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Measuring absolute branching ratios of charmed baryons in B decays

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Abstract. The B factories are expected to provide huge samples of single B decay events with little background by reconstructing one of the B mesons produced in $\Upsilon(4S)$ decays. This represents a new experimental paradigm: such samples will allow to make measurements of a quality previously thought unrealistic. As example we discuss how absolute branching ratios for exclusive as well as inclusive charm baryon decays can be extracted. One starts out by observing decays like $B^- \to \bar{p}X$ as a signature for $B^- \to \Lambda_c \bar{p} X$ etc. and then exploits various correlations of the flavour of the B meson with the baryon number of the (anti)proton and other observables like the charge of a lepton, baryon number of another baryon etc. An integrated luminosity of about 500 fb^{-1} as could be available by 2005 should be sufficient for the task.

1 The goal

On the map for weak decays of charm baryons there are still large regions of terra incognita, which one wants to explore for two reasons. One needs *absolute* branching ratios for exclusive and inclusive decays of charm baryons as an engineering input for other studies concerning B decays and their charm content, production rates etc.

Secondly, heavy quark expansions (HQE) have been developed into a mature theoretical technology for treating decays of heavy flavour hadrons. Employing the operator product expansion one expresses inclusive observables like lifetimes and total semileptonic widths in inverse powers of the heavy quark mass. Of course for charm decays one cannot count on more than a semiquantitative description. The weak decays of charm *baryons* provide a very rich phenomenology for probing HQE: beyond the lifetimes of Ξ_c^+ as well as Ξ_c^0 – and preferably also of Ω_c – one would like to measure also the inclusive semileptonic branching ratios of the charm baryons; this will be explained below.

In this short note we sketch the situation with inclusive charm baryon decays in Sect.2, describe the method in Sect.3 and present numerical estimates in Sect.4, before summarizing in Sect.5.

2 Inclusive decays of charm baryons

The $D^+ - D^0$ and the $D_s - D^0$ lifetime ratios can readily be accommodated [1]. Preliminary results from FOCUS and CLEO show, however, the $\Xi_c^+ - \Lambda_c^+$ lifetime ratio to be significantly larger than predicted:

$$\frac{\tau(\Xi_c^+)}{\tau(\Lambda_c)} = \begin{cases} \sim 1.6 & \text{quark model [2]} \\ \sim 1.3 & \text{HQE + quark model [3]} \\ 2.8 \pm 0.3 & \text{CLEO [4]} \\ 2.29 \pm 0.14 & \text{FOCUS [5]} \end{cases} \quad (1)$$

This discrepancy could signal the inadequacy of the quark models used to evaluate the expectation values of the four-quark operators that enter in order $1/m_c^3$ [6]; or it could point to limitations in (quark-hadron) duality at the charm scale [7,8].

One can expect that the HQE yields a more reliable description for the *semi*leptonic widths of charm hadrons: there are fewer contributions, and duality can be expected to provide a better approximation here than in nonleptonic transitions. Theorists thus have fewer excuses left here (although they can still come up with one).

Due to isospin invariance

$$\Gamma_{SL}(B^+) = \Gamma_{SL}(B_d) + \mathcal{O}(|V(ub)/V(cb)|^2) \, ,$$
$$\Gamma_{SL}(D^+) = \Gamma_{SL}(D^0) + \mathcal{O}(|V(cd)/V(cs)|^2) \, ;$$

the ratio of the semileptonic branching ratios for these mesons therefore has to reflect their lifetime ratio. A priori there could be significant $SU(3)_{Fl}$ violations in $\Gamma_{SL}(B_s)$ vs. $\Gamma_{SL}(B_d)$ and $\Gamma_{SL}(D_s)$ vs. $\Gamma_{SL}(D^0)$; yet the HQE tells us that $SU(3)_{Fl}$ represents a good symmetry for these mesonic widths [9].

