T}$ distributions. These Monte Carlo generated tracks were then fitted in the same way as the data. By varying the mean values of the dE/dx and T distributions for the generated particles within reasonable values, the number of misidentified protons in the sample was obtained as a function of the generated momentum. Up to momenta of 1 GeV/c the misidentification probability is less than 2%, but raises rapidly with increasing momentum [4].

Charged particles were required to have polar angles in the barrel region of the detector, $|\cos\theta| < 0.7$, to ensure good particle identification. Furthermore, only tracks with a proper time-of-flight and dE/dx signal were considered, in order to avoid distortions due to double hits in the time of flight counters.

In order to determine the branching ratio for the decay $B \to pX$, the continuum data have been scaled appropriately to the $\Upsilon(4S)$ energy. In addition to the luminosity ratio, the energy dependence of the continuum cross section (-2% correction) and the influence of initial-state radiation, including the contribution of the lower mass Υ resonances (-5% correction), have been considered. The radiative correction also accounts for the enhanced baryon production in 3-gluon decays [5, 6].

The efficiency of antiproton detection includes a momentum dependent $\bar{p}$ absorption correction (≈ 5%), the geometrical losses due to the polar angle cut (30%) and a factor allowing for the losses due to multiple hits in the time-of-flight system (≈ 25%). The latter depends on the charged multiplicity of the events and has been derived directly from the data [4].

The acceptance corrected $\bar{p}$ momentum distribution from B decays is soft and for momenta above 1.2 GeV/c the rate is compatible with being zero (Fig. 2). Between 0.4 GeV/c and 1.2 GeV/c we found 8896 antiprotons on the $\Upsilon(4S)$ resonance and 2190 in the continuum data. After subtracting the continuum contribution there remain 2163 ± 173 antiprotons from $\Upsilon(4S)$ decays in this momentum range. Integrating the measured differential distribution in the interval 0.4 GeV/c $< p <$ 1.2 GeV/c, one derives the result

$$\mathrm{Br}(\Upsilon(4S) \to \bar{p}X) = (5.8 \pm 0.4 \pm 0.4)\%|_{0.4\,\mathrm{GeV/c} < p < 1.2\,\mathrm{GeV/c}}.$$

The first error is statistical and the second systematic.

In order to extract the branching ratio for the entire momentum range, the observed spectrum has to be extrapolated outside the measured region. Because there are no model predictions for the exact

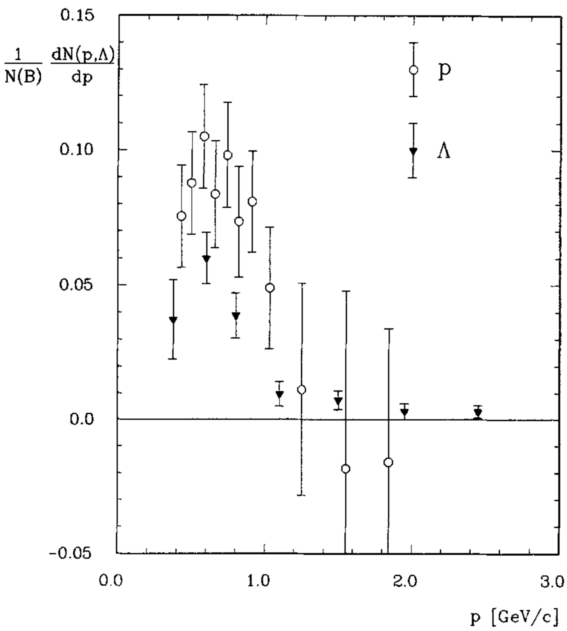

Fig. 2. Momentum spectra of p and Λ from B meson decays. For the proton spectrum the errors include the systematic uncertainties of the fit procedure. For the Λ only the statistical error is given

shape of the spectrum this generates large uncertainties in the final number. Assuming that the ratio of protons with momenta above and below 1.2 GeV/c is the same as that observed in the Λ momentum spectrum from B decays, a correction of $(0.9 \pm 0.3 \pm 0.5)\%$ is obtained for the upper momentum cut. By extrapolating the spectrum linearly to zero momentum, taking into account possible variations in the spectrum near 0.4 GeV/c, one obtains a contribution of $\left(1.5 \pm 0.1^{+1.1}_{-0.8}\right)\%$ for the region below 0.4 GeV/c. Assuming CP invariance for the decay $B \to pX$ and $\mathrm{Br}(\Upsilon(4S) \to B\bar{B}) = 100\%$, the final result is

