Predictions for masses of $\Xi_b$ baryons

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ABSTRACT

The recent observation by CDF of $\Sigma^\pm_b$ ($uub$ and $ddb$) baryons within 2 MeV of the predicted $\Sigma_b - \Lambda_b$ splitting has provided strong confirmation for the theoretical approach based on modeling the color hyperfine interaction. We now apply this approach to predict the masses of the $\Xi_b$ family of baryons with quark content $usb$ and $dsb$ — the ground state $\Xi_b$ at 5790 to 5800 MeV, and the excited states $\Xi_b'$ and $\Xi_b^{*}$. The main source of uncertainty is the method used to estimate the mass difference $m_b - m_c$ from known hadrons. We verify that corrections due to the details of the interquark potential and to $\Xi_b - \Xi_b'$ mixing are small.

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1 Introduction

For many years the only confirmed baryon with a $b$ quark was the isospin-zero $\Lambda_b$. A recent measurement of its mass by the CDF Collaboration is $M(\Lambda_b) = 5619.7 \pm 1.2 \pm 1.2$ MeV [1]. It has the quark content $\Lambda_b = bud$, where the $ud$ pair has spin and isospin $S(ud) = I(ud) = 0$. Now CDF has reported the observation of candidates for the $\Sigma^+_b$ and $\Sigma'^+_b$ [2] with masses consistent with quark model predictions [3, 4, 5, 6, 7],

$$M(\Sigma^+_b) - M(\Lambda_b) = 195.5^{+1.0}_{-1.0} \text{ (stat.) MeV}$$

$$M(\Sigma'^+_b) - M(\Lambda_b) = 188.0^{+2.0}_{-2.3} \text{ (stat.) MeV}$$

with isospin-averaged mass difference $M(\Sigma_b) - M(\Lambda_b) = 192$ MeV, to be compared with the prediction [5, 8] $M_{\Sigma_b} - M_{\Lambda_b} = 194$ MeV.

The $\Sigma^\pm_b$ states consist of a light quark pair $uu$ or $dd$ with $S = I = 1$ coupled with the $b$ quark to $J = 1/2$, while in the $\Sigma'^\pm_b$ states the light quark pair and the $b$ quark are coupled to $J = 3/2$. The CDF sensitivity appears adequate to detect further heavy baryons, such as those with quark content $bsu$ or $bsd$. The $S$-wave levels of these quarks consist of the $J = 1/2$ states $\Xi^{0, -}_b$ and $\Xi'^{(0, -)}_b$ and the $J = 3/2$ states $\Xi'^{(0, -)}_b$. In this paper we predict the masses of these states and estimate the dependence of the predictions on the form of the interquark potential. This exercise has been applied previously to hyperfine splittings of known heavy hadrons [9].

We discuss the predictions for $M(\Xi_b)$ in Section 2, starting with an extrapolation from $M(\Xi_c)$ without correction for hyperfine (HF) interaction and then estimating this correction. In the $\Xi_b$ the light quarks are approximately in a state with $S = 0$, while another heavier state $\Xi'^*_b$ is expected in which the light quarks mainly have $S = 1$. There is also a state $\Xi'^*_b$ expected with light-quark spin 1 and total $J = 3/2$. Predictions for $\Xi'^*_b$ and $\Xi'^*_b$ masses are discussed in Section 3. We estimate the effect of mixing between light-quark spins $S = 0$ and 1 in Section 4, while Section 5 summarizes.

2 $\Xi_b$ mass prediction

In our model the mass of a hadron is given by the sum of the constituent quark masses plus the color-hyperfine (HF) interactions:

$$V_{ij}^{HF} = v \frac{\sigma_i \cdot \sigma_j}{m_i m_j} \langle \delta(r_{ij}) \rangle$$

where the $m_i$ is the mass of the $i$'th constituent quark, $\sigma_i$ its spin, $r_{ij}$ the distance between the quarks and $v$ is the interaction strength. We shall neglect the mass differences between $u$ and $d$ constituent quarks, writing $v$ to stand for either $u$ or $d$. All the hadron masses (the ones used and the predictions) are for isospin-averaged baryons and are given in MeV.
The $s$ and $u$ quarks in $\Xi_q$ ($q$ standing for $c$ or $b$) are assumed to be in relative spin 0 and the total mass is given by the expression:

$$\Xi_q = m_q + m_s + m_u - \frac{3v\langle \delta(r_{us}) \rangle}{m_q m_s}$$  \hspace{1cm} (3)

