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Marek Karliner and Jonathan L. Rosner
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Baryons with two heavy quarks: Masses, production, decays, and detection

Marek Karliner\textsuperscript{a†} and Jonathan L. Rosner\textsuperscript{b‡}

\textsuperscript{a} School of Physics and Astronomy
Raymond and Beverly Sackler Faculty of Exact Sciences
Tel Aviv University, Tel Aviv 69978, Israel

\textsuperscript{b} Enrico Fermi Institute and Department of Physics
University of Chicago, 5620 S. Ellis Avenue, Chicago, IL 60637, USA

ABSTRACT

The large number of $B_c$ mesons observed by LHCb suggests a sizable cross section for producing doubly-heavy baryons in the same experiment. Motivated by this, we estimate masses of the doubly-heavy $J = 1/2$ baryons $\Xi_{cc}$, $\Xi_{bb}$, and $\Xi_{bc}$, and their $J = 3/2$ hyperfine partners, using a method which accurately predicts the masses of ground-state baryons with a single heavy quark. We obtain $M(\Xi_{cc}) = 3627 \pm 12$ MeV, $M(\Xi_{cc}^*) = 3690 \pm 12$ MeV, $M(\Xi_{bb}) = 10162 \pm 12$ MeV, $M(\Xi_{bb}^*) = 10184 \pm 12$ MeV, $M(\Xi_{bc}) = 6914 \pm 13$ MeV, $M(\Xi_{bc}^*) = 6933 \pm 12$ MeV, and $M(\Xi_{bc}^*) = 6969 \pm 14$ MeV. As a byproduct, we estimate the hyperfine splitting between $B_c^*$ and $B_c$ mesons to be $68 \pm 8$ MeV. We discuss P-wave excitations, production mechanisms, decay modes, lifetimes, and prospects for detection of the doubly heavy baryons.

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I Introduction

Some simple arguments based on the quark model have been shown to accurately predict the spectrum of baryons containing a single $b$ quark \cite{1,2}. The question then arises: Can such methods be applied to systems with two or more heavy quarks? So far the only experimental evidence for such states comes from the SELEX experiment, which has reported a state at 3520 MeV containing two charm quarks and a down quark \cite{3,4}, with a conference report of states at 3460 MeV and 3780 MeV containing two charm quarks and an up quark \cite{5}. Despite several searches \cite{6–10}, no other experiment has confirmed this result. On the

\begin{small}
\textsuperscript{†}marek@proton.tau.ac.il
\textsuperscript{‡}rosner@hep.uchicago.edu
\end{small}
optimistic side, one should notice that a large number of $B_c$ mesons has been seen both by the Tevatron experiments [11, 12] and by LHCb [13–19]. From this one can infer [20] a substantial cross section for simultaneous production of two pairs of heavy quarks and their subsequent coalescence into a doubly-heavy hadron.

In this paper we estimate the mass of the lowest-lying $J = 1/2$ $ccu$ or $ccd$ state, finding a value consistent with many other estimates lying well above the SELEX results. We estimate its branching fractions to various final states and discuss the possibility of observing $bcu$, $bcd$, $bbu$, and $bbd$ ground-state baryons. We also estimate the masses of the hyperfine ($J = 3/2$) partners of these states, comment briefly on P-wave excitations, and discuss production, decays, and detection of these states.

In order to have a self-contained discussion, we review calculations based on similar methods for baryons and mesons containing only $u,d,$ and $s$ quarks (Sec. II) and those containing a single charmed quark (Sec. III) or a single bottom quark (Sec. IV). These last two sections also include for completeness discussions of states with both charm (or beauty) and strangeness. Although we do not discuss $ccs$, $bcs$, or $bbs$ states in the present paper, regarding their observation as far in the future, we give enough information that their masses may be readily calculated using the present methods.

In what follows we shall neglect the difference between the masses of $u$ and $d$, referring to them collectively as $q$. Masses of states with nonzero isospin are taken to be isospin averages. (Isospin splittings of doubly heavy baryons are expected not to exceed several MeV [21, 22]). We calculate the masses of the lowest-lying states of $ccq$ in Sec. V, $bbq$ in Sec. VI, and $bcq$ in Sec. VII, commenting briefly on P-wave excitations in Sec. VIII. Likely decay modes are noted in Sec. IX, some suggestions for observing the states are made in Sec. X, while Sec. XI concludes.

II States containing only $u$, $d$, and $s$ quarks

A Baryons

The following contributions suffice to describe the ground-state baryons containing $u,d,s$ [23, 24].

- The effective masses of the $u,d,$ and $s$ quarks
- Their mutual hyperfine interactions

(With the addition of heavy-quark masses, these methods were already used in Refs. [23] and [25] to estimate masses of baryons with two heavy quarks.)

In Table I we summarize that description. For all masses we use values quoted by the Particle Data Group [26] unless otherwise noted. Effective masses of quarks in baryons and mesons can and do differ from one another [27], so we shall use superscripts $b$ and $m$ to denote the former and latter. The parameters of this table then may be interpreted as summarizing all interactions between $qq$, $qs$, and $ss$. We shall assume these same interactions occur also in a baryon containing one $c$ or $b$ quark. The average magnitude of the errors in this description is about 5 MeV. We shall use a similar method [23, 28], with appropriate corrections, to calculate masses of states with one or two heavy quarks.
Table I: Quark model description of ground-state baryons containing $u, d, s$. Here we take $m_u^b = m_d^b = m_s^b = 363$ MeV, $m_s^b = 538$ MeV, and hyperfine interaction term $a/(m_q^b)^2 = 50$ MeV.

| State (mass in MeV) | Spin | Expression for mass | Predicted mass (MeV) |
|---------------------|------|---------------------|----------------------|
| $N(939)$            | 1/2  | $3m_q^b - 3a/(m_q^b)^2$ | 939                  |
| $\Delta(1232)$     | 3/2  | $3m_q^b + 3a/(m_q^b)^2$ | 1239                 |
| $\Lambda(1116)$    | 1/2  | $2m_q^b + m_s^b - 3a/(m_q^b)^2$ | 1114                 |
| $\Sigma(1193)$     | 1/2  | $2m_q^b + m_s^b + a/(m_q^b)^2 - 4a/m_q^b m_s^b$ | 1179                 |
| $\Sigma(1385)$     | 3/2  | $2m_q^b + m_s^b + a/(m_q^b)^2 + 2a/m_q^b m_s^b$ | 1381                 |
| $\Xi(1318)$        | 1/2  | $2m_q^b + m_s^b + a/(m_q^b)^2 - 4a/m_q^b m_s^b$ | 1327                 |
| $\Xi(1530)$        | 3/2  | $2m_s^b + m_q^b + a/(m_s^b)^2 + 2a/m_s^b m_q^b$ | 1529                 |
| $\Omega(1672)$     | 3/2  | $3m_s^b + 3a/(m_s^b)^2$ | 1682                 |

Table II: Quark model description of ground-state mesons containing $u, d, s$. Here we take $m_u^m = m_d^m = m_s^m = 310$ MeV, $m_s^m = 483$ MeV, $b/(m_q^m)^2 = 80$ MeV.

| State (mass in MeV) | Spin | Expression for mass | Predicted mass (MeV) |
|---------------------|------|---------------------|----------------------|
| $\pi(138)$          | 0    | $2m_q^m - 6b/(m_q^m)^2$ | 140                  |
| $\rho(775), \omega(782)$ | 1    | $2m_q^m + 2b/(m_q^m)^2$ | 780                  |
| $K(496)$            | 0    | $m_q^m + m_s^m - 6b/(m_q^m m_s^m)$ | 485                  |
| $K^*(894)$          | 1    | $m_q^m + m_s^m + 2b/(m_q^m m_s^m)$ | 896                  |
| $\phi(1019)$        | 1    | $2m_s^m + 2b/(m_s^m)^2$ | 1032                 |

B Mesons

A similar approach describes ground-state mesons composed of $u, d, s$ quarks, as shown in Table II. As effective masses of quarks in mesons and baryons differ from one another, the parameters in Table II will not be directly related to those in Table I. We do not discuss $\eta, \eta'$, whose masses are strongly affected by octet-singlet mixing. Here the average magnitude of errors is about 6 MeV.

The overprediction of the $\phi$ mass may indicate slightly stronger binding between two strange quarks. We should keep this possibility in mind when discussing other states with two strange quarks, but these do not occur for $\Xi_{(cc,bb,bb)}$. Some hint of this effect is also present when comparing the predicted $M(\Xi)$ and $M(\Omega)$ with experiment, though the predicted $M(\Xi^*)$ comes within 1 MeV of the observed value.
III States with one charmed quark

A Mesons

We discuss mesons first because the $c\bar{s}$ interaction in $D_s^{(*)}$ displays a significant binding effect. This is then related using a simple QCD argument to the $cs$ binding in baryons, which is important to keep in mind when predicting $\Xi_c^{(*)}$ and $\Omega_c^{(*)}$ masses.

The model of Sec. II predicts

$$M(D(1867.2)) = m_q^m + m_c^m - 6b/(m_q^m m_c^m), \quad M(D^*(2008.6)) = m_q^m + m_c^m + 2b/(m_q^m m_c^m). \quad (1)$$

The new parameter in these expressions is $m_c^m$, which may be estimated using

$$m_c^m = [3M(D^*) + M(D)]/4 - m_q^m = (1973.3 - 310) \text{ MeV} = 1663.3 \text{ MeV} \quad (2)$$

Using this value and $b/(m_q^m)^2 = 80 \text{ MeV}$ one estimates the hyperfine splitting between $D$ and $D^*$ to be $M(D^*) - M(D) = 8b/(m_q^m m_c^m) = 119.3 \text{ MeV}$, to be compared with the observed value of 141.4 MeV. Thus there seems to be a hyperfine enhancement between $c$ and $\bar{q}$ relative to $q$ and $\bar{q}$. This difference does not seem to occur between $cq$ and $qq$ hyperfine interactions, however, as we shall see when discussing charmed baryons.