No such argument can be made for the semileptonic widths of the baryons beyond $\Gamma_{SL}(\Xi_c^+) = \Gamma_{SL}(\Xi_c^0)$. On

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the contrary, one expects large differences in the semileptonic widths of charmed baryons; e.g.,

$$\Gamma_{SL}(\Xi_c) \sim 2 \cdot \Gamma_{SL}(\Lambda_c) \quad (2)$$

through order $1/m_c^3$ [10]. This enhancement is due mainly to a *constructive* interference of the decay s quark with the s quark in the Ξ_c wavefunction. Taking (1) and (2) together suggests that $\mathrm{BR}_{SL}(\Xi_c^+)$ could be about five times larger than $\mathrm{BR}_{SL}(\Lambda_c^+)$! Of course, $\mathrm{BR}_{SL}(\Xi_c^+)/\mathrm{BR}_{SL}(\Xi_c^0) \simeq \tau(\Xi_c^+)/\tau(\Xi_c^0) \sim 3$ due to isospin invariance. These expectations can be summarized as follows:

$$\mathrm{BR}_{SL}(\Xi_c^+) \gg \mathrm{BR}_{SL}(\Lambda_c^+) \sim \mathrm{BR}_{SL}(\Xi_c^0) \quad (3)$$

It is highly desirable to find out whether such a dramatic effect exists. As indicated above, one has a simpler and more stable theoretical situation in *inclusive semi*leptonic decays. It would provide information on the baryonic expectation value of four-quark operators that affect also the Λ_c, Ξ_c^+ and Ξ_c^0 lifetimes. Invoking heavy quark symmetry they can be extrapolated to corresponding expectation values in the beauty sector [6], where they affect the lifetimes of Λ_b and $\Xi_b^{0,-}$ and the endpoint spectrum in semileptonic B decays [9].

It should also teach us lessons about the validity of duality at the charm scale[1]. Beyond the intellectual value of such lessons, they could help us in properly interpreting $D^0 - \bar{D}^0$ oscillations [11] as well as treating $B \to l\nu D^*$ [8].

Since contributions of order $1/m_c^4$ can be quite sizeable, the factor of two in (2) has to be taken with quite a grain of salt. Accordingly one is not necessarily asking for a precise measurement here.

3 The method

The ideal set-up for measuring *absolute* branching ratios for exclusive channels and for inclusive transitions would be to employ tagged events in $e^+e^- \to \Lambda_c\bar{\Lambda}_c$ and $e^+e^- \to \Xi_c\bar{\Xi}_c$. There are plans to create a tau-charm factory at Cornell; yet those plans do not envision to reach the Ξ_c production threshold. The best value of $\mathrm{BR}(\Lambda_c \to pK^-\pi^+)$ has been inferred from continuum charm production $e^+e^- \to \Lambda_c X$ [12]; yet the semileptonic branching ratio could not be obtained in such an environment, since the production rates for the various charm baryons are not known independently.

An alternative method is proposed here based on analyzing charm baryon production in B decays, which could be utilised at the BELLE and BABAR beauty factories. The past success of BELLE and BABAR gives confidence that large data sets can be accumulated in $e^+e^- \to B\bar{B}$, where one of the mesons is fully reconstructed. Such a scenario represents a new paradigm in beauty physics: one can then envision to undertake measurements that before had not been viewed as feasible. The case of charm baryon branching ratios discussed here is just one example for this paradigm.

The basic method consists of three steps: first one reconstructs one of the B mesons, which reveals the flavour of the other meson and at the same time reduces the number of tracks one has to contend with; then one identifies an (anti)proton among the remaining tracks to enrich the sample in charm baryons; finally one searches for one or more other particles that define the decay mode of the charm baryon one wants to study. A crucial tool here is the use of correlations between the B flavour, the baryon number of the (anti)proton, the charge of the lepton etc.

It is quite conceivable that flavour tagging with only *partial* reconstruction of the first B meson might suffice despite the presumably lower purity of the sample and the higher combinatorial background for the recoil B meson, since the relevant correlations remain intact. Only detailed experimental studies can answer this question.

To give a more explicit description we focus on charged B mesons for simplicity: $e^+e^- \to B^+B^-$. Let us assume the B^+ has been reconstructed; then one knows that the remaining tracks have to belong to the other B which we call the 'recoil' B; its flavour is known as that of a B^- from the reconstructed B^+. Next one searches for decays of the recoil B^- into final states containing an antiproton – $B^-_{recoil} \to \bar{p}X^0$ – which tells us that this final state has to contain a baryon as well; with $|V(cb)| \gg |V(ub)|$ there are three classes of such decays:

(i) $B^- \to \bar{p} + \Lambda_c^+ + X$;
(ii) $B^- \to \bar{p} + \Xi_c K + X$;
(iii) $B^- \to \bar{p} + p/nD + X$.