$$\mathrm{Br}(B \to pX) = \left(8.2 \pm 0.5^{+1.3}_{-1.0}\right)\%.$$

2.2 *Analysis of the decay $B \to \Lambda X$*

For this study, only tracks with a transverse momentum $p_t > 0.06$ GeV/c and a polar angle $|\cos\theta| < 0.92$ were considered. All mass hypotheses for charged particles were accepted for which the likelihood ratio [3] constructed from the combined time-of-flight and energy loss measurements exceeded 5%. Protons were required to have a momentum above 0.3 GeV/c. A cut on the χ^2 of the secondary vertex of the $p\pi^-$ combinations was applied to select stable particles. The Λ candidates were also required to have a polar angle with $|\cos\theta| < 0.85$. The radial distance R of the secondary vertex to the beam axis was constrained to the interval $4\,\mathrm{cm} < R < 40\,\mathrm{cm}$. In order to reject background from converted photons, the opening angle between the p and π^- was required to satisfy $\cos(p, \pi^-) < 0.998$. Λ hyperons from strangeness exchange reactions in the inner detector walls were suppressed by forcing the angle between the Λ flight direction and the vector **d** connecting the main and the secondary vertex to fulfill $\cos(\mathbf{p}, \mathbf{d}) > 0.995$. The latter cut was not applied to particles used in the search for Ξ^- hyperons in Sect. 2.3. Λ contributions from background sources after all cuts was determined to be less than 1% [7].

Acceptance losses were corrected by associating an overall efficiency with each particle combination. This efficiency was determined from a Monte Carlo simulation of the complete detector [8] as a product of two factors. The factor ε_{comb} includes the reconstruction probability, the losses due to absorption and decay of particles, the vertex reconstruction efficiency and losses due to particle identification cuts. ε_{geom} accounts for the geometrical acceptance, as well as losses due to kinematical cuts. The systematic error due to this factorization assumption has been determined by a Monte Carlo calculation to be less than 2%. An overall weight

$$w = \frac{s \cdot r_c}{\varepsilon_{geom} \cdot \varepsilon_{comb}}$$

was assigned to each particle combination, where s is the center of mass energy square and r_c is a factor representing the radiative corrections to the continuum data.

The measured invariant $p\pi^-$ mass distribution is shown in Fig. 3a and b for $\Upsilon(4S)$ and continuum data, respectively. Only Λ particles with a scaled momentum

$$x_p = p/p_{max} > 0.05$$

are included in the plot. An almost background free signal is observed. The distribution peaks at 1.116 GeV/c^2, its width of 1.8 MeV/c^2 is compatible with the expected value derived from the Monte Carlo calculation. The small background contribution was subtracted from the momentum distributions using mass side bands. The mass interval 1.105 GeV/c^2 to 1.125 GeV/c^2 was used as the signal region, while the side bands 1.095 GeV/c^2 to 1.105 GeV/c^2 and 1.125 GeV/c^2 to 1.135 GeV/c^2 were used to estimate the combinatorial background.

After background subtraction, the signals contain 5428 ± 77 Λ baryons on the $\Upsilon(4S)$ and 2166 ± 49 in the continuum. Subtracting the continuum component one is left with a signal of 943 ± 136 Λ baryons