Charmed-strange mesons display an effect of enhanced $c\bar{s}$ binding. Anticipating this, we may write

$$M(D_s(1968.5)) = B(c\bar{s}) + m_s^m + m_c^m - 6b/(m_s^m m_c^m),$$
$$M(D_s^*(2112.3)) = B(c\bar{s}) + m_s^m + m_c^m + 2b/(m_s^m m_c^m), \quad (3)$$

allowing one to solve for the binding term

$$B(c\bar{s}) = [3M(D_s^*) + M(D_s)]/4 - m_s^m - m_c^m = -69.9 \text{ MeV} \quad (4)$$

This quantity will be related to the binding between $c$ and $s$ quarks when we discuss charmed-strange baryons. This term represents the additional binding to $c$ of the heavier $\bar{s}$ quark in comparison with that of the $\bar{u}$ or $\bar{d}$, due to the shorter Compton wavelength of the $\bar{s}$ which allows it to sit more deeply in the interquark potential.

Comparing Eqs. (1) and (3), one would conclude that

$$M(D_s^*) - M(D_s) = (m_q^m/m_s^m)[M(D^*) - M(D)] = 90.6 \text{ MeV}, \quad (5)$$

a factor of 0.63 times the observed value of 143.8 MeV which is almost the same as $M(D^*) - M(D)$. The scaling of the wave function describing the $c\bar{s}$ or $c\bar{q}$ bound state in a confining potential accounts for this behavior [29]. We shall estimate the $cs$ hyperfine interaction in baryons directly from the $\Omega_c^* - \Omega_c$ splitting, finding a similar enhancement with respect to the nominal value implied by Table I.

B Baryons

An approach to charmed baryon masses similar to that leading to the predictions for $u,d,s$ baryons in Table I must take account of enhanced $cs$ binding and an enhanced $cs$ hyperfine interaction. The effect of $cs$ binding may be related to $c\bar{s}$ binding by means of a color-SU(3)
Table III: Relative attraction or repulsion $\langle T_1 \cdot T_2 \rangle$ of quarks $Q\bar{Q}$ or $QQ$ in various states.

| State | Color | $\langle T_1 \cdot T_2 \rangle$ |
|-------|-------|-------------------------------|
| $Q\bar{Q}$ | 1 | $-4/3$ |
| $Q\bar{Q}$ | 8 | $1/6$ |
| $QQ$ | 3* | $-2/3$ |
| $QQ$ | 6 | $1/3$ |

argument. The interactions between two quarks in various color states are summarized in Table III. The quarks in a $c\bar{s}$ meson are in a color singlet, while a $cs$ pair in a baryon is in a color antitriplet. The $cs$ interaction strength in a color triplet is half that of $c\bar{s}$ in a color singlet, so we shall assume, for every $cs$ pair in a charmed-strange baryon, that

$$B(cs) = B(c\bar{s})/2 = -35.0 \text{ MeV}. \quad (6)$$

As we shall see, this provides a contribution of reasonable magnitude.

The scaling of energy levels linearly with coupling strength is not an automatic feature. In a power-law central potential of the form $V(r) = \lambda r^\nu$, spacings $\Delta E$ of energy levels depend on $\lambda$ via the relation $[30] \Delta E \propto \lambda^{2/(2+\nu)}$. Thus, in the Coulomb potential ($\nu = -1$) the Rydberg scales as $a^2$; harmonic oscillator level spacings ($\nu = 2$) scale as the square root of the force constant; and $\Delta E \propto \lambda$ for a logarithmic potential, which has been shown to interpolate not only between charmonium and bottomonium interactions [30], but also to apply approximately to $ss$ excitations [32].

The hyperfine splitting between $\Omega_c^*$ and $\Omega_c$ would be given by $6a/(m_b^s m_b^q)$, but we shall parametrize it independently by replacing $a$ with $a_{cs}$. Accounting for enhanced $cs$ binding and hyperfine interaction, the predictions for baryon masses then may be summarized in Table IV. Here we have used the experimental value of $M(\Lambda_c)$ in Table IV to estimate $m_c^b = M(\Lambda_c) - 2m_q^b + 3a/(m_q^b)^2 = 1710.5 \text{ MeV}$.

The hyperfine splitting between $\Sigma_c^*$ and $\Sigma_c$ is predicted to be $6a/(m_q^b m_c^b) = 63.7 \text{ MeV}$, to be compared with the observed value of $64.5 \text{ MeV}$. Thus there does not seem to be an enhancement of the hyperfine interaction between $c$ and $q$ over the value inferred from Table I.

The states $\Xi_c$ and $\Xi_c'$ will mix with one another as a result of SU(3) breaking. This effect, leading to mass shifts of the order of several MeV [33], has been ignored.

The naive hyperfine term $6a/(m_q^b m_c^b) = 43.0 \text{ MeV}$ is 0.61 times a term $6a_{cs}/(m_q^b m_c^b) = 70.7 \text{ MeV}$ evaluated using the splitting between $\Omega_c^*$ and $\Omega_c$. Thus the $cs$ hyperfine interaction in baryons undergoes the same enhancement with regard to the naive value as does the $c\bar{s}$ hyperfine interaction in mesons.

The average magnitude of the errors in the predictions of Table IV is about 9 MeV, not much higher than that for the light-quark baryons in Table I.
The predicted hyperfine splitting is observed value of 45.8 MeV. For comparison, the predicted hyperfine splitting by a calculation similar to that in Sec. III, one finds

\[ a/(m_q^b)^2 = 50 \text{ MeV}. \]

The spin of the \( q\bar{s} \) pair is taken to be zero in \( \Xi_c \) and one in \( \Xi_c' \).

| State \((M, m_c)\) in MeV | Spin | Expression for mass | Predicted \( M \) (MeV) |
|--------------------------|------|---------------------|------------------------|
| \( \Lambda_c(2286.5) \)   | 1/2  | \( 2m_q^b + m_b^c - 3a/(m_q^b)^2 \) | Input |
| \( \Sigma_c(2453.4) \)    | 1/2  | \( 2m_q^b + m_b^c + a/(m_q^b)^2 - 4a/(m_q^b m_b^c) \) | 2444.0 |
| \( \Sigma_c^*(2518.1) \)  | 3/2  | \( 2m_q^b + m_b^c + a/(m_q^b)^2 + 2a/(m_q^b m_b^c) \) | 2507.7 |
| \( \Xi_c(2469.3) \)      | 1/2  | \( B(cs) + m_q^b + m_b^c + m_b^c - 3a/(m_q^b m_b^c) \) | 2475.3 |
| \( \Xi_c'(2575.8) \)     | 1/2  | \( B(cs) + m_q^b + m_b^c + m_b^c + a/(m_q^b m_b^c) \) | 2565.4 |
| \( \Xi_c(2645.9) \)      | 3/2  | \( B(cs) + m_q^b + m_b^c + m_b^c + a/(m_q^b m_b^c) \) | 2632.6 |
| \( \Omega_c(2695.2) \)   | 1/2  | \( 2B(cs) + 2m_q^b + m_b^c + a/(m_q^b)^2 - 4a/(m_q^b m_b^c) \) | 2692.1 |
| \( \Omega_c'(2765.9) \)  | 3/2  | \( 2B(cs) + 2m_q^b + m_b^c + a/(m_q^b)^2 + 2a/(m_q^b m_b^c) \) | 2762.8 |

\(^a\) Difference between experimental values used to determine \( 6a_{cs}/(m_q^b m_b^c) = 70.7 \text{ MeV}. \)

IV States with one \( b \) quark

A Mesons

We discuss \( B_s \) and \( B_s^* \) mesons in order to estimate binding effects of a \( b \) quark with an \( s \) antiquark, so as to assess \( bs \) binding in a baryon, and in order to obtain an effective mass of a \( b \) quark in a meson. The model of Sec. II predicts

\[ M(B(5279.4)) = m_q^m + m_b^m - 6b/(m_q^m m_b^m), \quad M(B^*(5325.2)) = m_q^m + m_b^m + 2b/(m_q^m m_b^m). \]  

By a calculation similar to that in Sec. III, one finds

\[ m_b^m = [3M(B^*) + M(B)]/4 - m_q^m = (5313.8 - 363) \text{ MeV} = 5003.8 \text{ MeV}. \]

The predicted hyperfine splitting is \( M(B^*) - M(B) = 39.7 \text{ MeV} \), a factor of 0.87 times the observed value of 45.8 MeV. For comparison, the predicted hyperfine splitting \( M(D^*) - M(D) \) was found in the previous Section to be 119.3 MeV, a factor of 0.84 times the observed value of 141.4 MeV. This near-equality is a consequence of the often-quoted relation

\[ (45.78 \pm 0.35) \text{ MeV} = M(B^*) - M(B) = (m_{c}^m/m_{b}^m)[M(D^*) - M(D)] = (47.0 \pm 0.1) \text{ MeV}, \]

in which light-quark masses do not appear.

Allowing for a binding term \( B(bs) \), the pseudoscalar and vector \( b\bar{s} \) states have masses

\[ M(B_s(5366.77 \pm 0.24)) = B(bs) + m_s^m + m_b^m - 6b/(m_s^m m_b^m), \]

\[ M(B_s^*(5415.4^{+2.4}_{-2.1})) = B(bs) + m_s^m + m_b^m + 2b/(m_s^m m_b^m), \]

where we have indicated errors on masses in MeV because those of \( B_s^* \) are non-negligible. Repeating the calculation of the previous section, we find

\[ B(bs) = [3M(B_s^*) + M(B_s)]/4 - m_b^m - m_s^m = (-83.6 \pm 1.8) \text{ MeV}. \]

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This binding term is slightly larger than the value of $B(cs)$ found above, because the reduced mass of the $b\bar{s}$ system is greater than that of $c\bar{s}$, leading to a shorter Compton wavelength and a more deeply bound system.