Since Ξ_c production requires the excitation of an $s\bar{s}$ rather than a $q\bar{q}$ pair, class (ii) will be reduced relative to class (i) by a factor of roughly three:

$$\mathrm{BR}(B \to \Xi_c^{+,0} X) \sim 1/3 \cdot \mathrm{BR}(B \to \Lambda_c^+ X) \quad (4)$$

The background class (iii) will be likewise reduced relative to class (i); even more importantly, its rate can be determined by observing the D decays utilising known branching ratios.

To bias the sample towards Ξ_c production, one selects $B^-_{recoil} \to \bar{p}K^+/\bar{\Lambda} + X^-$ requiring the correlation between the flavour of the B meson and the observed baryon number and strangeness of the final state. Again, there are several classes of such decays:

(iv) $B^- \to \bar{p}K^+/\bar{\Lambda} + \Xi_c + X$;
(v) $B^- \to \bar{p}K^+/\bar{\Lambda} + \Lambda_c\bar{K} + X$;
(vi) $B^- \to \bar{p}K^+/\bar{\Lambda} + p/nD_s/D\bar{K} + X$

The background class (iii) can be controlled by observing the $D_{(s)}$ decays. The sample will still contain a roughly equal amount of Ξ_c baryons and $\Lambda_c K$ combinations. We will return to the problem of controlling the latter, which represents a background here.

[1] It has been noted that roughly a third of the observed value of $\Gamma_{SL}(D)$ remains unaccounted for in the HQE result through order $1/m_c^3$. If that is an actual deficit, it might have its origin in a systematic underestimate of the charm quark mass m_c, which would have practically the same weight in all semileptonic charm widths; or it could be due to large *non*-factorizable contributions, which presumably would affect the various charm hadrons differently

3.1 Exclusive branching ratios

First one conducts a validation or calibration measurement, namely to extract $\mathrm{BR}(\Lambda_c^+ \to pK^-\pi^+)$ by using the following ratio

$$\frac{\Gamma(B^-_{recoil} \to \bar{p}(pK^-\pi^+)_{\Lambda_c} X)}{\Gamma(B^-_{recoil} \to \bar{p}X)} \simeq \mathrm{BR}(\Lambda_c \to pK^-\pi^+) \quad (5)$$

and comparing the result with what is known from other measurements (and might be known even better in the future from data taken at a tau-charm factory). This will tell us to which degree one indeed controls the background and can identify $\Gamma(B^- \to \bar{p}+X)$ with $\Gamma(B^- \to \Lambda_c^+\bar{p}+X)$.

If this cross check works out satisfactorily, then one can turn to the more ambitious task of deducing Ξ_c branching ratios by analyzing the sample of $B^-_{recoil} \to \bar{p}K^+/\bar{\Lambda}+X^-$ events. The background due to class (vi) can, as already stated, be controlled with the observation of $D_{(s)}$ decays. Class (v) can be determined by measuring $B^-_{recoil} \to \bar{p}K^+/\bar{\Lambda} + (pK^-\pi^+)_{\Lambda_c} + X^-$ using $\mathrm{BR}(\Lambda_c \to pK^-\pi^+)$. Let us call the remaining rate the 'reduced' width; then one can infer:

$$\frac{\Gamma(B^-_{recoil} \to \bar{p}K^+/\bar{\Lambda} + (f)_{\Xi_c} + X)}{\Gamma^{reduced}(B^-_{recoil} \to \bar{p}K^+/\bar{\Lambda} + X)} \simeq \mathrm{BR}(\Xi_c \to f) \quad (6)$$

for a final state f like $\Xi\pi\pi$ etc.

3.2 Inclusive branching ratios

One can look for a (relatively soft) lepton with positive charge coming from a semileptonic Λ_c decay. Then one has

$$\frac{\Gamma(B^-_{recoil} \to \bar{p}l^+X)}{\Gamma(B^-_{recoil} \to \bar{p}X)} \simeq \mathrm{BR}_{SL}(\Lambda_c) \quad (7)$$

The strength of this method is that it employs a highly nontrivial correlation between the flavour of the recoil B (inferred from the reconstructed B), the baryon number of the antiproton and the charge of the lepton.

