HEAVY BARYON MASSES

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Abstract

Simple and plausible rules are used to correlate the masses of the ground-state baryons containing single heavy (b or c) quarks. A comparison with the experimental data shows that the observed mass difference between the $\Sigma_b$ and the $\Sigma_b^*$ is unexpectedly large. Predictions for the masses of the yet undiscovered heavy baryons are given.

1 Introduction

The subject of this report are heavy baryons containing one heavy quark each. Since the lifetime of the $t$-quark is too short for hadronization, the heavy quark $Q$ is the $c$-quark, or the $b$-quark. From $SU(3)$ symmetry applied to the light diquark in the baryon, or from the simple quark model, one expects for each $Q$: 
• A spin 1/2 sextet consisting of the isotriplet $\Sigma_Q$, the isodoublet $\Xi'_Q$ and the isosinglet $\Omega_Q$;
• A spin 3/2 sextet consisting of the isotriplet $\Sigma^*_Q$, the isodoublet $\Xi^*_Q$ and the isosinglet $\Omega^*_Q$;
• A spin 1/2 antitriplet consisting of the isosinglet $\Lambda_Q$ and the isodoublet $\Xi_Q$.

Each of the states enumerated here should have excited states, but we limit our discussion to the $2 \times 8$ ground state isomultiplets. At present the isomultiplets $\Sigma_c$, $\Omega_c$, $\Lambda_c$, $\Xi_c$, $\Xi^*_c$ and $\Lambda_b$ are reasonably well known\(^{1,2,3}\). The isomultiplets $\Xi'_c$, $\Omega^*_c$, $\Xi'_b$, $\Omega_b$, $\Xi_b$, $\Xi^*_b$ and $\Omega^*_b$ have not yet been observed. The $\Sigma^*_c$ has been observed\(^4\), but with poor statistics (8 events). For the $\Sigma_b$ and the $\Sigma^*_b$ only preliminary data is available\(^3\).

Rather surprisingly, almost any model yields ”good” predictions for the masses of these baryons. Thus e.g. Martin and Richard\(^5\) quote ten predictions for the mass of the $\Omega_c$, most of them made before the particle was discovered, and the error nowhere exceeds 100MeV, i.e. about 4 per cent. This makes one suspect that behind the detailed models there are some simple rules, which are enough to get the good predictions and are so obvious that they are explicitly, or implicitly, included in an approximate way in all the models. Let us stress two advantages of identifying these simple rules. They make it easy to distinguish at a glance the unexpected from the expected in the experimental data. They also help to identify the ”really good” models, which can explain the small discrepancies between the predictions of the simple rules and the data. A tentative set of such rules is formulated in the following section.

2 Simpleminded rules for the baryon masses

• **Rule I** For $B = \Sigma$, $\Sigma'$, $\Omega$, $\Xi^*$, $\Omega^*$, $\Lambda$, $\Xi$ the difference $\delta_1 = M_{B_b} - M_{B_c}$ does not depend on $B$. Using the measured values\(^1,3\) of $\Lambda_b$ and $\Lambda_c$ one finds $\delta_1 = (3.353 \pm 0.016)$GeV. This (approximate!) rule is suggested by the heavy quark effective theory. In order to estimate its uncertainty one can use the analogous rule for mesons, which gives $M_{B_s} = M_B + M_{D_s} - M_D$. From the Particle Data Group numbers\(^1\) the
right-hand-side is 5.380 GeV, while according to a recent measurement\textsuperscript{7} $M_{B_s} = (5.370 \pm 0.03)$ GeV. Thus, to Rule I we ascribe a systematic error of $\pm 10$ MeV on top of the experimental uncertainty in the value of $\delta_1$.

- **Rule II** The mass differences between the adjacent isomultiplets in the sextets are all equal. From the measured values of $M_{\Sigma_c}$ and $M_{\Omega_c}$ one finds for this mass difference $\delta_2 = 0.127$ GeV. Since the systematic error of this rule is bigger than the experimental uncertainty of $\delta_2$, we have neglected this uncertainty. Rule II is suggested by the quark model, where these mass differences are essentially due to the replacement of a light quark ($u, d$) by the somewhat heavier $s$-quark. In order to estimate the systematic error of Rule II, we looked on the deviations of the experimental data from the predictions of the analogous rule for the decuplet of light baryons and on the predictions of a model described by Rosner\textsuperscript{6}, where this rule is only an approximation. Both suggest an error of $\pm 10$ MeV.