The predicted hyperfine splitting between $B_s$ and $B^*_s$ is $8a/(m_bm_s) = 25.5$ MeV, to be compared with the observed value of $48.7^{+2.3}_{-2.1}$ MeV. Alternatively, one may evaluate this quantity to be $m_q^m/m_s^m$ times the observed value of $M(B^*) - M(B) = 45.8$ MeV, giving $29.4$ MeV or a factor of $0.60 \pm 0.03$ times the observed value. For comparison, the same scaling argument applied in Sec. III gave $M(D^*_s) - M(D_s)$ a factor of $0.63$ times its observed value. Thus the relation

$$48.7^{+2.3}_{-2.1} \text{ MeV} = M(B^*_s) - M(B_s) \simeq (m_q^m/m_s^m)[M(D^*_s) - M(D_s)] = 47.8 \text{ MeV},$$

in which light-quark masses do not appear, holds quite well.

B Baryons

Recent progress in $b$-flavored baryon studies has been so great that we have found it necessary to construct our own averages of masses. These are summarized in Table V. We have omitted measurements superseded by those of higher statistics by the same collaboration, and measurements older than 2011.

We start with a value of the $b$ quark mass in baryons obtained from the observed value of $M(\Lambda_b) = 5619.5 \pm 0.3$ MeV:

$$m_b^b = M(\Lambda_b) - 2m_q + 3a/(m_q^b)^2 = 5043.5 \text{ MeV}$$

The observed and calculated masses of the ground state $b$-flavored baryons are summarized in Table VI. We note several points.

- Although the predicted $\Sigma_b$ and $\Sigma^*_b$ masses are a bit below the observed ones, their predicted hyperfine splitting is $21.6$ MeV, while the observed value is $19.6 \pm 0.7$ MeV (neglecting a common systematic error of $1.7$ MeV). Thus there is no evidence for enhancement of the term $a/(m_q^b m_b^b)$ beyond the value based on Table I.

- The rescaling of $a/(m_q^b m_b^b)$ to $a_{bs}/(m_q^b m_b^b)$ is taken to be identical to that for the $cs$ hyperfine interaction in baryons, which we saw was very close to that for the $cs$ and $b\bar{s}$ mesons. It could be tested in principle using the hyperfine difference prediction

$$M(\Omega_b^*) - M(\Omega_b) = 6a_{bs}/(m_q^b m_b^b) = 24.3 \text{ MeV},$$

but this involves detection of the very soft photon in the decay $\Omega_b^* \rightarrow \gamma \Omega_b$, probably impossible. The enhancement of $a_{cs}$ and $a_{bs}$ with respect to $a$ is due to the deeper binding of the $cs$ and $bs$ system in comparison with $cq$ or $bq$, but a quantitative relation between $B(cs)$ and $a_{cs}$ or between $B(bs)$ and $a_{bs}$ does not seem obvious to us. A possible reason for lack of such a relation is that $B(cs)$ and $B(bs)$ parametrize spin-independent binding, while $a_{cs}$ and $a_{bs}$ measure the strength of a spin-dependent interaction between the relevant quarks.

- The predictions for $M(\Xi_b)$ and $M(\Omega_b)$ are not far from those of Ref. [1]: $5795 \pm 5$ MeV and $6052.1 \pm 5.6$ MeV, respectively. In that work some use was made of potential models, whereas in the present estimates such effects are parametrized by binding terms or modification of hyperfine interactions.
Table V: Averages of $b$-baryon masses based on recent experiments.

| Baryon | Reference | Mass (MeV)  |
|--------|-----------|-------------|
| $\Lambda_b$ | [34] | 5619.30 ± 0.34 |
|          | [35] | 5620.15 ± 0.31 ± 0.47 |
|          | [36] | 5619.7 ± 0.7 ± 1.1 |
| Average |          | 5619.5 ± 0.3 |
| $\Sigma^+_b$ | [37] | 5811.3 ± 0.8 ± 1.7 |
| $\Sigma^-_b$ | [37] | 5815.5 ± 0.6 ± 1.7 |
| Average (Over charges) |          | 5814.26 ± 1.76 |
| $\Sigma^{++}$ | [37] | 5832.1 ± 0.7 ± 1.7 |
| $\Sigma^{*-}$ | [37] | 5835.1 ± 0.6 ± 1.7 |
| Average (Over charges) |          | 5833.83 ± 1.81 |
| $\Xi^0_b$ | [38] | 5793.5 ± 2.3 |
|          | [35] | 5788.7 ± 4.3 ± 1.4 |
|          | [39] | 5791.80 ± 0.39 ± 0.17 ± 0.26 |
| Average |          | 5791.84 ± 0.50 |
| $\Xi^-_b$ | [40] | 5795.8 ± 0.9 ± 0.4 |
|          | [35] | 5793.4 ± 1.8 ± 0.7 |
| Average |          | 5795.30 ± 0.88 |
| Average (Over charges) |          | 5792.68 ± 0.43 |
| $\Xi^{0b}_b$ | [41] | 5949.71 ± 1.25$^b$ |
| $\Omega^-_b$ | [40] | 6046.0 ± 2.2 ± 0.5 |
|          | [35] | 6047.5 ± 3.8 ± 0.6 |
| Average |          | 6046.38 ± 1.95 |

$^a$ Common systematic error added in quadrature.

$^b$ Ref. [41] quotes $M(\Xi^{0b}_b) - M(\Lambda_b) - M(\pi^+) = (14.84 ± 0.74 ± 0.28)$ MeV.

- The average magnitude of errors in predictions of Table VI is about 8 MeV, a bit below that for charmed baryons in Table IV. We shall use these two errors and those in Table I to extrapolate to the case of two heavy quarks, estimating prediction errors of 12 MeV for $M(\Xi_{cc})$ and $M(\Xi_{bb})$. For $M(\Xi_{bc})$ an additional systematic error is associated with ignorance of the $B_c^0-B_c^+ \pi^0$ splitting.

V Calculation of ccq mass

The mass of the ccq state may be regarded as the sum of the following contributions:

- The masses of the two charmed quarks
- Their binding energy in a color 3* state
- Their mutual hyperfine interaction
- Their hyperfine interaction with the light quark q
Table VI: Quark model description of ground-state baryons containing one bottom quark. Here we take $m_q = m_b^q \equiv m_b^q = 363$ MeV, $m_b = 538$ MeV, $m_b = 5043.5$ MeV, and $a/(m_b^q)^2 = 50$ MeV. The parameter $a_{bs}$ is rescaled from $a$ in the same manner as for charmed baryons: $a_{bs} = a_{cs} = (70.7/43.0)a$.

| State (M)       | Spin | Expression for mass                                                                 | Predicted M (MeV) |
|-----------------|------|--------------------------------------------------------------------------------------|-------------------|
| $\Lambda_b$     | 1/2  | $2m_q^b + m_b^q - 3a/(m_b^q)^2$                                                      | Input             |
| $\Sigma_b$      | 1/2  | $2m_q^b + m_b^q + a/(m_b^q)^2 - 4a/(m_b^q m_b^s)$                                   | 5805.1            |
| $\Sigma_b'$     | 3/2  | $2m_q^b + m_b^q + a/(m_b^q)^2 + 2a/(m_b^q m_b^b)$                                   | 5826.7            |
| $\Xi_b$         | 1/2  | $B(bs) + m_b^q + m_b^s + m_b^s - 3a/(m_b^q m_b^s)$                                 | 5801.5            |
| $\Xi_b^-$       | 1/2  | $B(bs) + m_b^q + m_b^s + m_b^s + a/(m_b^q m_b^s)$                                  | 5921.3            |
| $\Xi_b'$        | 3/2  | $B(bs) + m_b^q + m_b^s + m_b^s + a/(m_b^q m_b^s)$                                  | 5944.1            |
| $\Omega_b$      | 1/2  | $2B(bs) + 2m_b^s + m_b^b + a/(m_b^q)^2 - 4a_{bs}/(m_b^q m_b^b)$                    | 6042.8            |
| $\Omega_b^-$    | 3/2  | $2B(bs) + 2m_b^s + m_b^b + a/(m_b^q)^2 + 2a_{bs}/(m_b^q m_b^b)$                    | 6066.7            |

- The mass of the light quark $q$

When more than one heavy quark is present, one must take into account the binding energy between them. We do this by comparing the sum of the charm quark masses in the $1S$ charmonium levels $\eta_c$ and $J/\psi$ with their spin-weighted mass

$$\bar{M} (cc: 1S) \equiv [3M(J/\psi) + M(\eta_c)]/4 = 3068.6 \text{ MeV}.$$  \hspace{1cm} (15)

We estimated the effective charm quark mass in a meson to be $m_c^m = 1663.3$ MeV. The binding energy in $1S$ charmonium is thus $[3068.6 - 2(1663.3)]$ MeV $= -258.0$ MeV. Using the color-SU(3) relations in Table III we then estimate the $cc$ binding energy in a baryon to be $-129.0$ MeV.

The $cc$ hyperfine interaction $a_{cc}/m_c^2$ is estimated as follows. The $cc$ hyperfine splitting in the meson sector is given by $M(J/\psi) - M(\eta_c) = 113.2$ MeV = $4a_{cc}/(m_c^m)^2$. Assuming that the quark-antiquark interaction $a_{q\bar{q}}$ is half of the quark-antiquark interaction $a_{qq}$, and neglecting the small difference between $m_c^m$ and $m_c$, we have $a_{cc}/(m_c^m)^2 = 1/2 \cdot [M(J/\psi) - M(\eta_c)]/4 = 14.2$ MeV [42].

