Hadron physics: a quark-model analysis

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Abstract. We discuss recent results on heavy and light baryon spectroscopy.

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INTRODUCTION

Hadron spectroscopy has undergone a great renaissance in recent years [1]. The new findings include: low-lying excitations of D and B mesons, long-awaited missing states and new states near 4 GeV/c² in the charmonium spectrum, charmed and bottom baryons, and evidence for doubly charmed baryons. The light hadron sector remains also restless reporting new scalar mesons or showing a deep theoretical interest in the high energy part of both the meson and baryon spectra. In this talk we center our attention in the heavy baryon spectroscopy as well as some anomalous states present in the light baryon spectra.

HEAVY BARYONS

Heavy baryons containing a single heavy quark are particularly interesting. The light degrees of freedom (quarks and gluons) circle around the nearly static heavy quark. Such a system behaves as the QCD analogue of the familiar hydrogen bounded by the electromagnetic interaction. When the heavy quark mass \(m_Q\) \(\to \infty\), the angular momentum of the light degrees of freedom is a good quantum number. Thus, heavy quark baryons belong to either SU(3) antisymmetric \(\bar{3}_F\) or symmetric \(6_F\) representations. The spin of the light diquark is 0 for \(\bar{3}_F\), while it is 1 for \(6_F\). Thus, the spin of the ground state baryons is 1=2 for \(\bar{3}_F\), representing the \(\Lambda_b\) and \(\Xi_b\) baryons, while it can be both 1=2 or 3=2 for \(6_F\), allocating \(\Sigma_b\), \(\Sigma'_b\), \(\Xi'_b\), \(\Omega_b\) and \(\Omega'_b\), where the star indicates spin 3=2 states. Therefore heavy hadrons form doublets. For example, \(\Sigma_b\) and \(\Sigma'_b\) will be degenerate in the heavy quark limit. Their mass splitting is caused by the chromomagnetic interaction at the order 1=\(m_Q\). These effects can be, for example, taken into account systematically in the framework of heavy quark effective field theory. The mass difference between states belonging to the \(\bar{3}_F\) and \(6_F\) representations do also contain the dynamics of the light diquark subsystem, hard to accommodate in any heavy quark mass expansion. Therefore, exact solutions of the three-body problem for
TABLE 1. Masses, in MeV, of charmed and bottom baryons.