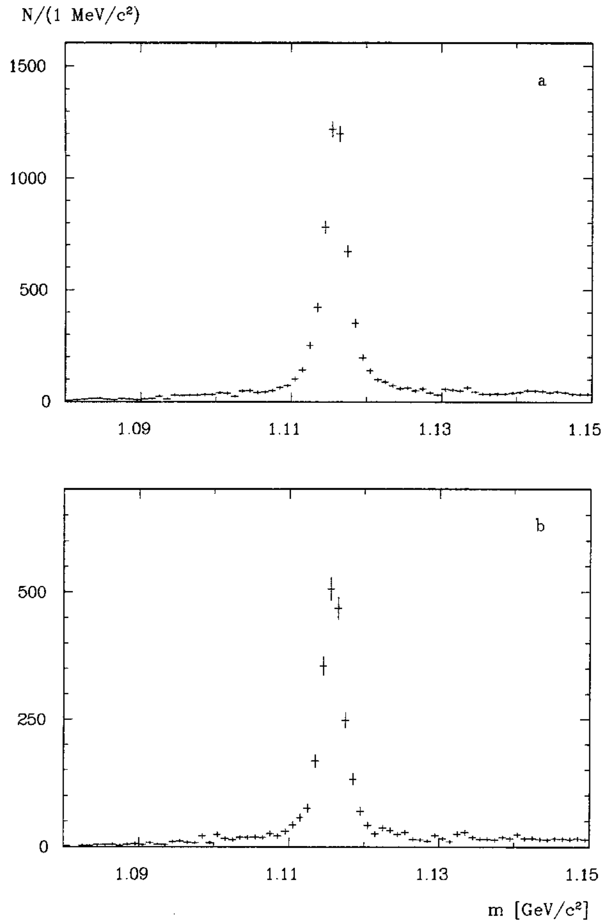

Fig. 3a, b. Invariant mass distributions of $p\pi^-$ combinations with $0.1 < x_p < 0.5$ for **a** $\Upsilon(4S)$ data and **b** continuum data

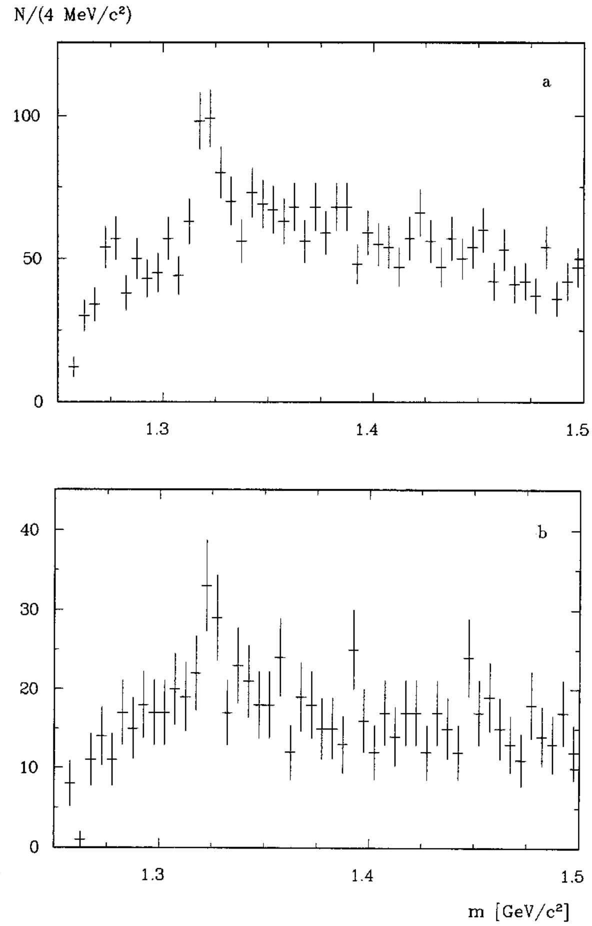

Fig. 4a, b. Invariant mass distributions of $\Lambda\pi^-$ combinations in the momentum range $0.1 < x_p < 0.2$ for **a** $\Upsilon(4S)$ data and **b** continuum data

from B decays. The Λ spectrum from B meson decays has been determined by subtracting the continuum data, which were scaled to the energy of the $\Upsilon(4S)$ resonance and corrected for radiative effects (Sect. 2.1). The continuum subtraction was made using x_p, assuming the shape of the continuum component of the spectrum scales in this variable. In Fig. 2 the measured Λ spectrum, as a function of p, is shown.

Integrating the measured rate in the interval $0.35 < p < 2.4$ GeV/c covered by the data of Fig. 2 one obtains a branching ratio of $3.7 \pm 0.5\%$. A linear extrapolation of the data to $p = 0$ yields a final branching ratio of

$$\mathrm{Br}(B \to \Lambda X) = (4.2 \pm 0.5 \pm 0.6)\% .$$

The dominant contribution to the systematic error is the uncertainty in the number of $\Upsilon(4S)$ events.