- **Rule III** The hyperfine splittings, i.e. the mass differences between the members of the spin 1/2 sextet and the corresponding members of the spin 3/2 sextet are inversely proportional to the heavy quark masses. This is again suggested by the heavy quark effective theory. From the measured masses of $\Sigma_c$, $\Omega_c$ and $\Xi^*_c$, using Rule II, we obtain for $Q = c$ the splitting $\delta_{3c} = 63$ MeV and from that for $Q = b$ the splitting $\delta_{3b} = 21$ MeV. For mesons the analogous rule works very well, $(M_{B_s} - M_B)/(M_{D^*} - M_D) \approx \frac{1}{3}$ as expected. The preliminary DELPHI data\textsuperscript{3}, however, give $M_{\Sigma_b} - M_{\Sigma_c} = (56 \pm 13)$ MeV. As discussed further this result is unexpected and when confirmed can be of great importance for model builders. For the moment we ascribe to Rule III the large systematic uncertainty $\pm 20$ MeV, which reduces the discrepancy between the prediction of this rule and the preliminary data to below two standard deviations.

Let us comment on the number of free parameters in our rules. We take from experiment $\delta_1, \delta_2, \delta_{3c}, \delta_{3b}, M_{\Sigma_b}, M_{\Lambda_b}$ and $M_{\Xi_b}$ i.e. seven parameters. This is rather standard. E.g. a typical quark model would have used $m_u = m_d, m_s, m_c, m_b$ and three parameters in the potential (one should keep in mind the constant, which is often not written explicitly).
3 Tests

There are three masses, which can be obtained using the rules given in the preceding section and compared with already available experimental data.

For $\Sigma_\ast^c$ we find the mass $M_{\Sigma_c}^\ast + \delta_{3c} = (2.516 \pm 0.010)$ GeV in reasonably good agreement with the experimental result $^4 (2.530 \pm 0.007)$ GeV.

For $\Sigma_b$ we find $M_{\Sigma_b} = M_{\Lambda_b} + (0.168 \pm 0.005)$ GeV in very good agreement with the DELPHI$^3$ result $(M_{\Lambda_b} + (0.173 \pm 0.009)$ GeV. Note that calculating the mass difference with respect to the $\Lambda_b$ one reduces the error on both the theoretical prediction and the experimental result$^3$.

For the $\Sigma_b^\ast$ we find a mass $M_{\Lambda_b} + (0.189 \pm 0.020)$ GeV, while the DELPHI result is $M_{\Lambda_b} + (0.229 \pm 0.009)$ GeV. Due to the large uncertainty ascribed to our prediction the discrepancy in standard deviations is not outrageous, but we would like to stress that the potential theoretical problem here is serious.

Let us consider two ways of visualizing this.

By hyperfine splitting (HFS) we understand the difference between the mass of the heavy hadron, where the spin of the light component is parallel to the spin of the heavy quark, and the mass of the corresponding heavy hadron, where these spins are antiparallel. For the ratio of the HFS in the $b$-sector to the HFS in the $c$-sector data give $1/3$ for mesons and 0.9 for baryons. This large increase is not expected. The ratio of the HFS for baryons to the HFS for mesons is below 0.5 in the $c$-sector and about 1.2 in the $b$-sector, which is also unexplained.

4 Predictions and conclusions

Our predictions for the masses of the yet undiscovered baryons are:

\[
\begin{align*}
M_{\Xi_c}^\ast & = 2.580 \pm 0.010 \text{GeV} \\
M_{\Omega_c}^\ast & = 2.770 \pm 0.010 \text{GeV} \\
M_{\Xi_b} & = M_{\Lambda_b} + (0.183 \pm 0.010) \text{GeV} \\
M_{\Xi_b^\ast} & = M_{\Lambda_b} + (0.295 \pm 0.010) \text{GeV} \\
M_{\Omega_b} & = M_{\Lambda_b} + (0.422 \pm 0.010) \text{GeV} \\
M_{\Xi_b^\ast} & = M_{\Lambda_b} + (0.316 \pm 0.020) \text{GeV} \\
M_{\Omega_b^\ast} & = M_{\Lambda_b} + (0.443 \pm 0.020) \text{GeV}
\end{align*}
\]
The errors on these predictions are estimated using analogies only. They correspond to one standard deviation rather than to the maximum conceivable uncertainties. The predicted values may be interpreted as predictions of one more model, however, they may be also useful as benchmarks. If a model gives predictions less good than these, their agreement with experiment within some stated uncertainties may be used as an argument for the soundness of the model, but the predictions as such are of little interest. If the predictions of a model are better than those from our simple rules, it is interesting to identify the physics behind these improvements. A possible problem is the $\Sigma^*_b$, $\Sigma_b$ HFS as compared with the analogous splittings in the $c$-sector and in the meson sectors. One should keep in mind, however, that the experimental data suggesting that there is a problem is still preliminary.

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6 References

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