| State | J^P | Charm | Bottom |
|-------|-----|-------|--------|
|       |     | CQC   | Exp. [3] | [4] | [5]     | CQC   | Exp. [3] | [4] | [5]     |
|       |     |       |         |       |         |       |         |       |         |
| Λ_1   | 1^- | 2285  | 2286    | 2285  | 2268  | 2297  | 5624  | 5624  | 5638  | 5612  | 5622  |
| Λ_1   | 1^- | 2785  | 2765    | 2865  | 2791  | 2772  | 6106  | 6188  | 6107  | 6086  |       |
| Λ_1   | 1^- | 2627  | 2595    | 2635  | 2625  | 2598  | 5947  | 5978  | 5939  | 5930  |       |
| Λ_1   | 1^- | 2880  | 2880    | 2885  | 2816  | 3017  | 6245  | 6268  | 6180  | 6328  |       |
| Λ_3^+ | 3^- | 3061  | 2930    | 2887  | 2874  |       | 6388  | 6248  | 6181  | 6189  |       |
| Λ_3^+ | 3^- | 3308  | 3160    | 3073  | 3262  |       | 6637  | 6488  | 6401  | 6540  |       |
| Λ_5^+ | 5^- | 2888  | 2880    | 2930  | 2887  | 2883  |       |       |       |       |       |
| Σ_1   | 1^- | 2435  | 2454    | 2455  | 2455  | 2439  | 5807  | 5808  | 5845  | 5833  | 5805  |
| Σ_1   | 1^- | 2904  | 3025    | 2958  | 2864  |       | 6247  | 6370  | 6294  | 6202  |       |
| Σ_1   | 1^- | 2772  | 2765    | 2805  | 2748  | 2795  | 6103  | 6155  | 6099  | 6108  |       |
| Σ_1   | 1^- | 2893  | 2885    |       | 3176  |       | 6241  | 6245  |       | 6401  |       |
| Σ_1   | 3^- | 2502  | 2518    | 2535  | 2519  | 2518  | 5829  | 5829  | 5875  | 5858  | 5834  |
| Σ_1   | 3^- | 2944  | 2940    | 3065  | 2995  | 2912  | 6260  | 6385  | 6308  | 6222  |       |
| Σ_1   | 3^- | 2772  | 2800    | 2805  | 2763  | 2761  |       |       |       |       |       |
| Ξ_1   | 1^- | 2471  | 2471    | 2467  | 2492  | 2481  | 5801  | 5793  | 5806  | 5844  | 5812  |
| Ξ_1   | 1^- | 3137  | 3123    | 2992  | 2923  |       | 6258  | 6306  |       | 6264  |       |
| Ξ_1   | 1^- | 2574  | 2578    | 2567  | 2592  | 2578  | 5939  | 5941  | 5958  | 5937  |       |
| Ξ_1   | 1^- | 3212  | 3087    |       | 2984  |       | 6360  | 6416  |       | 6327  |       |
| Ξ_1   | 1^- | 2799  | 2792    | 2792  | 2763  | 2801  | 6109  | 6116  | 6108  | 6119  |       |
| Ξ_1   | 1^- | 2902  | 2897    | 2859  | 2928  |       | 6223  | 6236  | 6192  | 6238  |       |
| Ξ_1   | 1^- | 3004  | 2980    | 2993  |       | 3186  |       |       |       |       |       |
| Ξ_1   | 3^- | 2642  | 2646    | 2647  | 2650  | 2654  | 5961  | 5971  | 5982  | 5963  |       |
| Ξ_1   | 3^- | 3071  | 3076    | 3057  | 2984  | 3030  | 6373  | 6356  | 6294  | 6341  |       |
| Ξ_1   | 5^- | 3049  | 3055    | 3057  |       | 3042  |       |       |       |       |       |
| Ξ_1   | 5^- | 3132  | 3123    | 3167  |       | 3123  |       |       |       |       |       |
| Ω_1   | 1^- | 2699  | 2698    | 2675  | 2718  | 2698  | 6056  | 6034  | 6081  | 6065  |       |
| Ω_1   | 1^- | 3159  | 3195    | 3152  | 3065  |       | 6479  | 6504  | 6472  | 6440  |       |
| Ω_1   | 1^- | 3035  | 3005    | 2977  | 3020  |       | 6340  | 6319  | 6301  | 6352  |       |
| Ω_1   | 1^- | 3125  | 3075    |       | 3371  |       | 6458  | 6414  |       | 6624  |       |
| Ω_1   | 3^- | 2767  | 2768    | 2750  | 2776  | 2768  | 6079  | 6069  | 6102  | 6088  |       |
| Ω_1   | 3^- | 3202  | 3235    | 3190  | 3119  |       | 6493  | 6519  | 6478  | 6518  |       |

Heavy hadrons are theoretically desirable because they will serve to test the reliability of approximate techniques: heavy quark mass expansions, variational calculations, or quark-diquark approximations.

We have solved the Schrödinger equation by the Faddeev method in momentum space with the constituent quark model (CQC) of Ref. [2]. The results are shown in Table 1 compared to experiment and other theoretical approaches. All known experimental data are nicely described. Such an agreement and the exact method used to solve the three-body problem make our predictions also valuable as a guideline to experimentalists.