The $\Xi_b$ mass can thus be predicted using the known $\Xi_c$ baryon mass as a starting point and adding the corrections due to mass differences and HF interactions:

$$\Xi_b = \Xi_c + (m_b - m_c) - \frac{3v}{m_u m_s} \left( \langle \delta(r_{us}) \rangle_{\Xi_b} - \langle \delta(r_{us}) \rangle_{\Xi_c} \right)$$  \hspace{1cm} (4)

The experimentally determined masses for the charmed-strange baryons $\Xi_c$, $\Xi'_c$, and $\Xi^*_c$ are [10]:

$$\Xi_c = 2469.5 \pm 0.5 \text{ MeV} \hspace{1cm} \Xi'_c = 2577 \pm 4 \text{ MeV} \hspace{1cm} \Xi^*_c = 2646.3 \pm 1.8 \text{ MeV} .$$  \hspace{1cm} (5)

### 2.1 Constituent quark mass difference

The mass difference $(m_b - m_c)$ can be obtained from experimental data using one of the following expressions:

- We can simply take the difference of the masses of the $\Lambda_q$ baryons, ignoring the differences in the HF interaction:
  $$m_b - m_c = \Lambda_b - \Lambda_c = 3333.2 \pm 1.2 .$$  \hspace{1cm} (6)

- We can use the spin averaged masses of the $\Lambda_q$ and $\Sigma_q$ baryons:
  $$m_b - m_c = \left( \frac{2\Sigma^*_q + \Sigma_b + \Lambda_b}{4} - \frac{2\Sigma^*_c + \Sigma_c + \Lambda_c}{4} \right) = 3330.4 \pm 1.8 .$$  \hspace{1cm} (7)

- Since the $\Xi_q$ baryon has strangeness 1, it might be better to use masses of mesons with $S = 1$:
  $$m_b - m_c = \left( \frac{3B^*_s + B_s}{4} - \frac{3D^*_s + D_s}{4} \right) = 3324.6 \pm 1.4 .$$  \hspace{1cm} (8)

### 2.2 HF interaction correction

The HF interaction correction can also be based on $\Xi_c$ baryon experimental data:

$$\frac{v}{m_u m_s} \left( \langle \delta(r_{us}) \rangle_{\Xi_b} - \langle \delta(r_{us}) \rangle_{\Xi_c} \right) = \frac{v\langle \delta(r_{us}) \rangle_{\Xi_c}}{m_u m_s} \left( \frac{\langle \delta(r_{us}) \rangle_{\Xi_b}}{\langle \delta(r_{us}) \rangle_{\Xi_c}} - 1 \right)$$  \hspace{1cm} (9)

$$= \frac{2\Xi^*_c + \Xi'_c - 3\Xi_c}{12} \left( \frac{\langle \delta(r_{us}) \rangle_{\Xi_b}}{\langle \delta(r_{us}) \rangle_{\Xi_c}} - 1 \right)$$

$$= \left( \frac{\langle \delta(r_{us}) \rangle_{\Xi_b}}{\langle \delta(r_{us}) \rangle_{\Xi_c}} - 1 \right) \left( 38.4 \pm 0.5 \right) \text{ MeV}$$
However, this expression requires the calculation of the $\delta$ function expectation values. These were calculated using 3-body wavefunctions obtained by a variational method as described in [9]. The only input required for these calculations is the shape of confining potential, because the coupling constants cancel out when taking the ratio of the $\delta$ function expectation values. The potentials considered in this work are the linear, Coulomb and Cornell (Coulomb + linear) potentials. We also wrote down the results obtained without the HF corrections. Note that in the case of the Cornell potential we have an additional parameter, which determines the ratio between the strengths of the linear and Coulombic parts of the potential. In these calculations we used the parameters extracted in [11] from analysis of quarkonium spectra (or $K = 0.45$ when using the parameterization described in [9]).

As a test case we compared the values obtained from experimental data and variational calculations for the ratio of contact probabilities in $\Xi$ and $\Xi_c$.

$$\frac{2\Xi^* + \Xi'_c - 3\Xi_c}{2(\Xi^* - \Xi)} = \frac{6v\langle\delta(r_{us})\rangle_{\Xi_c}}{m_u m_s} = \frac{\langle\delta(r_{us})\rangle_{\Xi_c}}{\langle\delta(r_{us})\rangle_{\Xi}}$$

The results given in Table 1 show good agreement between data and theoretical predictions using the Cornell potential.

|                  | $\langle\delta(r_{us})\rangle_{\Xi_c}/\langle\delta(r_{us})\rangle_{\Xi}$ |
|------------------|---------------------------------------------------------------|
| Experimental data [10] | $1.071 \pm 0.069$                                           |
| Linear           | $1.022 \pm 0.072$                                           |
| Coulomb          | $1.487 \pm 0.002$                                           |
| Cornell          | $1.063 \pm 0.047$                                           |

Table 1: Comparison between experimental data and predictions of the ratio of $u$ and $s$ contact probabilities in $\Xi$ and $\Xi_c$ (Eq. (10)).

