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Another Source of Baryons in B Meson Decays

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Abstract

It is usually assumed that the production of baryons in B meson decays is induced primarily by the quark level process $b \to c\bar{u}d$, where the charm quark hadronizes into a charmed baryon. With this assumption, the Λ_c momentum spectrum would indicate that the transition $B \to \Lambda_c X$ is dominated by multi-body B decays. However, a closer examination of the momentum spectrum reveals that the mass m_X against which the Λ_c is recoiling almost always satisfies $m_X \gtrsim m_{\Xi_c}$. This fact leads us to examine the hypothesis that the production of charmed baryons in B decays is in fact dominated by the underlying transition $b \to c\bar{c}s$, and is seen primarily in modes with two charmed baryons in the final state. We propose a number of tests of this hypothesis. If this mechanism is indeed important in baryon production, then there are interesting consequences and applications, including potentially important implications for the "charm deficit" in B decays.

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The interpretation of data on the production of charmed baryons in the weak decay of B mesons often involves significant model-dependence. In particular, it consistently has been assumed in experimental analyses that baryon production arises predominantly from the quark-level process $b \to c\bar{u}d$, where the charm quark fragments to a Λ_c or Σ_c, which is in turn observed in the cascade decay to a Λ [1–4]. In this letter, we will suggest that this may in fact not be the case, that rather, the dominant quark-level process for charmed baryon production is $b \to c\bar{c}s$. This process is usually neglected, because of the phase space suppression arising from the mass of the additional charm quark. We will present circumstantial evidence that the $b \to c\bar{c}s$ process actually contributes significantly to the production of charmed baryons, and propose a more stringent test of our hypothesis which makes use of baryon-lepton sign correlations. If this indeed turns out to be the case, there are a number of interesting theoretical and experimental consequences, which we will discuss.

The only charmed baryons which have so far been reconstructed in B decays are the Λ_c and Σ_c, which is observed in its decay to $\Lambda_c\pi$. Since final states are included with their charge conjugates to improve the statistics [1–3], it is not known whether a given Λ_c actually comes from the decay of a B or a $\overline{B}$. However, under the usual assumption that the Λ_c is produced directly in the decay of a $\overline{B}$ meson to a single charmed hadron, the data exhibit a curious feature. As pointed out in Refs. [1–3], there is absolutely no evidence for two-body decays of the form $\overline{B} \to \Lambda_c X$. Such evidence would come from the momentum spectrum of the Λ_c. We display the most recent CLEO data in Fig. 1, which is taken from Ref. [3]. The spectrum is clearly much too soft to be consistent with two-body decays. If one fits the spectrum to $\overline{B} \to \Lambda_c\overline{N}(n\pi)$ (where N is a nucleon), then one has to take $n \geq 3$ [2,3].

In fact, the higher-statistics CLEO study [2,3] is consistent with finding very few Λ_c's with momentum $P_{\Lambda_c} \gtrsim 1.5\,\text{GeV}$. This is equivalent to a strong statement about the invariant mass m_X of the hadronic state against which the Λ_c is recoiling, namely $m_X \gtrsim 2.3\,\text{GeV} \approx m_{\Lambda_c}$. (In fact, the binned data are not inconsistent with the even stronger condition $m_X \gtrsim m_{\Xi_c}$.) This is most puzzling, if one believes that the production of Λ_c's is induced by the quark-level transition $b \to c\bar{u}d$, leading to $\overline{B} \to \Lambda_c X$. One would need to posit a mechanism for suppressing those final states X with invariant mass $m_p \leq m_X \lesssim m_{\Lambda_c}$.