As compared to other results in the literature we see an overall agreement for the low-lying states both with the quark-diquark approximation of Ref. [5] and the variational calculation in a harmonic oscillator basis of Ref. [4]. It is worth noticing that the relativistic quark-diquark approximation and the harmonic oscillator variational method predict a lower 3^=2^- excited state for the Λ_b baryon. Such result can be easily under-
TABLE 2. Masses, in MeV, of different bottom baryons with two-light quarks with (Full) and without ($V_\pi = 0$) the contribution of the one-pion exchange potential.

| State | Full | $V_\pi = 0$ | $\Delta E$ |
|-------|------|-------------|------------|
| $\Sigma_b (1=2^+)$ | 5807 | 5822 | 15 |
| $\Sigma_b (3=2^+)$ | 5829 | 5844 | 15 |
| $\Lambda_b (1=2^+)$ | 5624 | 5819 | 195 |
| $\Lambda_b (3=2^+)$ | 6388 | 6387 | 1 |

stood by looking at Table 2 where it is made manifest the influence of the pseudoscalar interaction between the light quarks on the $\Lambda_b (1=2^+)$ ground state, diminishing its mass by 200 MeV. If this attraction were not present for the $\Lambda_b (1=2^+)$, the $\Lambda_b (3=2^+)$ it would be lower in mass as reported in Refs. [4, 5] (a similar effect will be observed in the charmed baryon spectra). Thus, the measurement and identification of the $\Lambda_b (3=2^+)$ is a relevant feature that will help to clarify the nature of the interaction between the light quarks in heavy baryon spectroscopy, determining the need of pseudoscalar forces consequence of the spontaneous chiral symmetry breaking in the light flavor sector.

In the case of charmed baryons, there are some excited states that it is not even known if they are excitations of the $\Lambda_c$ or $\Sigma_c$. Besides, a number of new $\Xi_c^+$ and $\Xi_c^+$ states have been also discovered recently [2]. As can be seen all known experimental states fit nicely into the description of our model not leaving too many possibilities open for the assigned quantum numbers as we resume in Table 3.

Finally, we can make parameter free predictions for ground states as well as for spin, orbital and radial excitation of doubly charmed and bottom baryons. Our results are shown in Table 4. For doubly charmed baryons, the ground state is found to be at 3579 MeV, far below the result of Ref. [4] and in perfect agreement with lattice nonrelativistic QCD [6], but still a little bit higher than the non-confirmed SELEX result, 3519 MeV [7].

TABLE 3. Possible model states and spin-parity assignments for recently discovered charmed baryons. The 'star' indicates radial excitations.

| Experimental resonance (MeV) | Model states |
|-----------------------------|--------------|
| $\Lambda_c$ or $\Sigma_c$   |              |
| 2765                        | $\Sigma_c (1=2^+)$ or $\Lambda_c (1=2^+)$ |
| 2880                        | $\Lambda_c (1=2^+)$ or $\Lambda_c (5=2^+)$ |
| 2940                        | $\Sigma_c (3=2^+)$ |
| 2800                        | $\Sigma_c (3=2^+)$ |

| $\Xi_c$ or $\Xi_c^+$       |              |
| 3055                        | $\Xi_c (5=2^+)$ |
| 3123                        | $\Xi_c (1=2^+)$ or $\Xi_c^+(5=2^+)$ |
| 2980                        | $\Xi_c (1=2^+)$ |
| 3076                        | $\Xi_c (3=2^+)$ |
TABLE 4. Ground state and excitation energies, $\Delta E$, of doubly charmed and bottom baryons. The 'star' indicates radial excitations. Masses are in MeV.