We may then summarize the contributions to $M(\Xi_{cc})$ in Table VII. The third line gives the contribution of the hyperfine interaction between the two charmed quarks, while the fourth gives their total hyperfine interaction with the light quark $q$. The predicted value $M(\Xi_{cc}) = 3627 \pm 12$ MeV lies among a number of other estimates summarized in Table VIII, but well above the values claimed for $\Xi_{cc}^+$ and $\Xi_{cc}^{++}$ by the SELEX Collaboration.

The hyperfine splitting is given by $M(\Xi_{cc}^*) - M(\Xi_{cc}) = 6a/m_q m_c = 63.7$ MeV, yielding $M(\Xi_{cc}^*) = 3690 \pm 12$ MeV. This state lies too close in mass to $\Xi_{cc}$ to decay to it by pion emission, so it must decay radiatively.
Table VII: Contributions to the mass of the lightest doubly charmed baryon $\Xi_{cc}$.

| Contribution | Value (MeV) |
|--------------|-------------|
| $2m_c^b + m_q^b$ | 3783.9 |
| $cc$ binding | $-129.0$ |
| $a_{cc}/(m_c^b)^2$ | 14.2 |
| $-4a/m_b^bm_c^b$ | $-42.4$ |
| Total | 3627 ± 12 |

VI Calculation of $bbq$ mass

One may apply very similar methods to calculate the mass of the lowest-lying $\Xi_{bb}$ state. The spin-weighted average of the $b\bar{b}$ : $1S$ levels is

$$\bar{M}(b\bar{b} : 1S) \equiv [3M(\Upsilon) + M(\eta_b)]/4 = 9444.7 \text{ MeV}.$$ (16)

The spin-weighted average of the ground-state bottom mesons is

$$\bar{M}(b\bar{q} : 1S) \equiv [3M(B^*) + M(B)]/4 = 5313.8 \text{ MeV}.$$ (17)

Subtracting $m_q^m = 310$ MeV, we arrive at $m_b^m = 5003.8$ MeV. The binding energy in $1S$ bottomonium is thus $[9444.7 - 2(5003.8)]$ MeV = $-562.8$ MeV. By arguments similar to those in the previous section, we then calculate the binding energy between the two $b$ quarks in $\Xi_{bb}$ to be half this, or $-281.4$ MeV.

The mass of a bottom quark in a baryon, $m_b^b = 5043.5$ MeV, was obtained in Sec. IV. By the same approach as for $\Xi_{cc}$, the $bb$ hyperfine interaction term $a_{bb}/(m_b^b)^2$ may be taken as $(1/8) \cdot [M(\Upsilon) - M(\eta_b)] = 7.8$ MeV [42].

We summarize the contributions to $M(\Xi_{bb})$ in Table IX. The resulting value $M(\Xi_{bb}) = 10162 \pm 12$ MeV tends to lie a bit below some (but not all) estimates, as seen in Table X.

The hyperfine splitting is given by $M(\Xi_{bb}^*) - M(\Xi_{bb}) = 6a/m_b^bm_b^b = 21.6$ MeV, yielding $M(\Xi_{bb}^*) = 10184 \pm 12$ MeV. This state decays radiatively to $\Xi_{bb}$.

VII Calculation of $bcq$ mass

The methods of the previous two sections may be applied to calculate the ground-state mass of $\Xi_{bc}$, with one qualification. The $^3S_1$ state of $b\bar{c}$, the $B_{c^+}$, has not yet been observed, so we shall have to estimate its mass. One method is to note that hyperfine interactions between quarks with masses $m_1$ and $m_2$ are proportional to $|\Psi(0)|^2/(m_1m_2)$, so we need to evaluate the magnitude of $|\Psi(0)|^2$ for the $b\bar{c}$ system by interpolating between $c\bar{c}$ and $b\bar{b}$.

A convenient parametrization is to assume that $|\Psi(0)|^2$ behaves as some power $p$ of the reduced mass $\mu_R = (m_1m_2)/(m_1 + m_2)$. With the quark masses $m_c^m = 1663.3$ MeV and $m_b^m = 5003.8$ MeV and the hyperfine splittings

$$M(J/\psi) - M(\eta_c) = 113.2 \text{ MeV}, \quad M(\Upsilon) - M(\eta_b) = 62.3 \text{ MeV},$$

(18)

one finds this power to be 1.46, very close to the value of 1.5 that one would expect from a logarithmic potential. Such a potential has been shown to successfully interpolate between
Table VIII: Comparison of predictions for $M(\Xi_{cc})$.

| Reference | Value (MeV) | Method |
|-----------|-------------|--------|
| Present work | 3627 ± 12 | QCD-motivated quark model |
| [23] | 3550–3760 | QCD-motivated quark model |
| [25] | 3668 ± 62 | QCD-motivated quark model |
| [28] | 3651 | Potential and bag models |
| [43] | 3613 | Potential model |
| [45] | 3610 | Heavy quark effective theory |
| [46] | 3660 ± 70 | Feynman-Hellmann + semi-empirical |
| [47] | 3676 | Mass sum rules |
| [48] | 3660 | Relativistic quasipotential quark model |
| [49] | 3607 | Three-body Faddeev equations. |
| [50] | 3527 | Bootstrap quark model + Faddeev eqs. |
| [51] | $ucc$: 3649 ± 12, $dcc$: 3644 ± 12 | Quark model |
| [52] | 3480 ± 50 | Potential approach + QCD sum rules |
| [53] | 3690 | Nonperturbative string |
| [54] | 3620 | Relativistic quark-diquark |
| [55] | 3520 | Bag model |
| [56] | 3643 | Potential model |
| [57] | 3642 | Relativistic quark model + Bethe-Salpeter |
| [58] | 3612$^{+17}_{-17}$ | Variational |
| [59] | 3678 | Quark model |
| [61] | 3540 ± 20 | Instantaneous approx. + Bethe-Salpeter |
| [62] | 4260 ± 190 | QCD sum rules |
| [63] | 3608(15)(13$_{A}^{+}$)$_{A}^{+}$, 3595(12)$_{A}^{+}$ | Quenched lattice |
| [64] | 3549(13)(19)$_{A}^{+}$ | Quenched lattice |
| [65] | 3665 ± 17 ± 14$_{78}^{+6}$ | Lattice, domain-wall + KS fermions |
| [66] | 3603(15)$_{A}^{+}$ | Lattice, $N_f = 2 + 1$ |
| [67] | 3513(23)$_{A}^{+}$ | LGT, twisted mass ferm., $m_\pi = 260$ MeV |
| [68] | 3595(39)(20)$_{A}^{+}$ | LGT, $N_f = 2 + 1$, $m_\pi = 200$ MeV |
| [69] | 3568(14)$_{A}^{+}$ | LGT, $N_f = 2 + 1$, $m_\pi = 210$ MeV |
Table IX: Contributions to the mass of the lightest baryon $\Xi_{bb}$ with two bottom quarks.

| Contribution         | Value (MeV) |
|----------------------|-------------|
| $2m_b^2 + m_q^2$     | 10450.0     |
| $bb$ binding         | −281.4      |
| $a_{bb}/(m_b^2)^2$   | 7.8         |
| $-4a/m_q^2 m_b^2$    | −14.4       |
| Total                | 10162 ± 12  |

Table X: Comparison of predictions for $M(\Xi_{bb})$.

| Reference  | Value (MeV) | Method                                      |
|------------|-------------|---------------------------------------------|
| Present work | 10162 ± 12  | QCD-motivated quark model                   |
| [25]       | 10294 ± 131 | QCD-motivated quark model                   |
| [28]       | 10235       | QCD-motivated quark model                   |
| [44]       | 10210       | Potential models                            |
| [46]       | 10340 ± 100 | Feynman-Hellmann + semi-empirical formulas  |
| [48]       | 10230       | Relativistic quasipotential quark model      |
| [52]       | 10090 ± 50  | Potential approach and QCD sum rules         |
| [53]       | 10160       | Nonperturbative string                       |
| [55]       | 10272       | Bag model                                   |
| [59]       | 10322       | Quark model                                 |
| [60]       | 10045       | Coupled channel formalism                   |
| [61]       | 10185 ± 5   | Instantaneous approx. + Bethe-Salpeter      |
| [62]       | 9780 ± 70   | QCD sum rules                               |
the charmonium and bottomonium spectra [30], and now seems to give approximately the
correct spacing between the 1S and 2S of the $B_c$ system as well [31]. With this power, the
hyperfine splitting between $b$ and $\bar{c}$ in the ground state is then estimated to be 68.0 MeV.

[This quantity also may be estimated by taking the geometric mean of the charmonium
and bottomonium hyperfine splittings, with the result of 84.0 MeV. The 16 MeV difference
between these two estimates can be viewed as an indication of the error associated with
determining $b\bar{c}$ hyperfine splitting]. The spin-weighted average ground state $b\bar{c}$ mass is then

$$M(b\bar{c} : 1S) = M(B_c) + (3/4)(68.0 \text{ MeV}) = (6274.5 + 52.0) \text{ MeV} = 6325.5 \text{ MeV} \ . \quad (19)$$

The rest of the calculations proceed as in the previous two sections. The binding energy
in the spin-weighted average $b\bar{c}$ ground state is $6325.5 - 5003.8 - 1663.2 = -341.5 \text{ MeV}$, so
in a $bc$ baryon it is half this, or $-170.8 \text{ MeV}$. The $bcq$ mass (before accounting for binding
and hyperfine interactions) is

$$m^b_b + m^b_c + m^b_q = (5043.5 + 1710.5 + 363) \text{ MeV} = 7117.0 \text{ MeV} \ . \quad (20)$$

The error associated with $c\bar{s}$ binding may be taken to be $3/4$ times that of the hyperfine
splitting between $b$ and $\bar{c}$, or $(3/4)(16 \text{ MeV}) = 12 \text{ MeV}$. We then take the error on the $cs$
binding to be 6 MeV. The strength of the $bc$ hyperfine interaction is determined by the
same approach as for $\Xi_{cc}$ and $\Xi_{bb}$, i.e., $a_{bc}/(m^b bcm^c) = (1/8) \cdot b\bar{c}$ hyperfine splitting. As a
result, a small error also is introduced to the $bc$ hyperfine interaction.