These facts lead us to the hypothesis that the production of charmed baryons in B meson decays is dominated not by the transition $b \to c\bar{u}d$ but by $b \to c\bar{c}s$. In contrast to $b \to c\bar{u}d$, this process can yield naturally the Λ_c momentum spectrum which is observed. We illustrate this in Fig. 2, where we plot the predicted momentum spectrum under the fairly generic assumption that Λ_c's are produced equally in the two-body modes $\overline{\Xi}_c\Lambda_c$, $\overline{\Xi}'_c\Lambda_c$, $\overline{\Xi}_c\Sigma_c$ and $\overline{\Xi}'_c\Sigma_c$. Here two charmed baryons are produced per B decay, for example via the quark diagrams shown in Fig. 3. In Fig. 2, the smearing due to the small boost of the B meson in the $\Upsilon(4S)$ rest frame has been included. The Σ_c is seen in its cascade decay to Λ_c, while the Ξ_c is too light to decay strongly and hence cannot yield a Λ_c. By the Ξ'_c, we mean the spin-$\frac{1}{2}$ $SU(3)$ 6 state similar to the Ξ_c, which is a $\overline{3}$ under $SU(3)$. It is the strange analogue of the Σ_c, and its mass splitting from the Ξ_c has been measured to be 95 MeV [5]. We stress that we present this plot simply to illustrate how naturally the data can be reproduced by the assumption that Λ_c's are produced in B decay via $b \to c\bar{c}s$, rather than in $\overline{B}$ decay via $b \to c\bar{u}d$. This simple model fails to account for the approximately 20% of Λ_c's which have momenta below 0.55 GeV, which must come from the decays of higher charmed baryon resonances or from many-body decays.

We note that the $b \to c\bar{c}s$ transition cannot actually saturate the production of charmed baryons in B decays, because CLEO has recently observed the exclusive mode $\overline{B} \to \Lambda_c\overline{p}\pi^+\pi^-$ at the 0.2% level, while obtaining tight upper limits on $\overline{B} \to \Lambda_c\overline{p}(n\pi)$, for $n = 1, \ldots, 4$ [7]. The observed mode constitutes a tiny 4% fraction of the Λ_c yield in B decays. Since nonperturbative QCD is involved, there is no firm theoretical calculation of the relative strengths of baryon production via the $b \to c\bar{c}s$ and $b \to c\bar{u}d$ transitions, although various model estimates exist [6].

Of course, while the evidence in Figs. 1 and 2 is appealing, it is clearly somewhat circumstantial. A more stringent test of our hypothesis can be constructed by analyzing correlations between charmed baryons from one B and the sign of a hard lepton produced by the weak decay of the other B in the event. With appropriate cuts, the sign of the lepton can be used to tag the parent of the charmed baryon as a B or $\overline{B}$; for example, a hard ℓ^+ arising from $\bar{b}$ decay on the other side of the event indicates that the charmed baryon came from the decay of a b quark. Such a study has already been performed by CLEO for $\Lambda\ell^{\pm}$ correlations [2]. One must be careful to compensate for the effects of $B-\overline{B}$ mixing.*

For example, let us consider $\Lambda_c\ell^{\pm}$ and $\Xi_c\ell^{\pm}$ sign correlations. If Λ_c's are produced only via the transition $b\rightarrow c\bar{u}d$, then we expect to observe the correlation $\Lambda_c\ell^+$. If instead they are produced via $b\rightarrow c\bar{c}s$, then we expect to find $\Lambda_c\ell^-$. (This is strictly true only in the momentum range $P_{\Lambda_c}\geq 0.87\,\mathrm{GeV}$. Below this momentum, the correlations may partially be spoiled by the presence of a $\overline{\Lambda}_c\Lambda_c\overline{K}X$ final state, where the $\Lambda_c\overline{K}$ comes, for example, from the decay of a highly excited $\Xi_c^{(r)}$ resonance.) Both the $b\rightarrow c\bar{c}s$ and the $b\rightarrow c\bar{u}d$ mechanisms predict a $\Xi_c\ell^+$ correlation, while $\Xi_c\ell^-$ correlations should come only from $b\rightarrow c\bar{c}s$.

It is useful to assemble the information which may be gained from these correlations into a single unified test of our hypothesis. Unfortunately, this cannot be done without introducing a certain amount of model-dependence, but we will make it as minimal, and as explicit, as possible. We consider four mechanisms for the production of charmed baryons in $\overline{B}$ decay, corresponding to the quark-level transitions $b\rightarrow c\bar{u}d$, $b\rightarrow c\bar{c}s$, $b\rightarrow c\bar{u}s$ and $b\rightarrow c\bar{c}d$. The last two modes are Cabibbo-supressed, but we include them for completeness. We might naïvely expect them to contribute at the level of five to ten percent of the Cabibbo-allowed modes. We neglect the production of charmed baryons in semileptonic B decays, which is expected to be small. Let the notation $B_{\bar{u}d}$ denote that part of the branching ratio of $Br(B\rightarrow$ baryons) which comes from $b\rightarrow c\bar{u}d$, and define $B_{\bar{c}s}$, $B_{\bar{c}d}$ and $B_{\bar{u}s}$ analogously. We also denote by $R_{H_c\ell^{\pm}}\equiv N_{H_c\ell^{\pm}}/N_{\mathrm{tagged}}$ the yield of charmed hadrons H_c correlated with hard charged leptons $\ell^{\pm}$, divided by the total number of lepton-tagged $B\overline{B}$ events. We assume that $B-\overline{B}$ mixing has been corrected for, and, of course, acceptance and detection

*This point is discussed in detail in Ref. [8], where it is pointed out that this has not always been done correctly in the past.

efficiencies have been included.