An even more ambitious enterprise is to measure Γ_{SL} (Ξ_c). Since the semileptonic width has to be the same for Ξ_c^0 and Ξ_c^+, yet Ξ_c^0 has a much shorter lifetime, measuring the larger $\mathrm{BR}_{SL}(\Xi_c^+)$ represents a more favourable challenge. One can study the 'reduced' width as defined above for $B_{recoil} \to \bar{\Lambda}X^-$ or $B_{recoil} \to \bar{p}K^+X^-$ as a tag for $B_{recoil} \to \bar{\Lambda}/\bar{p}K^+ + \Xi_c^+ + X^-$ and then again searches for (relatively soft) positive leptons:

$$\frac{\Gamma(B^-_{recoil} \to \bar{\Lambda}/\bar{p}K^+l^+X)}{\Gamma(B^-_{recoil} \to \bar{\Lambda}/\bar{p}K^+X)} \simeq \mathrm{BR}_{SL}(\Xi_c^+) \quad (8)$$

Here one has to exploit the correlation between the flavour of the recoil B, the baryon number of $\bar{\Lambda}$ or $\bar{p}$, the strangeness of $\bar{\Lambda}$ or K^+ and the charge of the lepton. One should note that a sample with leptons will be enriched in its Ξ_c^+ content due to the latter's enhanced semileptonic branching ratio, see (3).

4 Numerical estimates

Existing data yield

$$\mathrm{BR}(B \to \Lambda_c^+X) \simeq 6\% \quad (9)$$

Hence one guestimates

$$\mathrm{BR}(B \to \Xi_cX) \simeq 1 - 2\% \quad (10)$$

We use as benchmark figure that a sample size of 500 fb^{-1} will yield about 10^6 *reconstructed* B mesons [13]. With (9) and (10) one gets about $3 \cdot 10^4$ $\bar{p}\Lambda_cX$ and 10^4 $\bar{p}\Xi_cX$ events, where we have assumed equal rates for $B \to \bar{p}+X$ and $B \to \bar{n}+X$. With $\mathrm{BR}(\Lambda_c^+ \to pK^-\pi^+) \simeq 5\%$ one estimates 1500 calibration events $B \to (pK^-\pi^+)_{\Lambda_c} + \bar{p} + X$.

For $\mathrm{BR}_{SL}(\Lambda_c) \sim 4\%$ and $\mathrm{BR}_{SL}(\Xi_c^+) \sim 20\%$ one gets about 1000 $B \to \bar{p}\Lambda_cX \to \bar{p}l^+X$ events and maybe the same number $B \to \bar{p}K\Xi_c^+X \to \bar{p}Kl^+X$.

While one will presumably encounter very significant backgrounds, these sample sizes should allow meaningful studies of the branching ratios and maybe even of the lepton energy *spectra*.

5 Conclusions

Based on the performance demonstrated by BELLE and BABAR we can expect to have a million $\Upsilon(4S)$ events in a few years where one of the B mesons has been fully reconstructed meaning that all remaining tracks belong to the other B meson. This will not only revolutionize measurements of $B \to l\nu X_u$, $B \to \gamma X_{s,d}$ in an obvious way, but also allow other measurements that previously seemed unfeasible or were not even thought about.

Here we have presented just some examples of this new experimental paradigm concerning the measurement of absolute branching ratios of charm baryons for exclusive as well as inclusive semileptonic modes. Such a sample size should yield about 10^3 identifiable $\Lambda_c \to l^+X$ events with possibly a similar number for $\Xi_c^+ \to l^+X$. In that case one can contemplate even to study the lepton spectrum. It could provide us with insights into the validity of the HQE and limitations to local duality at the charm scale beyond what can be learnt from the integrated width.

In studying inclusive semileptonic decays of charm baryons, a *partial* reconstruction of the first B meson might actually suffice; in that case considerably larger sample sizes might become available. In any case, pilot studies based on partial reconstruction should be undertaken well before 500 fb^{-1} have been accumulated.

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