The presence of three distinct quarks in $\Xi_{bc} = bcq$ means that there are two ways of
coupling them up to spin $1/2$ in an S-wave ground state. Taking the basis defined by the
combined spin of the two lightest quarks, as was done for the $\Xi_c = csq$ and $\Xi_b = bsq$, we
call the state with $S(cq) = 0$ the $\Xi_{bc}$ and that with $S(cq) = 1$ the $\Xi'_{bc}$. Tables XI and XII
show the respective contributions to their masses, and Tables XIII and XIV compare our
predictions with others. The $\Xi_{bc}$ will decay radiatively to $\Xi_{bc}$. The uncertainties on the
masses of these two states are calculated by adding in quadrature the spread between the
two masses in each table and the global error assumed to be 12 MeV.

The mass of the $J = 3/2$ state is given by $M(\Xi'_{bc}) = M(\Xi'_{bc}) + 3a/ (m^b_b m^b_c) + 3a_{bc}/ (m^b_b m^b_c) =
M(\Xi_{bc}) + 36.3 \text{ MeV}$. Using the $M(\Xi'_{bc})$ value in the first column of Table XII we then obtain
$M(\Xi'_{bc}) = 6969 \pm 14 \text{ MeV}$. As in previous cases, this state decays radiatively to the $J = 1/2$
ground state.

**VIII P-wave excitations**

In the event that a $\Xi_{(cc,bb, bc)}$ state is accompanied by a pion nearby in phase space, the two
can have come from a P-wave excitation. Let us take the example of $\Xi_{cc}$.

Heavy quark symmetry implies that in transitions involving a single pion the $cc$ state
maintains its spin of 1, while in such P-wave states the light quark $q$ couples with a unit of
orbital angular momentum to form a state of total light-quark angular momentum $j = 1/2$
or $j = 3/2$. We can then expect a rich family of P-wave states with

$$(j = 1/2) \otimes (J(cc) = 1) \rightarrow J_{\text{tot}} = 1/2, 3/2 ;$$

$$(j = 3/2) \otimes (J(cc) = 1) \rightarrow J_{\text{tot}} = 1/2, 3/2, 5/2 \ . \quad (21)$$

The parity of the $\Xi_{cc}$ is positive, whereas that of the states in Eq. (21) is negative. Heavy
quark symmetry predicts that the states with $j = 1/2$ will decay via S wave pion emission,
Table XI: Contributions to the mass of the lightest baryon $\Xi_{bc}$ with one bottom and one charmed quark and the $cq$ pair in a spin-singlet state.

| Contribution | Value (MeV) from $|\Psi(0)|^2 \sim \mu_R^{1.46}$ | Value (MeV) from $\sqrt{HF(bb)\cdot HF(\bar{c}c)}$ |
|--------------|--------------------------------------------|---------------------------------------------|
| $m_b^b + m_c^b + m_q^b$ | 7117.0 | 7117.0 |
| $bc$ binding | $-170.8$ | $-164.8$ |
| $-3a/(m_c^b m_q^b)$ | $-31.8$ | $-31.8$ |
| Total | $6914 \pm 13$ | $6920 \pm 13$ |

Table XII: Contributions to the mass of the lightest baryon $\Xi'_{bc}$ with one bottom and one charmed quark and the $cq$ pair in a spin-triplet state.

| Contribution | Value (MeV) from $|\Psi(0)|^2 \sim \mu_R^{1.46}$ | Value (MeV) from $\sqrt{HF(bb)\cdot HF(\bar{c}c)}$ |
|--------------|--------------------------------------------|---------------------------------------------|
| $m_b^b + m_c^b + m_q^b$ | 7117.0 | 7117.0 |
| $bc$ binding | $-170.8$ | $-164.8$ |
| $a/(m_b^b m_q^b)$ | 10.6 | 10.6 |
| $-2a/(m_c^b m_q^b) - 2a_{bc}/(m_b^b m_c^b)$ | $-24.2$ | $-28.2$ |
| Total | $6933 \pm 12$ | $6935 \pm 12$ |
Table XIII: Comparison of predictions for $M(\Xi_{bc})$.

| Reference | Value (MeV) | Method                                         |
|-----------|-------------|------------------------------------------------|
| Present work | 6914 ± 13   | QCD-motivated quark model                      |
| [25]      | 6916 ± 139  | QCD-motivated quark model                      |
| [28]      | 6938        | Potential models                               |
| [44]      | 6930        | Mass sum rules                                 |
| [46]      | 6990 ± 90   | Feynman-Hellmann + semi-empirical formulas      |
| [47]      | 7029        | Relativistic quasipotential quark model         |
| [48]      | 6950        | Three-body Faddeev equations.                   |
| [49]      | 6915        | Potential approach and QCD sum rules            |
| [52]      | 6820 ± 50   | Nonperturbative string                         |
| [53]      | 6960        | Relativistic quark-diquark                      |
| [54]      | 6933        | Bag model                                      |
| [55]      | 6800        | Variational                                    |
| [58]      | 7011        | Quark model                                    |
| [60]      | 6789        | Coupled channel formalism                      |
| [61]      | 6840 ± 10   | Instantaneous approx. + Bethe-Salpeter          |
| [62]      | 6750 ± 50   | QCD sum rules                                  |

Table XIV: Comparison of predictions for $M(\Xi'_{bc})$.

| Reference | Value (MeV) | Method                                         |
|-----------|-------------|------------------------------------------------|
| Present work | 6933 ± 12   | QCD-motivated quark model                      |
| [25]      | 6976 ± 99   | QCD-motivated quark model                      |
| [28]      | 6971        | Potential approach and QCD sum rules            |
| [46]      | 7040 ± 90   | Feynman-Hellmann + semi-empirical formulas      |
| [47]      | 7053        | Mass sum rules                                 |
| [48]      | 7000        | Relativistic quasipotential quark model         |
| [52]      | 6850 ± 50   | Potential approach and QCD sum rules            |
| [54]      | 6963        | Relativistic quark-diquark                      |
| [55]      | 6870        | Bag model                                      |
| [58]      | 6948        | Variational                                    |
| [59]      | 7047        | Quark model                                    |
| [60]      | 6818        | Coupled channel formalism                      |
| [62]      | 6950 ± 80   | QCD sum rules                                  |
whereas states with $j = 3/2$ will decay via D wave pion emission, and hence will be narrower. This is particularly true of the $J_{tot} = 5/2$ state, which is pure $j = 3/2$ and hence immune from mixing.

Let us neglect the fine-structure interaction between the $j = 3/2$ light-quark system and the heavy $cc$ diquark. Even in P-wave mesons with a single heavy quark, this interaction gives rise to a splitting of only 41 MeV between $D_1(2421)$ and $D_2^*(2462)$, and 20 MeV between $B_1(5723)$ and $B_2^*(5743)$. The spin-weighted average of $D_1(2421)$ and $D_2^*(2462)$ masses is 2446 MeV, lying 473 MeV above the spin-weighted average of $D$ and $D^*$ masses. The spin-weighted average of $B_1(5723)$ and $B_2^*(5743)$ masses is 5736 MeV, lying 422 MeV above the spin-weighted average of $B$ and $B^*$ masses. The $cc$ diquark is intermediate in mass between the $c$ and $b$ quarks, so one might expect the narrow P-wave excitations of $\Xi_{cc}$ to occupy an interval of no more than a few tens of MeV, lying between 420 and 470 MeV above the spin-weighted average of $\Xi_{cc}$ and $\Xi_{cc}^*$ masses.

**IX  Likely decay modes and lifetimes**

Many of the references quoted in Tables VIII, X, XIII, and XIV also discuss likely branching ratios and production mechanisms. In addition, we note early suggestions by Bjorken [70, 71] and Moinester [72]. Here we give some general guidelines, avoiding specific calculations depending on details of form factors and fragmentation. We pay special attention to those modes which can show up in the online selection criteria (“triggers”) of experiments at $e^+e^-$ colliders, the Tevatron, and the LHC. We concentrate on those decays involving the most-favored Cabibbo-Kobayashi-Maskawa matrix elements, such as $c \rightarrow sW^+$ and $b \rightarrow cW^-$. In lifetime estimates we shall neglect the effects of Pauli interference, concentrating on effects of factorized decays and $2 \rightarrow 2$ internal transitions. Although we do not present detailed branching fractions, Tables 9-18 through 9-20 of Ref. [28] are a useful guide.

A  $\Xi_{cc}^{++} = ccu$

The decay of $\Xi_{cc}^{++}$ begins with the decay of either charm quark to a strange quark and a virtual $W^+$ (“$W^{++}$”). In this and other processes, a virtual $W^+$ gives rise to a positively charged hadronic state limited only by available phase space. In this case the minimum mass of the $csu$ remnant is that of the $\Xi_c(2469)$. Given our prediction of $M(\Xi_{cc}) = (3627 \pm 12)$ MeV, one has 1158 MeV of available energy for the $W^{++}$ products, which can then be $\pi^+$, $\rho^+$, or the low-energy tail of the $a_1^+$. The $csu$ remnant has the quantum numbers of the $\Xi_c^+$. It may decay via virtual $W^+$ emission to an $ssu$ remnant which is either a $\Xi^0$ (hard to detect) or an excited state of it (decaying to $\Xi^-\pi^+$). Alternatively, the $csu$ remnant may fragment into states such as $\Lambda_c^+K^-\pi^+$, with the $\Lambda_c^+$ decaying to such final states as $pK^-\pi^+$.