We need to make some assumption about the relative probability of producing $s\bar{s}$ pairs during the fragmentation process, relative to $u\bar{u}$ or $d\bar{d}$ pairs. Although this could in principle depend on the particular kinematics of each decay, we will model it by a single probability p, such that for $p = 0$ no $s\bar{s}$ pairs are produced, and for $p = 1$ we have exact $SU(3)$ symmetry in the fragmentation process. Unfortunately, we must also make the dynamical assumption that if a decay is not two-body, then all the quarks present immediately after the decay of the b materialize in charmed hadrons, if possible. For example, we assume that if the underlying transition is $b \to c\bar{u}d$, that the charmed baryon is of the form cdq, where $q\bar{q}$ is produced during fragmentation. This assumption is probably not important in the $b \to c\bar{c}s$ and $b \to c\bar{c}d$ channels, where we suspect from the evidence given above that the decays are primarily two-body, but it is more worrisome for final states with only one charmed baryon. Of course, if such states in fact contribute only minimally to charmed baryon production (as we suggest), then the assumption is not so dangerous. Finally, there will be a small contamination, for example, from the decays of highly excited charmed baryon resonances, such as $\Xi_c^{(r)} \to \Lambda_c\overline{K}$, $\Sigma_c\overline{K}$, $D\Lambda$, $D\Sigma$, $D_s^+\Xi$, or $\Lambda_c^{(r)}$,$\Sigma_c^{(r)} \to Dp$, $\Xi_c K$.

We consider five charmed baryon-lepton sign correlations: $\Lambda_c\ell^\pm$, $\Xi_c\ell^\pm$, and $\Omega_c\ell^+$. Assuming that the fragmentation to baryons in the ground state $SU(3)$ $\overline{3}$ and 6 is preferred, and with $B - \overline{B}$ mixing removed, we find

$$
\begin{aligned}
R_{\Omega_c\ell^+} &= \frac{p}{2+p}\left(B_{\bar{c}s} + B_{\bar{u}s}\right), \\
R_{\Xi_c\ell^+} &= \frac{2}{2+p}\left(B_{\bar{c}s} + B_{\bar{u}s}\right) + \frac{p}{2+p}\left(B_{\bar{u}d} + B_{\bar{c}d}\right), \\
R_{\Xi_c\ell^-} &= \frac{p}{2+p}\left(B_{\bar{c}s} + B_{\bar{c}d}\right), \\
R_{\Lambda_c\ell^+} &= \frac{2}{2+p}\left(B_{\bar{u}d} + B_{\bar{c}d}\right), \\
R_{\Lambda_c\ell^-} &= \frac{2}{2+p}\left(B_{\bar{c}s} + B_{\bar{c}d}\right).
\end{aligned}
$$

Recall that $B_{\bar{c}d}$ and $B_{\bar{u}s}$ are Cabibbo-suppressed and expected to be small, so these equations contain more cross-checks than may appear at first glance. Our prediction is that the data will indicate $B_{\bar{c}s} \gg B_{\bar{u}d}$.

Another simple test of our hypothesis is to look for $\Lambda_c\overline{\Lambda}$ correlations, which will follow from $b \to c\bar{c}s$ if the branching ratio for $\Xi_c \to \Lambda X$ is significant. By contrast, the $b \to c\bar{u}d$ process will result in $\Lambda_c\bar{p}$ correlations instead. Of course, the best test would be to reconstruct fully the exclusive modes $B \to \Lambda_c\overline{\Xi}_c$, $B \to \Sigma_c\overline{\Xi}_c$, and so forth. Now that more than a thousand Λ_c's have been reconstructed, it should become feasible to search for such final states. Finally, we note that if charm-anticharm two-body decays dominate inclusive baryon production in B decays, then the decay daughters, such as p, Λ, Ξ and Σ, will show a characteristic momentum dependence different from that predicted by the $b \to c\bar{u}d$ mechanism. As the data on momentum spectra improve, it should become possible to discriminate between the various production mechanisms.