| State | $J^P$ | CQC | [8] | [3] | [6] | [4] |
|-------|------|-----|-----|-----|-----|-----|
| $\Xi_{bb}$ | 1=2 $^+$ | 10189 | 10340 | 10194 | 10340 |
| $\Delta E$ | 3=2 $^+$ | 29 | 30 | 41 | 20 | 27 |
| $\Xi_{bb}$ | 3=2 $^+$ | 312 | 386 | 238 |
| $\Delta E$ | 1=2 $^+$ | 293 | 355 | 236 |
| $\Xi_{bb}$ | 1=2 | 217 | 262 | 153 |
| $\Omega_{bb}$ | 1=2 | 423 | 462 | 370 |
| $\Xi_{cc}$ | 1=2 $^+$ | 10293 | 10370 | 10267 | 10454 |
| $\Delta E$ | 3=2 $^+$ | 28 | 30 | 38 | 19 | 32 |
| $\Xi_{cc}$ | 3=2 $^+$ | 329 | 383 | 267 |
| $\Delta E$ | 1=2 $^+$ | 311 | 359 | 239 |
| $\Xi_{cc}$ | 1=2 | 226 | 265 | 162 |
| $\Omega_{cc}$ | 1=2 | 390 | 410 | 309 |
| $\Omega_{cc}$ | 1=2 | 3579 | 3660 | 3587 | 3588 | 3676 |
| $\Delta E$ | 3=2 $^+$ | 77 | 80 | 93 | 70 | 77 |
| $\Omega_{cc}$ | 3=2 $^+$ | 446 | 486 | 366 |
| $\Delta E$ | 1=2 $^+$ | 397 | 435 | 353 |
| $\Omega_{cc}$ | 1=2 | 301 | 314 | 234 |
| $\Delta E$ | 1=2 | 439 | 472 | 398 |

It is therefore a challenge for experimentalists to confirm or to find the ground state of doubly charmed and bottom baryons.

The combined study of $Qqq$ and $QQq$ systems, where $Q$ stands for a heavy $c$ or $b$ quark and $q$ for a light $u$, $d$, or $s$ quark, will also provide some hints to learn about the basic dynamics governing the interaction between light quarks. The interaction between pairs of quarks containing a heavy quark $Q$ is driven by the perturbative one-gluon exchange. For the $Qqq$ system the mass difference between members of the $6_F$ SU(3) representation comes determined only by the perturbative one-gluon exchange, whether between members of the $6_F$ and $\bar{3}_F$ representations it presents contributions from the one-gluon exchange and also possible pseudoscalar exchanges. If the latter mass difference is attributed only to the one-gluon exchange (this would be the case of models based only on the perturbative one-gluon exchange), it will be strengthened as compared to models considering pseudoscalar potentials at the level of quarks, where a weaker one-gluon exchange will play the role. When moving to the $QQq$ systems
only one-gluon exchange interactions between the quarks will survive, with the strength determined in the $Qqq$ sector, where we have experimental data. This will give rise to larger masses for the ground states, due to the more attractive one-gluon exchange potential in the $Qqq$ sector, what requires larger constituent quark masses to reproduce the experimental data. This could be the reason for the larger masses of ground state doubly heavy baryons obtained with gluon-based interacting potentials \[4, 9\].

**LIGHT BARYONS**

In the Particle Data Group (PDG) book \[10\] the light-quark ($u$ and $d$) baryon spectrum is composed of forty resonances rated from one ( ) to four ( ) stars. The PDG average–mass region below 1950 MeV contains mostly four–star (well established) resonances, fourteen out of twenty three, the same being true for the $\Lambda$ strange sector, eight out of eleven. This makes this mass region the most suitable for testing any spectroscopic quark model. From the pioneering Isgur and Karl's non-relativistic quark model in the late 70's \[11\] more refined spectroscopic quark models for baryons, based on two-body interactions, have been developed \[12\]. We will refer to them as two-body quark models and we shall denote them generically as $3q^2_b$. As an overall result the masses of the fourteen four-star resonances, most times with the exception of $N_{P11}$ (1440), are rather well predicted ( 100 MeV difference with the PDG average value) by these models. Regarding the five three-star (likely to certain existence) resonances, the situation is much less favorable since the masses of two of them, $\Delta_{P33}$ (1600) and $\Delta_{D35}$ (1930); are generally overpredicted, up to 250 MeV above the PDG average value. Let us note that a similar discrepancy is observed for $\Delta_{S31}$ (1900) ( up to 100 MeV difference with the PDG average value) which can be related to $\Delta_{D35}$ (1930) as we shall show, and for $\Delta_{P31}$ (1750) ( up to 200 MeV above the PDG average). In the strange $\Lambda$ sector an outstanding overpredicted (by 80 150 MeV) state is the $\Lambda_{S01}$ (1405). Henceforth we shall call anomalies these significantly overpredicted mass resonances.