The decay chain $\Xi_{cc}^{++} \rightarrow \pi^+\Xi_c^+ \rightarrow 3\pi^+\Xi^-$ leads to pions all of the same sign. The CDF trigger based on two displaced tracks accepts only a pair of opposite-sign tracks, and would miss such a signature [73]. One might be able to pick up opposite-sign tracks from higher-multiplicity decays giving rise to a $\pi^+$ and $\pi^-$ or $K^-$, but one pays a price in higher multiplicity because such tracks are often soft and below the accepted transverse momentum threshold.
A crude estimate of the lifetime of the $\Xi_{cc}^{++}$ may be obtained by considering the two $c$ quarks to decay independently. Bjorken [70, 71] and Fleck and Richard [43] estimate $\tau(\Xi_{cc}^{++}) \simeq 200$ fs by this method. We reproduce this value by assuming an initial state with $M(\Xi_{cc}) = 3627$ MeV, a final state with $M(\Xi_c) = 2469$ MeV, a weak current giving rise to $e\nu, \mu\nu$, and three colors of $ud\bar{d}$, a kinematic suppression factor

$$F(x) = 1 - 8x + 8x^3 - x^4 + 12x^2 \ln(1/x) , \quad x_{cc} \equiv [M(\Xi_c)/M(\Xi_{cc})]^2 = 0.4634 ,$$

and a factor of 2 to count each decaying $c$ quark. The resulting decay rate is

$$\Gamma(\Xi_{cc}^{++}) = \frac{10 G_F^2 M(\Xi_{cc})^5}{192\pi^3} F(x_{cc}) = 3.56 \times 10^{-12} \text{ GeV}$$

leading to a predicted lifetime of $\tau(\Xi_{cc}^{++}) = 185$ fs. In this calculation two compensating effects have been neglected: (i) a form factor for the weak transition $\Xi_{cc} \rightarrow \Xi_c$, and (ii) the excitation of $csu$ states above $\Xi_{cc}^+$. Here and elsewhere we have assumed $V_{ud} = V_{cs} = 1$ for favored elements of the Cabibbo-Kobayashi-Maskawa matrix. A similar approach to semileptonic decays of hadrons containing a single heavy quark has been shown to reproduce observed rates with an accuracy of about 10% [74].

B $\Xi_{cc}^{++} = ccd$

We treat this final state separately because, in addition to decaying via the subprocess $c \rightarrow sud\bar{d}$ discussed in the previous subsection, it may decay via the subprocess $cd \rightarrow su$. The decays of $\Lambda_c = cud$ ($\tau = 200 \pm 6$ fs) and $\Xi_c^0 = csd$ ($\tau = 112^{+13}_{-10}$ fs) are probably enhanced by this subprocess with respect to those of $\Xi_{cc}^+ = csu$ ($\tau = 442 \pm 26$ fs), where it cannot occur. By comparing the $\Xi_{cc}^+$ and $\Xi_{cc}^0$ decay rates, and including a factor of 2 for the two charmed quarks participating in $cd \rightarrow su$, the enhancement to the decay rate becomes $8.78 \times 10^{-12}$ GeV and the lifetime becomes $\tau(\Xi_{cc}^{++}) = 53$ fs. Bjorken [70, 71] and Fleck and Richard [43] predict about 100 fs.

The subprocess $cd \rightarrow su$ in $\Xi_{cc}^{++} = ccd$ leads to an excited $csu$ state without the $\pi^+$ emitted in $\Xi_{cc}^{++}$ decay. The rest of the discussion proceeds as for $\Xi_{cc}^{++}$, but with slightly more available phase space. In particular, the fragmentation of $csu$ into $\Lambda_c^+ K^- \pi^+$ gives rise to a slightly more energetic $K^-$, advantageous for the CDF two-opposite-sign-track trigger.

C $\Xi_{bc}^{++} = bcu$

A factorization approach similar to that described for the $\Xi_{cc}$ states may be used to estimate one set of contributions to $\Xi_{bc} = bcq$ decays. There are two contributing subprocesses: $b \rightarrow cd\bar{u}$ and $c \rightarrow sud$. In the case of the first, the weak current can produce not only $e\nu, \mu\nu$, and $\bar{u}d\bar{u}$, but also $\tau\nu$ and $c\bar{s}$. An interesting consequence of the last is the decay $\Xi_{bc} \rightarrow J/\psi \Xi_c$, allowed for both charge states of $\Xi_{bc}$. The rate for this decay should not exceed the total in which the weak current produces a $c\bar{s}$ pair. For the sake of a very crude estimate, we shall neglect the masses of all allowed states produced by the weak current.

The $b \rightarrow cW^{*-}$ subprocess, under assumptions similar to those in the previous subsections, gives rise to a partial decay rate

$$\Gamma(\Xi_{bc} \rightarrow W^{*-}\Xi_{cc}) = \frac{9 G_F^2 M(\Xi_{bc})^5}{192\pi^3} F([M(\Xi_{cc})/M(\Xi_{bc})]^2)|V_{cb}|^2 = 6.87 \times 10^{-13} \text{ GeV},$$

(24)
where we have used $|V_{cb}| = 0.04$ and have assumed massless final states of $e\nu$, $\mu\nu$, $\tau\nu$, three colors of $\bar{u}d$, and three colors of $\bar{c}s$. The $c \to s W^+$ subprocess gives rise to a larger partial rate:

$$\Gamma(\Xi_{bc} \to W^+\Xi_b) = \frac{5}{192\pi^3} G_F^2 M(\Xi_{bc})^5 F\{[M(\Xi_b)/M(\Xi_{bc})]^2\} = 2.01 \times 10^{-12} \text{ GeV} \ . \quad (25)$$

In principle for $\Xi_{bc}^+ = bcu$ there should be a third contribution from the subprocess $bu \to cd$. However, the near-equality of the lifetimes of $\Xi_b^0 = bsu$ and $\Xi_b^- = bsd$ [35, 75, 76], as summarized in Table XV, suggests that this process carries little weight, so we shall neglect it. The sum of the two contributions to the $\Xi_{bc}^+$ decay rate is then $2.70 \times 10^{-12} \text{ GeV}$, yielding a lifetime of $\tau(\Xi_{bc}^+) = 244 \text{ fs}$.

For the $b \to c W^+$ subprocess, contributing to the decay of both $\Xi_{bc}$ states, the virtual $W$ can easily produce a negative pion. Subsequent decays of the $ccq$ intermediate state easily lead to a positive pion, so the CDF trigger should be able to respond to a pair of opposite-sign displaced tracks coming from $\Xi_{bc}$ decays.

One effect which we have not considered is the internal $2 \to 2$ transition $bc \to cs$. For both $\Xi_{bc} = bcq$ states, this leads to a final $csq$ state, an excited version of $\Xi_{c}^{(+,0)}$ which can decay to the same products as $\Xi_{c}^{(+,0)}$ or hadronically to states like $\Lambda D^0$. In principle one could relate the $bc \to cs$ process in $\Xi_{bc}$ to the $b \to c W^+$ annihilation process in $B_c^-$ decay.

**D**  $\Xi_{bc}^0 = bcd$

In addition to the contributions just calculated to the decay rate of $\Xi_{bc}^+$, we have seen the subprocess $cd \to su$ to be important in the difference between $\Xi_c^0$ and $\Xi_c^+$ lifetimes. If we take the additional contribution to the $\Xi_{bc}^0$ decay rate to be the same here, that provides an additional term of $4.39 \times 10^{-12} \text{ GeV}$, leading to

$$\Gamma(\Xi_{bc}) = 7.09 \times 10^{-12} \text{ GeV} \ , \ \tau(\Xi_{bc}) = 93 \text{ fs} \ . \quad (26)$$

The intermediate state produced by $cd \to su$ is that of an excited $bsu$ ("$\Xi_b^{*0}$") with the mass of $\Xi_{bc}$. The dominant subsequent decay is governed by the subprocess $b \to c W^+$, with enough phase space that the virtual $W^-$ can produce all three lepton pairs, $\bar{u}d$, and $\bar{c}s$. The last process can lead to $J/\psi$ production, for example in the decay $\Xi_{bc}^0 \to J/\psi \Xi_b^0$ or $\Xi_{bc}^0 \to J/\psi \Xi_b^- \pi^+$.