If our hypothesis holds up under further scrutiny, there are interesting theoretical and experimental consequences. First, it would indicate that the inclusive charm yield from B decays to baryons has been seriously underestimated. This would help resolve the "charm deficit", which is the apparent problem that the number n_c of charm quarks observed per B decay is closer to 1.00 ± 0.07 than to the expectation based on phase space, $n_c \approx 1.15$ [4].[†] In fact, the problem is more serious, because a theoretical analysis of the semileptonic branching ratio of the B meson suggests that n_c is *larger* than naïvely expected, closer to 1.3 [10,11].

The inclusive branching fraction of B mesons to charmed baryons comes from the measurement of [1–3]

$$\Big[Br(B \to \Lambda_c X) + Br(\overline{B} \to \Lambda_c X)\Big]\, Br(\Lambda_c \to pK^-\pi^+)\,.$$

The most accurate measurement of this quantity to date is from CLEO [3], who report $(0.181 \pm 0.022 \pm 0.024)\%$. Coincidentally, Refs. [2] and [8] both obtain a Λ_c yield of 6% per bottom meson, using very different assumptions. While Ref. [2] assumes that the $b \to c\bar{u}d$

[†]The experimental result uses the branching ratio $Br(B \to D_s^\pm X) \approx 8\%$. A recent measurement of this quantity is somewhat larger, $Br(B \to D_s^\pm X) = (12.24 \pm 0.51 \pm 0.89)\%$ [9]. Including this result would increase n_c by 0.04.

mechanism governs Λ_c production, Ref. [8] uses current data under the assumption of $b \to c\bar{c}s$ dominance. Those Λ_c's which are produced via $b \to c\bar{c}s$, rather than via $b \to c\bar{u}d$, contribute two charm quarks, rather than one, to the inclusive charm yield. Hence, if charmed baryon production is indeed dominated by $b \to c\bar{c}s$, then there is a new contribution to n_c of about 0.06, or maybe more. From a theoretical point of view this would be most welcome.

Our hypothesis must also be considered in the light of the $\Lambda\ell^{\pm}$ correlations which have already been observed. If one follows the usual assumption that the predominant source of Λ's is Λ_c's, then the $b \to c\bar{u}d$ mechanism would result in a significant $\Lambda\ell^{+}$ correlation, which already has been seen by CLEO [2]. This correlation can be explained in the $b \to c\bar{c}s$ mechanism only if it turns out that the branching ratio $Br(\Xi_c \to \Lambda X)$ is much larger than $Br(\Lambda_c \to \Lambda X)$. There also exists a measurement of inclusive Ξ^- production in B decays, $Br(B \to \Xi^- X) + Br(\overline{B} \to \Xi^- X) = 0.27\%$ [2,12], which can only be consistent with our hypothesis if $Br(\Xi_c \to \Xi^- X) + Br(\Lambda_c \to \Xi^- X)$ is small.

However, if charmed baryon production is indeed dominated by the $b \to c\bar{c}s$ transition, then much of the current ARGUS and CLEO data on charmed baryons must be reinterpreted. A thorough analysis, which is beyond the scope of this letter, will be presented in Ref. [8]. There it is found that a consistent alternative picture of the production and decay of charmed baryons emerges, in which all existing experimental constraints are satisfied. In this scenario, the dominant source of the Λ's which have been observed in B decays is the decay of Ξ_c rather than of Λ_c.

Finally, we point out that our hypothesis would imply that Ξ_c and Ω_c baryons are being produced at B factories at a rate far greater than has heretofore been appreciated. This raises the exciting possibility that their properties may be studied in great detail.