We carry out a general analysis of the anomalies: we identify them and we propose a plausible physical mechanism to give correctly account of their masses. Among the anomalies we find large-energy-step anomalies, that correspond either to radial excitations as the $\Delta_{P33}$ (1600) and the $N_{P21}$ (1440) or quark Pauli blocking induced states as the $\Delta_{D35}$ (1930) and the $\Delta_{P31}$ (1750) \[12\].

Given the large radial excitation energy and the large mass predicted for quark Pauli blocking induced states, one may wonder about the possibility that $4q\bar{q}$ components may be energetically competitive, despite the extra quark and antiquark masses. Thus, they could greatly contribute, altogether with $3q$ components, to the formation of the bound structures. In order to examine this possibility at a phenomenological level we look for $4q\bar{q}$ components in the form of inelastic meson-baryon channels in relative $S$ wave (the lowest energy partial wave) with adequate quantum numbers to couple to the anomalies and with thresholds close above their PDG masses. We shall name these components meson-baryon threshold channels or $mB$ channels.

Certainly meson-baryon channel coupling effects may be at work for other resonances not involving either large energy excitation steps or a large mass induced by quark Pauli blocking. The most prominent examples are the $\Lambda_{S01}$ (1405) being mostly interpreted, at
the hadron level, as an S wave $\pi N K$ quasi-bound system, and the $\Delta F_{35}(2000)$, a bizarre state since its average mass is obtained from three different data analyses, two of them [13] reporting a mass about 1720 MeV and the other [14] giving a quite different value of 2200 MeV. Then by considering two differentiated resonances the $\Delta F_{35}(1720)$ would be a clear candidate for an anomaly.

To go beyond the qualitative analysis of the anomalies we shall consider a system of one confined channel, the $3q^{2b}$, in interaction with one free-channel, a meson-baryon threshold channel $mB$, with a hamiltonian matrix:

$$[H]^* = \begin{pmatrix} M_m + M_B & a \\ a & M_{3q^{2b}} \end{pmatrix}$$

where $M_{3q^{2b}}$ stands for the mass of the $3q^{2b}$ state, $M_m$ and $M_B$ for the masses of the meson and baryon respectively and $a$ for a fitting parameter giving account of the interaction.

In order to proceed to calculate the eigenvalues we have to choose a particular $3q^{2b}$ model and establish a criterion for the choice of the $mB$ channel for each anomaly. We shall use as $M_{3q^{2b}}$ the values calculated in Ref. [9]. As $mB$ we shall take for granted the $\pi K$ channel for $\Delta_{S_{01}}(1405)$ and the $\sigma N$ channel for $N_{P_{11}}(1440)$. For $\Delta_{D_{33}}(1930)$; $\Delta_{D_{33}}(1940)$ and $\Delta_{S_{31}}(1900)$ we shall select $\rho \Delta$ (equivalently we could have preferred the almost degenerate $\omega \Delta$) as suggested by our phenomenological analysis. For the same reason $\pi N_{D_{15}}(1675)$ will be employed for $\Delta F_{35}(1720)$: For $\Delta_{P_{31}}(1750)$ we shall use $\pi N_{S_{11}}(1650)$ and for $\Delta_{P_{33}}(1600)$ we shall take $\pi N_{P_{33}}(1520)$.

Although the value of $\hat{\mu}$ might vary depending on the configurations involved in each $(mB)\ 3q$ coupling we shall use for the sake of simplicity the same value in all cases. The $M$ results for $\hat{\mu}$= 85 MeV are numerically detailed in Table [5] where the values for $M_{3q^{2b}}$ and for $(M_m + M_B)$ in the chosen $mB$ channel as well as their probabilities to give $M$ are also displayed. As can be checked the improvement of the description with respect to $3q^{2b}$ is astonishing. All the predicted $M$ masses lye very close to the PDG average masses for the anomalies. In Fig. 1 the $M$ values for $\hat{\mu}$= 85 MeV are drawn as compared to the experimental mass intervals.