**E**  $\Xi_{bb} = bbq$

Although the $2 \to 2$ process $bu \to cd$ is possible in principle for $\Xi_{bb} = bbu$, we have seen that it seems to play little role in generating a lifetime difference between $\Xi_b^0$ and $\Xi_b^-$. Hence we may treat $\Xi_{bb}^0$ and $\Xi_{bb}^-$ generically as $\Xi_{bb} = bbq$ in what follows.
Table XVI: Summary of lifetime predictions for baryons containing two heavy quarks. Values given are in fs.

| Baryon  | This work | [28] | [52] | [71] | [72] |
|---------|-----------|------|------|------|------|
| Ξ⁺⁺     | ccu       | 185  | 430±100 | 460±50 | 500  | ~ 200  |
| Ξ⁺⁺     | ccu       | 53   | 120±100 | 160±50 | 150  | ~ 100  |
| Ξ⁺⁺     | bcu       | 244  | 330±80  | 300±30 | 200  | –      |
| Ξ⁺⁺     | bcu       | 93   | 280±70  | 270±30 | 150  | –      |
| Ξ⁰⁺⁺     | bbu       | 370  | –      | 790±20 | –    | –      |
| Ξ⁻⁻     | bbu       | 370  | –      | 800±20 | –    | –      |

The initial process in a Ξbb decay is the process \( bbq \rightarrow bcq + W^* \), where the minimum mass of the bcq remnant is that of the Ξbc, or 6914 MeV. As the predicted mass of Ξbb is 10162 MeV, there is enough phase space for the weak current to produce all three lepton pairs, \( \bar{u}d \), and \( \bar{c}s \). Neglecting all of their masses, the total decay rate is calculated to be

\[
\Gamma(\Xi_{bb}) = \frac{18}{192\pi^3} G_F^2 M(\Xi_{bb})^5 F\left\{\left[\frac{M(\Xi_{bc})}{M(\Xi_{bb})}\right]^2\right\}|V_{cb}|^2 = 1.78 \times 10^{-12} \text{ GeV} ,
\]

leading to a predicted lifetime \( \tau(\Xi_{bb}) = 370 \text{ fs} \).

An interesting decay involving the subprocess \( b \rightarrow J/\psi s \) twice is the chain

\[
\Xi_{bb} \rightarrow J/\psi \Xi_b^{(*)} \rightarrow J/\psi J/\psi \Xi^(*) ,
\]

where \( \Xi_b^{(*)} \) denotes a (possibly excited) state with the minimum mass of \( \Xi_b(5792) \), while \( \Xi^(*) \) denotes a (possibly excited) state with the minimum mass of Ξ. Although this state is expected to be quite rare and one has to pay the penalty of two \( J/\psi \) leptonic branching fractions, it has a distinctive signature and is worth looking for.

F Lifetime summary and discussion

We summarize our lifetime predictions and compare them with others in Table XVI. There is quite a spread in predicted values, but in all cases lifetimes are shortened when the \( 2 \rightarrow 2 \) process \( cd \rightarrow su \) is permitted, as in the case of the \( \Lambda_c^+ \), while the \( 2 \rightarrow 2 \) process \( bu \rightarrow cd \) seems to have little effect. Our very short lifetime for \( \Xi_{cc}^+ \) stems from two main effects: (i) the difference between the \( \Xi_0^+ \) and \( \Xi_1^+ \) lifetimes (112 vs 442 fs), used to estimate the effect of the \( cd \rightarrow su \) subprocess, and (ii) the factor of 2 in the \( cd \rightarrow su \) rate because the \( \Xi_{cc}^+ \) has two charmed quarks.

X Prospects for detection

Production of baryons containing two heavy quarks requires simultaneous production of two heavy quark-antiquark pairs. Subsequently, a heavy quark from one pair needs to coalesce with a heavy quark from the other pair, forming together a color antitriplet heavy diquark. The heavy diquark then needs to pick up a light quark to finally hadronize as a doubly-heavy baryon. The coalescence of the two heavy quarks requires that they be in each other’s
Table XVII: Fractions of different $b$-hadron species arising from $b$ quarks. From Ref. [77].

| Quantity                  | $Z$ decays  | Tevatron     |
|---------------------------|-------------|--------------|
| $B^+$ or $B^0$ fraction $f_u = f_d$ | $0.403 \pm 0.009$ | $0.330 \pm 0.030$ |
| $B^0_s$ fraction          | $0.103 \pm 0.009$ | $0.102 \pm 0.012$ |
| $b$-baryon fraction       | $0.090 \pm 0.015$ | $0.236 \pm 0.067$ |

vicinity in both ordinary space and in rapidity space. Computation of the corresponding cross section from first principles is difficult [28, 82–91], and is subject to considerable uncertainties due to nonperturbative effects. Instead, we use existing data [11–13] and theoretical estimates [92–94] of the closely-related process of $B_c$ production.

The two processes are closely related because production of $B_c$ also requires simultaneous production of two heavy quark-antiquark pairs. A priori, $B_c$ production has a somewhat higher probability, since in $B_c$ production a heavy quark from one pair needs to coalesce with a heavy antiquark (rather than a quark) from the other pair and there is no need to pick up an additional light quark. There is no suppression associated with the latter, as once the color anti-triplet heavy diquark is formed it can only hadronize by picking up a light quark. On the other hand, the attraction between a quark and an antiquark is two times stronger than the attraction between two quarks and we need to estimate the corresponding suppression factor. In order to see if $\Xi_{bc}$ and $B_c$ production rates are comparable, it would be useful to compare the analogous production rates of $\Xi_c$ and $D_s$ (or $\Xi_b$ and $B_s$) in experiments with large enough $E_{CM}$, whether in $e^+e^-$, $\bar{p}p$, or $pp$ collisions.

Although it is not directly related, one may consider the relative probability of a $b$ quark produced at high energy fragmenting into a meson (picking up a light antiquark) and a baryon (picking up a light diquark). The Heavy Flavor Averaging Group (HFAG) [77] has tabulated these quantities as measured in $Z$ decays and the Tevatron, as shown in Table XVII.

According to the HFAG analysis, depending on the production mechanism, the $b$ quark turns into a baryon between about 10 and 25% of the time. Fragmentation into a baryon is somewhat favored at low transverse momentum [77] in hadron collisions.

More recently, LHCb has carried out a thorough analysis of the $b$ quark fragmentation into mesons and baryons [78–81]. In particular, the rather striking Fig. 4 in Ref. [81] shows that the ratio of $\Lambda_b$ production to $B^0$ meson production for $p_T$ below 10 GeV is above 0.3 and goes above 0.5 for lower $p_T$.

A crude conclusion which we might draw from this comparison is that a baryon composed of two heavy quarks could be produced with at least 10% of the $B_c$ production rate. An even more optimistic estimate, supported by the above LHCb fragmentation data, is provided by an explicit calculation [28] which predicts the production rates for $\Xi_{cc}$ and $\Xi_{bc}$ to be as large as 50% of that for $(B_c + B^*_c)$ at the Tevatron, of the order of several nb. The cross section for $\Xi_{bb}$ is estimated in that work to be about a factor of 10 less.

The inclusive production cross section of the $B^+_c$ at the LHC, including the contribution from excited states, was estimated to be $\sim 1 \, \mu b$ for $\sqrt{s} = 14$ TeV, and $\sim 0.4 \, \mu b$ for $\sqrt{s} = 7$ TeV [94], based on a dominant contribution from $gg$ fusion: $gg \rightarrow B_c + b + \bar{c}$, computed by the complete order-$\alpha_s^4$ approach and by the fragmentation approach.
As a figure of merit, for 1 fb$^{-1}$ integrated luminosity 1 $\mu$b translates to $\sim 10^9$ $B^+_c$ mesons being produced at the LHC, one order of magnitude more than at the Tevatron. This number is considerably reduced by triggering on specific decay modes and folding in the detector efficiency, but nevertheless it leaves a sufficiently large number of $B_c$s to carry out a detailed study of the $B^+_c$ properties.

Based on 0.37 fb$^{-1}$ of data collected in $pp$ collisions at $\sqrt{s} = 7$ TeV LHCb has reported [9] the ratio of the production cross section times branching fraction between the $B^+_c \rightarrow J/\psi \pi^+$ and the $B^+ \rightarrow J/\psi K^+$ decays,

$$\frac{\sigma(pp\rightarrow B_c+X)\cdot B(B^+_c\rightarrow J/\psi \pi^+)}{\sigma(pp\rightarrow B^+X)\cdot B(B^+\rightarrow J/\psi K^+)} = (0.68 \pm 0.10 \text{ (stat.)} \pm 0.03 \text{ (syst.)} \pm 0.05 \text{ (lifetime)}) \times 10^{-2},$$

(29)

for $B^+_c$ and $B^+$ mesons with transverse momenta $p_T > 4$ GeV/$c$ and pseudorapidities $2.5 < \eta < 4.5$, corresponding to $162 \pm 18$ $B^+_c \rightarrow J/\psi \pi^+$ signal events. We may use this last figure to estimate the total number of $B^+_c$ produced within the LHCb acceptance.

A number of calculations of $B_c$ branching fractions are compared with one another in Ref. [95]. This reference is the one which best reproduces the observed ratio [15]

$$\frac{B(B^+_c \rightarrow J/\psi \pi^+)}{B(B^+_c \rightarrow J/\psi \mu^+\nu)} = 0.0469 \pm 0.0028 \pm 0.0046,$$

(30)

so we shall quote its result $B(B^+_c \rightarrow J/\psi \mu^+\nu) = 1.36\%$, which we have corrected using a recent measurement [16] $\tau(B^+_c) = (509 \pm 8 \pm 12)$ fs. With the measured ratio (30) this implies $B(B^+_c \rightarrow J/\psi \pi^+) = 6.4 \times 10^{-4}$.