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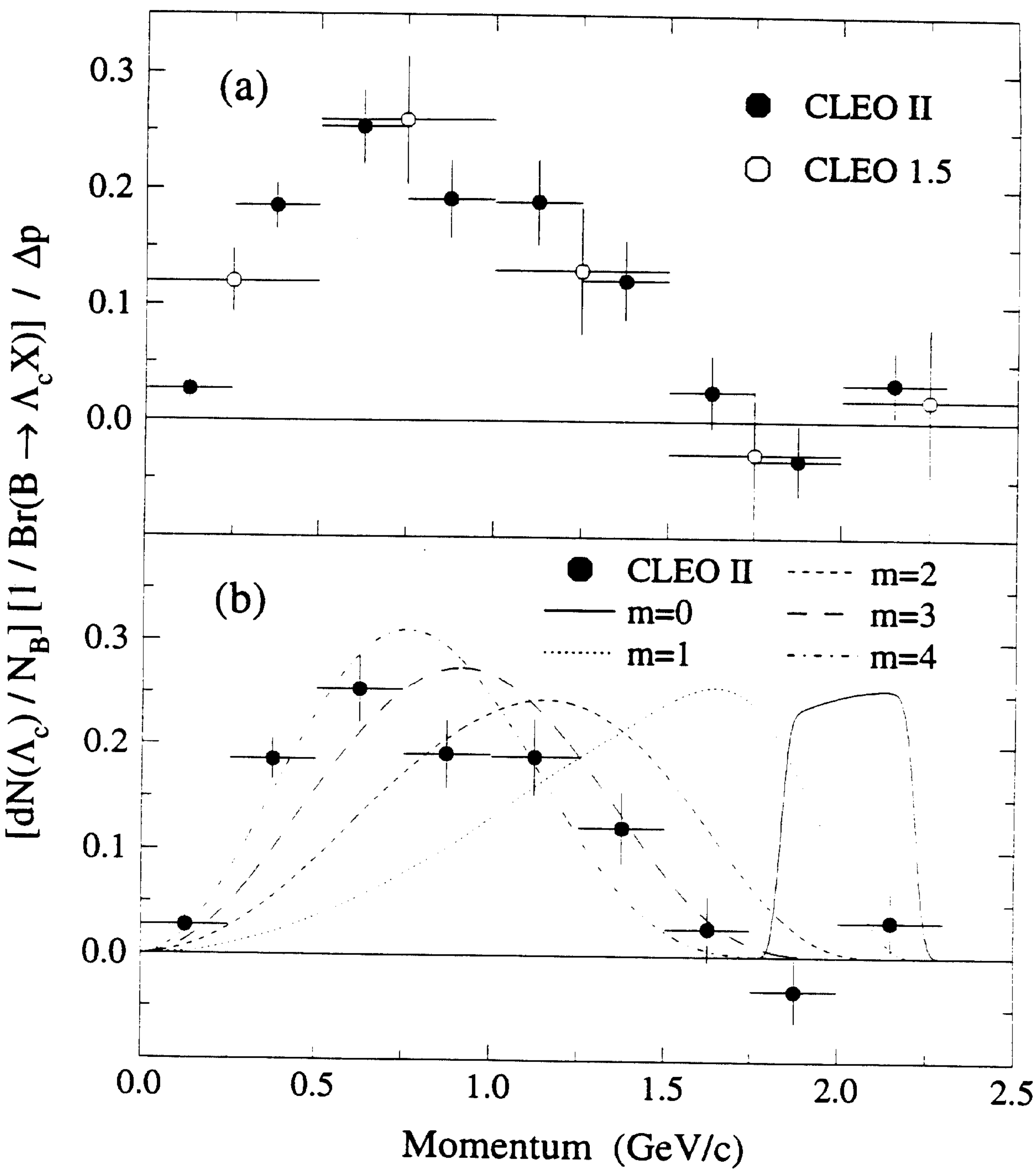
FIGURES