The final predictions for the $\Xi_b$ mass with the different assumptions regarding the constituent quark mass differences and the confinement potentials are given in Table 2. From previous experience we know that the predictions of the Coulomb potential model show a very strong dependence on the quark masses which is not observed in the data, hence one should probably give these predictions less weight. Ignoring the Coulomb potential, one gets a prediction for the $\Xi_b$ mass in the range of 5790 - 5800 MeV.
\[
m_b - m_c = \Lambda_b - \Lambda_c \quad \Sigma_b - \Sigma_c \quad B_s - D_s
\]

\[
\text{Eq. (6) \quad Eq. (7) \quad eq. (8)}
\]

| No HF correction  | 5803 ± 2 | 5800 ± 2 | 5794 ± 2 |
|-------------------|----------|----------|----------|
| Linear            | 5801 ± 11| 5798 ± 11| 5792 ± 11|
| Coulomb           | 5778 ± 2 | 5776 ± 2 | 5770 ± 2 |
| Cornell           | 5799 ± 7 | 5796 ± 7 | 5790 ± 7 |

Table 2: Predictions for the \( \Xi_b \) mass with various confining potentials and methods of obtaining the quark mass difference \( m_b - m_c \).

### 3 \( \bar{\Xi}^*_b, \bar{\Xi}'_b \) mass prediction

#### 3.1 Spin averaged mass \((2 \bar{\Xi}^*_b + \bar{\Xi}'_b)/3\)

The \( s \) and \( u \) quarks of the \( \Xi^*_q \) and \( \Xi'_q \) baryons are assumed to be in a state of relative spin 1. We then find

\[
\bar{\Xi}^*_q = m_q + m_s + m_u + v \left( \frac{\langle \delta(r_{qs}) \rangle}{m_q m_s} + \frac{\langle \delta(r_{qu}) \rangle}{m_q m_u} + \frac{\langle \delta(r_{us}) \rangle}{m_u m_s} \right)
\]

\[
\bar{\Xi}'_q = m_q + m_s + m_u + v \left( -2 \frac{\langle \delta(r_{qs}) \rangle}{m_q m_s} + \frac{\langle \delta(r_{qu}) \rangle}{m_q m_u} + \frac{\langle \delta(r_{us}) \rangle}{m_u m_s} \right)
\]

The spin-averaged mass of these two states can be expressed as

\[
\frac{2 \bar{\Xi}^*_q + \bar{\Xi}'_q}{3} = m_q + m_s + m_u + v \frac{\langle \delta(r_{us}) \rangle}{m_u m_s},
\]

and as for the \( \Xi_b \) case, the following prediction can be given:

\[
\frac{2 \Xi^*_b + \Xi'_b}{3} = \frac{2 \Xi^*_c + \Xi'_c}{3} + (m_b - m_c) + \frac{2 \Xi^*_c + \Xi'_c}{12} - 3 \Xi_c \left( \frac{\langle \delta(r_{us}) \rangle \Xi_b}{\langle \delta(r_{us}) \rangle \Xi_c} - 1 \right).
\]

The predictions obtained using the same methods described above are given in Table 3. In this case it is clear that the effect of the HF correction is negligible. Thus the difference between the spin averaged mass \((2 \bar{\Xi}^*_b + \bar{\Xi}'_b)/3\) and \( \Xi_b \) is roughly \( 150 - 160 \) MeV.

#### 3.2 \( \Xi^*_b - \Xi'_b \)

This mass difference is more difficult to predict, but it will be small due to the large mass of the \( b \) quark.

\[
\Xi^*_b - \Xi'_b = 3v \left( \frac{\langle \delta(r_{qs}) \rangle}{m_q m_s} + \frac{\langle \delta(r_{qu}) \rangle}{m_q m_u} \right)
\]
\[ m_b - m_c = \Lambda_b - \Lambda_c \quad \Sigma_b - \Sigma_c \quad B_s - D_s \]

| Method            | Eq. (6) | Eq. (7) | Eq. (8) |
|--------------------|---------|---------|---------|
| No HF correction   | 5956 ± 3 | 5954 ± 3 | 5948 ± 3 |
| Linear            | 5957 ± 4 | 5954 ± 4 | 5948 ± 4 |
| Coulomb           | 5965 ± 3 | 5962 ± 3 | 5956 ± 3 |
| Cornell           | 5958 ± 3 | 5955 ± 3 | 5949 ± 3 |

Table 3: Predictions for the spin averaged \( \Xi_b^\prime \) and \( \Xi_b^* \) masses with various confining potentials and methods of obtaining the quark mass difference \( m_b - m_c \).