With the above one can now compute the total $B_c$ production cross section directly from data:§ the total $B^+$ production cross section at LHCb is $38.9 \pm 0.3(\text{stat.}) \pm 2.5(\text{syst.}) \pm 1.3(\text{norm.})$ $\mu$b [96] and $B(B^+ \rightarrow J/\psi K^+) = (1.028 \pm 0.031) \times 10^{-3}$ [26]. Putting this all together, we obtain

$$\sigma(pp\rightarrow B_c+X) \approx \sigma(pp\rightarrow B^+X) \cdot \frac{B(B^+ \rightarrow J/\psi K^+)}{B(B^+_c \rightarrow J/\psi \pi^+)} \cdot 0.68 \cdot 10^{-2}$$

(31)

$$= \frac{38.9 \cdot 1.028 \times 10^{-3} \cdot 0.68 \cdot 10^{-2}}{6.4 \times 10^{-4}} \mu b = 0.4 \mu b$$

for $4 < p_T < 40$ GeV and $2.5 < \eta < 4.5$, whereas Ref. [94] predicts this value for the whole of phase space. With $162 \pm 18$ $B^+_c \rightarrow J/\psi \pi^+$ events $B(B^+_c \rightarrow J/\psi \pi^+) = 6.4 \times 10^{-4}$ indicates a total of

$$\frac{162 \pm 18}{(6.4 \times 10^{-4})(0.0593 \pm 0.0006)} \sim 4.3 \times 10^6 B_c$$

(32)

produced within the LHCb acceptance, where the second number in the denominator is $B(J/\psi \rightarrow \mu^+\mu^-)$. With an observed $B_c$ production cross section $0.4 \mu b$ in 0.37 fb$^{-1}$ there are a total of about $1.5 \times 10^8 B_c$ produced overall, indicating an acceptance a bit below 3%. One might expect the $\Xi_{cc}$ production cross section to be at most a tenth of this, or 40 nb, at 7 TeV.

§ We thank Vanya Belyaev for pointing out that the total $B^+$ production cross section at LHCb is available and can be used for this purpose.
There is an interesting question whether $\Xi_{cc}$ is LHCb’s best bet for discovering doubly-heavy baryons. The point is that because of Cabibbo suppression the $b$ quark lifetime is about 7 times longer than the $c$ quark, even though the $b$ quark is more than 3 times heavier and the phase space for weak quark decay of a heavy quark scales like $(m_b/m_c)^3$ times a kinematic function of the final and initial masses. Thus $\tau(\Lambda_b) \approx 1.5 \times 10^{-12}$ s vs. $\tau(\Lambda_c) \approx 2 \times 10^{-13}$ s, etc. The difference between actual $\Xi_{cc}$ and $\Xi_{bc}$ lifetimes, as shown in Table XVI, is not so pronounced. Longer lifetime makes it much easier to identify the secondary vertex. On the other hand, the cross section for producing bottom quarks is of course much smaller than for charmed quarks. So there is a tradeoff.

For sake of completeness, we also provide here a brief update on the status of search for doubly charmed baryons in $e^+e^-$ experiments. The most recent and most stringent limits in this case come from Belle [10]. They used a 980 fb$^{-1}$ data sample to search for $\Xi_{cc}^+$ and $\Xi_{cc}^{++}$ decaying into $\Lambda_c^+K^−\pi^+(\pi^+)$. They also set a 95% C.L. upper limit on $\sigma(e^+e^− \rightarrow \Xi_{cc}^+ + X) \times B(\Xi_{cc}^+ \rightarrow \Lambda_c^+K^−\pi^+(\pi^+))$ with the scaled momentum $0.5 < x_p < 1.0$: 4.1–25.0 fb for $\Xi_{cc}^+$ and 2.5–26.5 fb for $\Xi_{cc}^{++}$. They also set a 95% C.L. upper limit on $\sigma(e^+e^− \rightarrow \Xi_{cc}^{++} + X) \times B(\Xi_{cc}^{++} \rightarrow \Xi_{cc}^0\pi^+(\pi^+)) \times B(\Xi_{cc}^0 \rightarrow \Xi^+\pi^−)$ with the scaled momentum $0.45 < x_p < 1.0$: 0.076–0.35 fb for the $\Xi_{cc}^+$ and 0.082–0.40 fb for the $\Xi_{cc}^{++}$.

The CM energy of the B factories is sufficient only for production of $\Xi_{cc}$, as $\Xi_{bc}$ and $\Xi_{bb}$ are too heavy. So within the foreseeable future the latter can only be produced at LHC and perhaps at RHIC.

As in the case of doubly-heavy baryon production in LHCb, there is a significant uncertainty in theoretical predictions for the inclusive cross section $\sigma(e^+e^− \rightarrow \Xi_{cc} + X)$. Therefore, we suggest another approach, similar in spirit to what we proposed for LHCb. This approach is again directly based on observables which are in principle accessible in $e^+e^-$ machines.

One can make a rough estimate of the doubly-charmed baryon production rate by assuming that the suppression of $ccq$ baryons $\Xi_{cc}$ vs. $csq$ baryons $\Xi_c$ is of the same order of magnitude as the suppression of $\Xi_c$ vs. $ssq$ baryons $\Xi$. The physical content of this assumption is that the suppression due to replacing an $s$ quark in a baryon by a much heavier $c$ quark is approximately independent of the spectator quarks in the baryon:

$$\sigma(e^+e^− \rightarrow \Xi_{cc} + X) \sim \sigma(e^+e^− \rightarrow \Xi_{c} + X) \frac{\sigma(e^+e^− \rightarrow \Xi_{cc} + X)}{\sigma(e^+e^− \rightarrow \Xi_{c} + X)} \quad (33)$$

Information on inclusive $\Xi_c$ production in $e^+e^-$ annihilation at CM energy very close to Belle energy is readily available. The ARGUS experiment has measured [97] the following $\Xi^-$ rates per multihadronic event at $\sqrt{s} = 10$ GeV:

$$(2.06 \pm 0.17 \pm 0.23) \times 10^{-2} \quad \text{in direct } \Upsilon \text{ decays}$$

and

$$(0.67 \pm 0.06 \pm 0.07) \times 10^{-2} \quad \text{in the continuum.} \quad (34)$$

The situation with inclusive $\Xi_c$ production is less simple. Belle has seen $\Xi_c$ only in some specific channels, so what they measure is (production rate)\times(branching fractions into specific channels). The latter are not known well, so it is not easy to determine the production rate itself.
Table XVIII: Summary of our mass predictions (in MeV) for lowest-lying baryons with two heavy quarks. States without a star have $J = 1/2$; states with a star are their $J = 3/2$ hyperfine partners. The quark $q$ can be either $u$ or $d$. The square or curved brackets around $cq$ denote coupling to spin 0 or 1.

| State | Quark content | $M(J = 1/2)$ | $M(J = 3/2)$ |
|-------|---------------|--------------|--------------|
| $\Xi_{cc}^{(*)}$ | $ccq$ | 3627 ± 12 | 3690 ± 12 |
| $\Xi_{bc}^{(*)}$ | $b[cq]$ | 6914 ± 13 | 6969 ± 14 |
| $\Xi_{bc}'$ | $b(cq)$ | 6933 ± 12 | – |
| $\Xi_{bb}^{(*)}$ | $bbq$ | 10162 ± 12 | 10184 ± 12 |

Nevertheless, for our purpose it is sufficient to estimate the $\Xi_{cc}$ production rate to within a factor $2 \div 4$, which should be possible even within the existing uncertainties about $\Xi_{c}$ branching fractions.

The approximate formula in Eq. (33) and its generalizations to $\Xi_{bc}$ and $\Xi_{bb}$ production should also apply to $pp$ collisions:

$$\sigma(pp \to \Xi_{bc} + X) \sim \sigma(pp \to \Xi_{b} + X) \cdot \frac{\sigma(pp \to \Xi_{c} + X)}{\sigma(pp \to \Xi + X)}$$

(35)

$$\sim \sigma(pp \to \Xi_{c} + X) \cdot \frac{\sigma(pp \to \Xi_{b} + X)}{\sigma(pp \to \Xi + X)}$$

as well as

$$\sigma(pp \to \Xi_{bb} + X) \sim \sigma(pp \to \Xi_{b} + X) \cdot \frac{\sigma(pp \to \Xi_{b} + X)}{\sigma(pp \to \Xi + X)}.$$  (36)

XI Conclusions

The conclusive observation of baryons with two heavy quarks is long overdue. The weight of theoretical and experimental evidence suggests that whatever the SELEX experiment has reported [3,4], it is not the $\Xi_{cc}$: Its mass lies below almost all expectations, the isospin splitting between $\Xi_{cc}^{++}(3460)$ and $\Xi_{cc}^{+}(3520)$ candidates is implausibly large, and no other experiment has seen the effect. We have predicted $M(\Xi_{cc}) = 3627 \pm 12$ MeV and made several suggestions for its observation, including the decay to $\pi^+\Xi_{c}$, where both states of $\Xi_{c}^{+0}$ have been identified in previous studies. We also predict the masses of other states summarized in Table XVIII, and have estimated lifetimes for these states as summarized in Table XVI.

We also estimate the hyperfine splitting between $B_{c}^{*}$ and $B_{c}$ mesons to be 68 MeV, with an alternate method giving 84 MeV. P-wave excitations of the $\Xi_{cc}$ with light-quark total angular angular momentum $j = 3/2$, the analog of those observed for $D$ and $B$ mesons, are estimated to lie around 420–470 MeV above the spin-weighted average of the $\Xi_{cc}$ and
Ξ∗_cc masses. Production rates could be as large as 50% of those for B_c, which also requires the production of two heavy quark pairs. We are optimistic that with the increased data samples soon to be available in hadronic and e^+e^- collisions, the first baryons with two heavy quarks will finally be seen.

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**Note added**

After this work had been completed, a new set of lattice results appeared in Ref. [98]. As noted by the authors, in several cases their results are quite close to ours:

\[ M(\Xi^{cc}) = 3610(23)(22) \text{ MeV}, \quad M(\Xi^{cc*}) = 3692(28)(21) \text{ MeV}, \quad M(\Xi^{bb}) = 10143(30)(23) \text{ MeV}, \]
\[ M(\Xi^{bb*}) = 10178(30)(24) \text{ MeV}, \quad M(\Xi^{bc}) = 6943(33)(28) \text{ MeV}, \quad M(\Xi^{bc*}) = 6959(36)(28) \text{ MeV}, \]
\[ \text{and} \quad M(\Xi^{bc*}) = 6985(36)(28) \text{ MeV}. \]

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