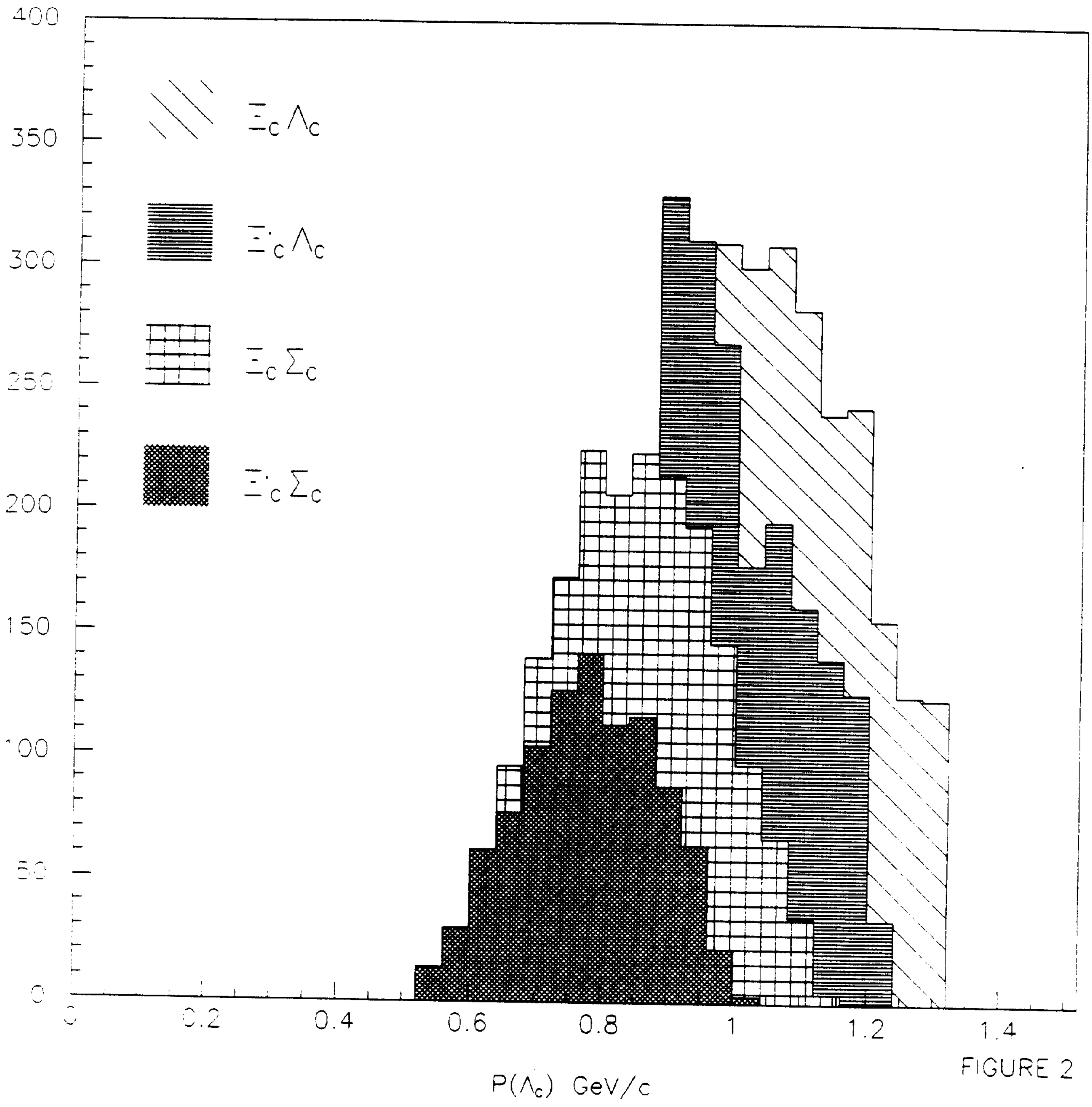
FIG. 1. The weighted average of the shape of the Λ_c^+ momentum spectrum in B decays compared (a) to the same spectrum derived from CLEO 1.5 data and (b) to shapes derived from Monte Carlo simulation of the decays $\overline{B} \to \Lambda_c^+ \overline{N}(m\pi)$, with $m = 0, \ldots, 4$ and N denoting p or n. All simulated curves have been normalized to data, with the exception of the case $m = 0$, where the normalization is arbitrary. The figure is taken from Ref. [3].

FIG. 2. The momentum spectrum P_{Λ_c}, under the assumption that Λ_c's are produced from B decays equally in the two-body modes $\overline{\Xi}_c \Lambda_c$, $\overline{\Xi}'_c \Lambda_c$, $\overline{\Xi}_c \Sigma_c \to \overline{\Xi}_c \Lambda_c \pi$ and $\overline{\Xi}'_c \Sigma_c \to \overline{\Xi}'_c \Lambda_c \pi$. The random boost of the B relative to the $\Upsilon(4S)$ has been accounted for. The data sample consists of 4000 Λ_c's.

FIG. 3. Quark diagrams for the production of two charmed baryons from the decay of a bottom meson.