| PDG Resonance | $mB$ threshold | Prob. | $3q^{2b}$ Prob. | $M$ | Experiment |
|---------------|----------------|-------|----------------|-----|------------|
| $\Delta_{P_{31}}(1600)$ | $[\pi N_{S_{11}}(1520)] (1660)$ | 81.1% | 1795 | 18.9% | 1619 | 1550–1700 |
| $N_{P_{11}}(1440)$ | $[\sigma N](1540)$ | 50.0% | 1540 | 50.0% | 1455 | 1420–1470 |
| $\Delta_{D_{33}}(1930)$ | $[\rho \Delta](2002)$ | 83.4% | 2155 | 16.6% | 1960 | 1900–2020 |
| $\Delta_{S_{31}}(1900)$ | $[\rho \Delta](2002)$ | 82.2% | 2145 | 17.8% | 1962 | 1840–2040 |
| $\Delta_{P_{31}}(1750)$ | $[\pi N_{S_{11}}(1650)] (1790)$ | 62.8% | 1835 | 37.2% | 1725 | 1710–1780 |
| $\Delta_{F_{35}}(1720)$ | $[\pi N_{D_{13}}(1675)] (1815)$ | 74.4% | 1910 | 25.6% | 1765 | 1660–1785 |
| $\Delta_{S_{01}}(1405)$ | $K N$ | 78.2% | 1550 | 21.8% | 1389 | 1400–1410 |
We interpret these results as providing strong quantitative support to our former qualitative description of the anomalies. Regarding their nature a look at the probabilities reveal they are mostly meson-baryon states. Actually a meson-baryon probability greater or equal than 50% can serve as a criterion to identify an anomaly. Nonetheless the coupling to the $3q$ component is essential to lower their masses making them more stable against decay into $m + B$.

It should be emphasized that similar results could be obtained for any other spectroscopic $3q^2b$ model through a fine tuning of the value of $\mathcal{g}_j$ (note that the small value of $\mathcal{g}_j$ as compared to $M_{3q^2b}$ and $(M_m + M_B)$ provides an a posteriori validation of our method): This comes from the expression of the eigenvalues where it is clear that even for $\mathcal{g}_j = 0$ one gets $M = M_m + M_B$ which according to our $mB$ choice is much closer to the PDG mass of the anomaly than $M_{3q^2b}$. This means that concerning the mass of the anomalies the coupling of meson-baryon to $3q$ components may play the role of a general healing mechanism for spectroscopic models.

**SUMMARY**

We have studied the heavy baryon spectra by means of the Faddeev method in momentum space. These results should be highly valuable both from the theoretical and experimental points of view. Theoretically, it should be a powerful tool for testing different
approximate methods to solve the three-body problem. Experimentally, the remarkable agreement with known experimental data make our predictions highly valuable as a guideline to experimentalists.

Heavy baryons constitute an extremely interesting problem joining the dynamics of light-light and heavy-light subsystems in an amazing manner. While the mass difference between members of the same SU(3) configuration, either $\bar{3}_F$ or $6_F$, is determined by the perturbative one-gluon exchange, the mass difference between members of different representations comes mainly determined by the dynamics of the light diquark, and should therefore be determined in consistency with the light baryon spectra. There is therefore a remnant effect of pseudoscalar forces in the two-light quark subsystem.

For light baryons we propose that $4q1\bar{q}$ components, in the form of $S$ wave meson-baryon channels which we identify, play an essential role in the description of the anomalies, say baryon resonances very significantly overpredicted by three-quark models based on two-body interactions. As a matter of fact by considering a simplified description of the anomalies as systems composed of a free meson-baryon channel interacting with a three-quark confined component we have shown they could correspond mostly to meson-baryon states but with a non-negligible $3q$ state probability which makes their masses to be below the meson-baryon threshold. The remarkable agreement of our results with data in all cases suggests the implementation of meson-baryon threshold effects as an essential physical mechanism to give account of spectral states poorly described by constituent quark models.

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