We can once again use the \( \Xi_c \) hadron masses:

\[
\frac{\Xi_b^* - \Xi_b^\prime}{\Xi_c^* - \Xi_c^\prime} = \frac{3v \left( \frac{\langle r_{bs} \rangle}{m_b m_s} + \frac{\langle r_{bu} \rangle}{m_b m_u} \right)}{3v \left( \frac{\langle r_{cs} \rangle}{m_c m_s} + \frac{\langle r_{cu} \rangle}{m_c m_u} \right)} = \frac{m_c}{m_b} \left( \frac{\langle r_{bs} \rangle}{m_b} + \frac{m_u}{m_u} \langle r_{bu} \rangle \Xi_b \right) + \frac{m_u}{m_u} \langle r_{bu} \rangle \Xi_b^\prime \right) \]

This expression is strongly dependent on the confinement model. In the results given in Table 4 we have used \( \frac{m_s}{m_u} = 1.5 \pm 0.1, \frac{m_b}{m_c} = 2.95 \pm 0.2. \)

| Method            | \( \Xi_b^* - \Xi_b^\prime \) |
|--------------------|-----------------------------|
| No HF correction   | 24 ± 2                      |
| Linear            | 28 ± 6                      |
| Coulomb           | 36 ± 7                      |
| Cornell           | 29 ± 6                      |

Table 4: Predictions for the mass difference between \( \Xi_b^* \) and \( \Xi_b^\prime \) with various confining potentials.

4 Effect of light-quark spin mixing on \( \Xi_b \) and \( \Xi_b^\prime \)

In estimates up to this point we have assumed that the light-quark spins in \( \Xi_b \) and \( \Xi_b^\prime \) are purely \( S = 0 \) and \( S = 1 \), respectively. The differing hyperfine interactions
between the $b$ quark and nonstrange or strange quarks leads to a small admixture of the opposite-$S$ state in each mass eigenstate \cite{12, 13, 14, 15}. The effective hyperfine Hamiltonian may be written \cite{14, 15}

$$H_{\text{eff}} = M_0 + \lambda (\sigma_u \cdot \sigma_s + \alpha \sigma_u \cdot \sigma_b + \beta \sigma_s \cdot \sigma_b),$$

(16)

where $M_0$ is the sum of spin independent terms, $\lambda \sim 1/(m_u m_s)$, $\alpha = m_s/m_b$, and $\beta = m_u/m_b$. The calculation of $M_{3/2}$ is straightforward, as the expectation value of each $\sigma_i \cdot \sigma_j$ in the $J = 3/2$ state is 1. For the $J = 1/2$ states one has to diagonalize the $2 \times 2$ matrix

$$M_{1/2} = \begin{bmatrix} M_0 - 3\lambda & \lambda \sqrt{3}(\beta - \alpha) \\ \lambda \sqrt{3}(\beta - \alpha) & M_0 + \lambda (1 - 2\alpha - 2\beta) \end{bmatrix}.$$  

(17)

The eigenvalues of $H_{\text{eff}}$ are thus

$$M_{3/2} = M_0 + \lambda (1 + \alpha + \beta),$$

(18)

$$M_{1/2, \pm} = M_0 + \lambda [-1 + (1 + \alpha + \beta) \pm 2\lambda (1 + \alpha^2 + \beta^2 - \alpha - \beta - \alpha\beta)^{1/2}].$$

(19)

In the absence of mixing ($\alpha = \beta$) one would have $M_{3/2} = M_0 + \lambda (1 + 2\alpha)$, $M_{1/2, +} = M_0 + \lambda (1 - 4\alpha)$, and $M_{1/2, -} = M_0 - 3\lambda$.