(a)
CLEO II
CLEO 1.5
(b)
CLEO II
m=0
m=1
m=2
m=3
m=4
[dN(Λc) / NB] [1 / Br(B → ΛcX)] / Δp
Momentum (GeV/c)
0.0
0.1
0.2
0.3
0.5
1.0
1.5
2.0
2.5



400
350
300
250
200
150
100
50
0
$\Xi_c \Lambda_c$
$\Xi'_c \Lambda_c$
$\Xi_c \Sigma_c$
$\Xi'_c \Sigma_c$
0
0.2
0.4
0.6
0.8
1
1.2
1.4
$P(\Lambda_c)$ GeV/c

FIGURE 2

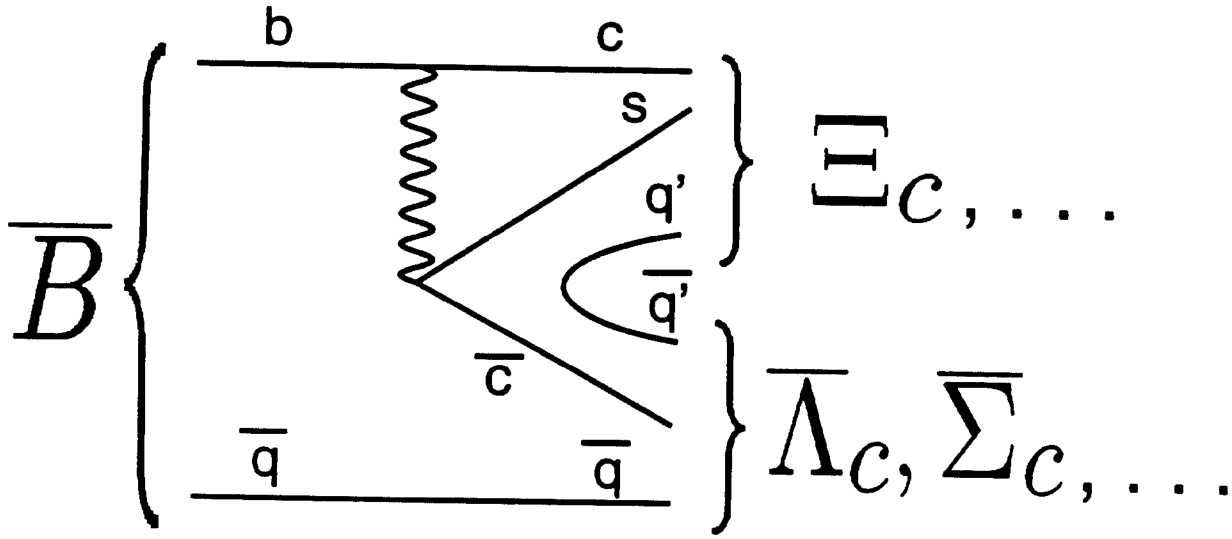


Figure 3.a

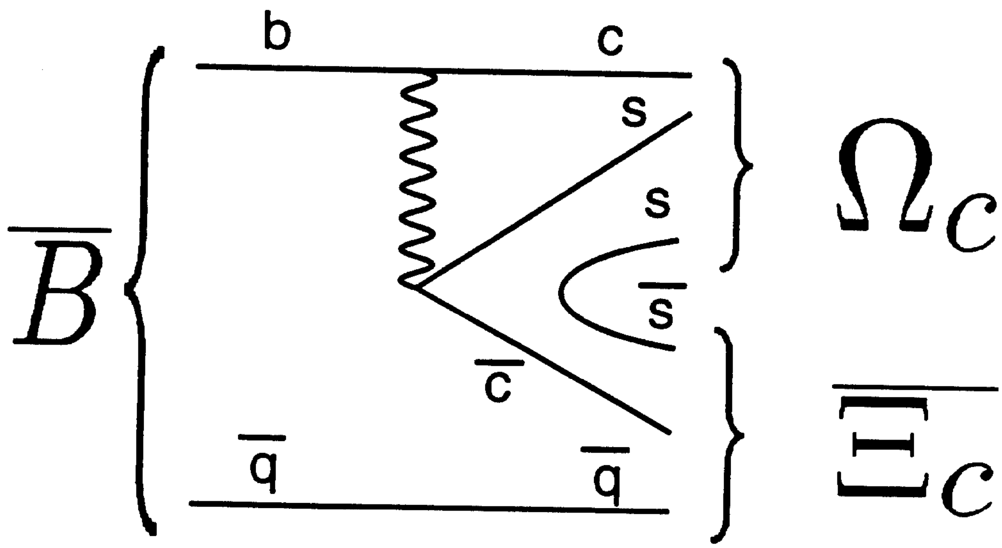


Figure 3.b