2.3 *Analysis of the decay* $B \to \Xi^- X$

A search for a Ξ^- signal was made by selecting events with $\Lambda\pi^-$ combinations in both the $\Upsilon(4S)$ and continuum data samples. The momentum range was restricted to $0.1 < x_p < 0.2$, since the results of the p and Λ studies leads one to expect the largest contribution to a possible signal in this region. Only those $p\pi^-$ combinations with $\chi^2 < 9$ for the Λ mass hypothesis and $p > 0.4$ GeV/c are included in Fig. 4. A mass constraint fit was applied to the $p\pi^-$ system. The invariant mass spectrum for $\Lambda\pi^-$ combinations with $0.1 < x_p < 0.2$ are shown in Fig. 4a and b for $\Upsilon(4S)$ and continuum data, respectively. In order to derive the $\Upsilon(4S)$ contribution, a gaussian was used to parametrize the Ξ^- signal, while the background was described by the product of a third order polynomial and a square root threshold factor. In both cases a signal is observed at a mass of 1321.2 ± 0.6 MeV/c^2 and with a width of $\sigma = 4.2$ MeV/c^2. These values coincide with the Monte Carlo expectation. In total, a signal of $108 \pm 18\,\Xi^-$ was found in the $\Upsilon(4S)$ data and 26 ± 10 in the continuum. Subtracting the continuum from the $\Upsilon(4S)$ data, $54 \pm 27\,\Xi^-$ remain as a 2 standard indication for possible Ξ^- production in B decays. This corresponds to a branching ratio of

$$\mathrm{Br}(B \to \Xi^- X) = (0.28 \pm 0.14)\%$$

or an upper limit of

$$\mathrm{Br}(B \to \Xi^- X) < 0.51\% \,(90\%\ \mathrm{C.L.}).$$

The extrapolation to the unobserved momentum range has been performed using the Λ spectrum (Sect. 2.2).

2.4 Baryon antibaryon correlations

Baryon antibaryon correlations in B meson decays were studied for $p\bar{p}$, $\Lambda\bar{p}$ and $\Lambda\bar{\Lambda}$ using the same data sample used for the $B \to \Lambda X$ and $B \to \Xi^- X$ analysis.

Only well identified protons with momenta $0.4 < p_p < 1.0$ GeV/c were used with a polar angle cut of $|\cos\theta| < 0.7$. In addition we required that the origin of the track has a maximum distance $\Delta z = 15$ cm from the main vertex in beam direction. This cut efficiently rejects background from protons produced and scattered back from nuclear interactions in the outer parts of the detector, but retaines a high acceptance for protons from Λ decays.

To demonstrate that the background from particle misidentification is negligible, Fig. 5 shows the shower energy distribution of the antiproton candidates after the cuts described above in comparison with the same distribution from a clean sample of antiprotons from $\bar{\Lambda}$ decays. Entries in the latter distribution have been weighted in order to obtain an equivalent momentum distribution. The peak at low shower energies originates from antiprotons which annihilate before reaching the shower counters. The corresponding distribution for pions has been included in the plot to show that the shower energy serves as independent tool for particle identification in this momentum range.

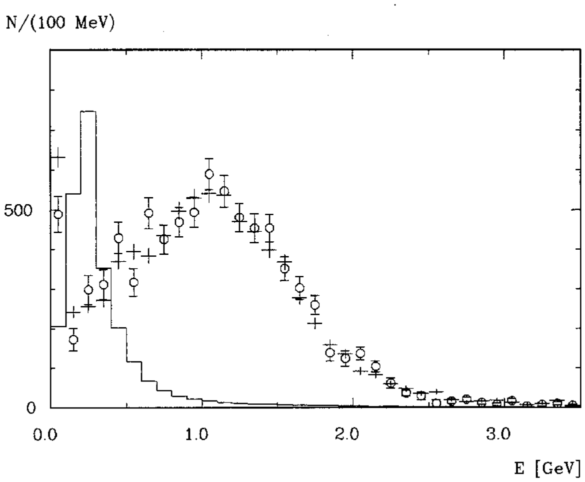

Fig. 5. Shower energy distribution of antiproton candidates (crosses), from which the likelihood from particle identification exceeds 30%, in the momentum range between 0.4–1 GeV/c in comparison with the corresponding distribution of a reference sample of well identified antiprotons from Λ decays (circles). The shower energy distribution for pions in the same momentum range is overlayed as a histogram