To see the effect of mixing, we rewrite the expression for $M_{1/2, \pm}$,

$$M_{1/2, \pm} = M_0 - \lambda (1 + \alpha + \beta) \pm 2\lambda \left[ \left(1 - 2\alpha^2 - \beta^2 - \alpha - \beta - \alpha\beta\right)^{1/2} \right]$$

(20)

The effect of the mixing is seen in the term $\frac{3}{4}(\alpha - \beta)^2$. Expanding $M_{1/2, \pm}$ to second order in small $\alpha - \beta$, we obtain

$$M_{1/2, \pm} \approx (\text{terms without mixing}) \pm \lambda \cdot \frac{\frac{3}{4}(\alpha - \beta)^2}{1 - \frac{\alpha + \beta}{2}}$$

(21)

For $m_u = 363$ MeV, $m_s = 538$ MeV, and $m_b = 4900$ MeV \cite{16}, one has $\alpha \simeq 0.11$, $\beta \simeq 0.07$, while the discussion in the previous section implies $\lambda \simeq 40$ MeV [Eq. (10)]. Hence the effect of mixing on our predictions is negligible, amounting to $\pm 0.04$ MeV.

Since we use the $\Xi_c$ and $\Xi'_c$ masses as input for $\Xi_b$, it is also important to check the mixing effects on the former. Since $m_b/m_c \sim 3$, this amounts to changing in the expressions above $\alpha \rightarrow 3\alpha$, $\beta \rightarrow 3\beta$. The corresponding effect of mixing on $\Xi_c$ and $\Xi'_c$ is $\sim 0.5$ MeV, still negligible.
5 Summary

We have shown that predictions for $M(\Xi_b)$ based on the masses of $\Xi_c$, $\Xi'_c$, and $\Xi^*_c$ lie in the range of 5790 to 5800 MeV, depending on how the mass difference $m_b - m_c$ is estimated. Wave function differences tend to affect these predictions by only a few MeV. The spin-averaged mass of the states $\Xi'_b$ and $\Xi^*_b$ is predicted to lie around 150 to 160 MeV above $M(\Xi_b)$, while the hyperfine splitting between $\Xi'_b$ and $\Xi^*_b$ is predicted to lie in the rough range of 20 to 30 MeV. We look forward to the verification of these predictions in experiments at the Fermilab Tevatron and the CERN Large Hadron Collider.

Note added: After this work was completed we received notice of the $\Xi_b^-$ observation at the Fermilab Tevatron in the $J/\psi\Xi^-$ decay mode by the D0 Collaboration [17]. After the first version of this paper appeared [18], the CDF Collaboration released their $\Xi_b^-$ results in the same decay channel [19]. The reported masses, Gaussian widths (due to instrumental resolution), and significances of the signal are summarized in Table 5 and in Fig. 1. The CDF Collaboration also observes a significant $\Xi_b^- \rightarrow \Xi^0 \pi^-$ signal with mass consistent with that found in the $J/\psi\Xi^-$ mode. The D0 mass is consistent with all our predictions for the isospin-averaged mass, while that of CDF allows us to rule out the (previously disfavored [2]) prediction based on the Coulomb potential. Both experiments also agree with a prediction in Ref. [4], $M(\Xi_b) = M(\Lambda_b) + (182.7 \pm 5.0) \text{ MeV} = (5802.4 \pm 5.3) \text{ MeV}$, where differences in wave function effects were not discussed and $m_b - m_c$ was taken from baryons only, whereas in our work the optional value of $m_b - m_c$ was obtained from $B_s$ and $D_s$ mesons which contain both heavy and strange quarks, as do $\Xi_b$ and $\Xi_c$. See also Ref. [6] and Table III therein for a compilation of earlier predictions for the $\Xi_b$ mass. That the value of $m_b - m_c$ obtained from $B$ and $D$ mesons depends upon the flavor of the spectator quark was noted in Ref. [5] where Table I shows that the value is the same for mesons and baryons not containing strange quarks but different when obtained from $B_s$ and $D_s$ mesons. Some reasons for this difference were noted and the issue requires further investigation. Here we have updated the prediction of Ref. [4] using the recent CDF [1] value of $M(\Lambda_b)$.

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Table 5: Observations of $\Xi_b^- \rightarrow J/\psi \Xi^-$ at the Fermilab Tevatron. Errors on mass are (statistical, systematic).

|           | D0 [17]          | CDF [19]         |
|-----------|------------------|------------------|
| Mass (MeV)| $5774 \pm 11 \pm 15$ | $5793 \pm 2.4 \pm 1.7$ |
| Width (MeV)| $37 \pm 8$       | $\sim 14$       |
| Significance| $5.5\sigma$      | $7.8\sigma$      |

Fig. 1 (adapted from [19]). Comparison of theoretical predictions and experimental results for the $\Xi_b^-$ mass from D0 [17] and CDF [19]. The theoretical predictions are denoted by the two horizontal bands, corresponding to Refs. [4] and [18], respectively.
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