Using this procedure 3042 ± 55 (1026 ± 32) $p\bar{p}$ candidates were found in the $\Upsilon(4S)$ (continuum) data. After subtraction of continuum and the small background of protons produced in nuclear interactions in the inner detector materials a signal of 918 ± 86 $p\bar{p}$ events remains from direct $\Upsilon(4S)$ decays. Correcting for acceptance and random $p\bar{p}$ combinations from different B decays and extrapolating the data to the full momentum range using the shape of the measured proton spectrum of Fig. 2, one obtains a branching ratio of

$$\mathrm{Br}(B \to p\bar{p}X) = (2.5 \pm 0.2 \pm 0.2)\%.$$

The fraction of events, where the proton is accompanied by an antiproton, is given by

$$\frac{2 \cdot \mathrm{Br}(B \to p\bar{p}X)}{\mathrm{Br}(B \to pX)} = 0.60 \pm 0.06 \pm 0.07,$$

which is in good agreement with the naive expectation of an equal proton and neutron rate in multiparticle final states.

For the analysis of $\Lambda\bar{p}\,(\bar{\Lambda}p)$ and $\Lambda\bar{\Lambda}$ correlations' Λ candidates were selected using the same cuts as described in Sect. 2.2. To enhance the contribution of $\Upsilon(4S)$ decays the accepted momentum interval was restricted to $0.4 < p_\Lambda < 1.3$ GeV/c. After subtracting background and continuum contributions one is left with a signal of 165 ± 36 $\Lambda\bar{p}$ and 12 ± 12 $\Lambda\bar{\Lambda}$ events from direct $\Upsilon(4S)$ decays. From these event rates one can derive the branching ratio

$$\mathrm{Br}(B \to \Lambda\bar{p}X) = (2.3 \pm 0.4 \pm 0.3)\%$$

which, combined with the inclusive Λ rate, yields a ratio

$$\frac{\mathrm{Br}(B \to \Lambda\bar{p}X)}{\mathrm{Br}(B \to \Lambda X)} = 0.54 \pm 0.11 \pm 0.10,$$

also in agreement with an equal rate of protons and neutrons.

For the branching ratio $B \to \Lambda\bar{\Lambda}$ one obtaines a 90% upper limit of

$$\mathrm{Br}(B \to \Lambda\bar{\Lambda}X) < 0.88\%$$

or

$$\frac{2 \cdot \mathrm{Br}(B \to \Lambda\bar{\Lambda}X)}{\mathrm{Br}(B \to \Lambda X)} < 0.42.$$

3 Discussion

The results presented on baryonic B meson decays can be used to obtain the total baryonic branching ratio $B \rightarrow$ baryons. Subtracting the contribution of Λ decays to the inclusive proton yield one obtains a "direct" proton branching ratio of

$$\mathrm{Br_{dir}}(B \rightarrow pX) = (5.5 \pm 1.6)\%.$$

Assuming the same branching ratio for $B \rightarrow nX$ and adding the measured Λ rate yields

$$\mathrm{Br}(B \rightarrow \text{baryons}) = (7.6 \pm 1.4)\%.$$

This value is consistent with the branching ratio $B \rightarrow \Lambda_c^+ X$ derived from our recent measurement of the product of branching ratios $\mathrm{Br}(B \rightarrow \Lambda_c^+ X) \cdot \mathrm{Br}(\Lambda_c^+ \rightarrow pK^- \pi^+)$ [1], using the branching ratio of the Λ_c decay into $pK^- \pi^+$ given in [9].

Also the observed ratio of the Λ and proton rates in B decays

$$\Lambda/p = \frac{\mathrm{Br}(B \rightarrow \Lambda)}{\mathrm{Br}(B \rightarrow p)} = 0.51 \pm 0.12,$$

which is slightly higher than in parton fragmentation processes [6], confirms the picture of the dominance of charmed baryons in the total baryon rate.

The question of whether strangeness is produced in the fragmentation of the spectator quark could be answered by observing Ξ^- production or $\Lambda\bar{\Lambda}$ correlations. Unfortunately, we are presently at the limit of getting a significant result and more data are needed.

4 Conclusion

We have measured and extracted the momentum spectra for the decays $B \rightarrow pX$ and $B \rightarrow \Lambda X$. The results agree with previous measurements of the CLEO collaboration [2]. The shape of the spectra also agrees very well with the expectations from the observed Λ_c^+ momentum spectrum in B decays [1], showing that baryons are produced dominantly in multiparticle final states and in connection with the formation of charmed baryons.

From the measured branching ratios an estimate for the total baryon rate in B decays yields $\mathrm{Br}(B \rightarrow \text{baryons}) = (7.6 \pm 1.4)\%$.

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