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NEW HADRONS WITH HEAVY QUARKS*

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We discuss several highly accurate theoretical predictions for masses of baryons containing the b quark which have been recently confirmed by experimental data. Proper treatment of the color-magnetic hyperfine interaction in QCD is crucial for obtaining these results. Several predictions are given for additional properties of heavy baryons. We also discuss the two charged exotic resonances Z_b with quantum numbers of a $(b\bar{b}u\bar{d})$ tetraquark, very recently reported by Belle in the channel $[\Upsilon(nS)\pi^+,\ n = 1,2,3]$. Among possible implications are deeply bound $I=0$ counterparts of the Z_b's and existence of a $\Sigma_b^+\Sigma_b^-$ dibaryon, a *beauteron*.

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1. Introduction

QCD describes hadrons as valence quarks in a sea of gluons and $\bar{q}q$ pairs. At distances above ~ 1 GeV^{-1} quarks acquire an effective *constituent mass* due to chiral symmetry breaking. In the zeroth-order approximation, the hadron mass M is then given by the sum of the masses of its constituent

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quarks m_i, $M = \sum_i m_i$. The binding and kinetic energies are "swallowed" by the constituent quarks masses. The first and most important correction comes from the color hyper-fine chromo-magnetic interaction (HFI)

$$M = \sum_i m_i + v_0 \left(\vec{\lambda}_i \cdot \vec{\lambda}_j\right) \frac{\vec{\sigma}_i \cdot \vec{\sigma}_j}{m_i m_j} \langle\psi|\delta(r_i - r_j)|\psi\rangle \,, \tag{1}$$

where v_0 fixes the overall strength, $\vec{\lambda}_{i,j}$ are the SU(3) color matrices, $\sigma_{i,j}$ are the quark spin operators and $|\psi\rangle$ is the hadron wave function. This contact spin–spin interaction is analogous to the EM hyperfine interaction, but is proportional to the product of the chromo-magnetic moments. Treating the HFI as a perturbation which does not modify the wave function and using the same quark masses inside mesons and baryons leads to many accurate predictions of hadron masses and magnetic moments. Still, the low-energy phenomenological model awaits a more solid QCD underpinning.

2. Effective masses of quarks

Differences of constituent ($\equiv$ *effective*) masses of quarks depend strongly on the flavor of the spectator or "neighbor" quark [1], *e.g.* $m_s - m_d \approx 180$ MeV when the spectator is u or d, but only ~ 90 MeV for b. The large size of the shift is surprising and its quantitative derivation from QCD is still an outstanding challenge for theory.

We can extract the ratio of the constituent quark masses from the ratio of the hyperfine splittings in the corresponding mesons

$$\frac{M(K^*) - M(K)}{M(D^*) - M(D)} \approx \frac{m_c}{m_s} \,. \tag{2}$$

We can extend relation (2) to baryons and compare the quark mass ratio obtained from mesons and baryons:

$$(m_c/m_s) = (M_{\Sigma^*} - M_\Sigma)/(M_{\Sigma_c^*} - M_{\Sigma_c}) = 2.84_{\mathrm{Bar}} \approx (M_{K^*} - M_K)/(M_{D^*} - M_D) = 2.81_{\mathrm{Mes}} \,,$$

$$(m_c/m_u) = (M_\Delta - M_p)/(M_{\Sigma_c^*} - M_{\Sigma_c}) = 4.36_{\mathrm{Bar}} \approx (M_\rho - M_\pi)/(M_{D^*} - M_D) = 4.46_{\mathrm{Mes}} \,.$$

We find the same value from mesons and baryons $\pm 2\%$. With more flavors there are additional meson/baryon mass relations, leading to a prediction for splitting between Σ_b and Λ_b

$$\frac{M_{\Sigma_b} - M_{\Lambda_b}}{M_\Sigma - M_\Lambda} = \frac{(M_\rho - M_\pi) - (M_{B^*} - M_B)}{(M_\rho - M_\pi) - (M_{K^*} - M_K)} = 2.51 \tag{3}$$

which yields $M(\Sigma_b) - M(\Lambda_b) = 194$ MeV [1, 2], later measured by CDF [3], with isospin-averaged mass difference $M(\Sigma_b) - M(\Lambda_b) = 192$ MeV. There is also the prediction for the spin splittings, $M(\Sigma_b^*)-M(\Sigma_b) = 22$ MeV, *versus* 21 MeV from the experiment [3]. The challenge is to derive from QCD the very simple model of hadronic structure at low energies which leads to such accurate predictions.

3. Magnetic moments of heavy quark baryons

In Λ, Λ_c and Λ_b baryons the light quarks are coupled to spin zero, so their magnetic moments are determined by the magnetic moments of the s, c and b quarks, respectively. The latter are proportional to the chromomagnetic moments which determine the hyperfine splitting in baryon spectra. We can use this to predict the Λ_c and Λ_b baryon magnetic moments by relating them to the hyperfine splittings, as was done for the μ_Λ in Ref. [5]

$$\mu_{\Lambda_c} = -2\mu_\Lambda \frac{M_{\Sigma_c^*} - M_{\Sigma_c}}{M_{\Sigma^*} - M_\Sigma} = -0.43 \text{ n.m.}\,; \quad \mu_{\Lambda_b} = \mu_\Lambda \frac{M_{\Sigma_b^*} - M_{\Sigma_b}}{M_{\Sigma^*} - M_\Sigma} = -0.067 \text{ n.m.} \tag{4}$$

We hope these observables can be measured in foreseeable future and view the predictions (4) as a challenge for the experimental community.

4. Predicting the masses of *b*-baryons

$\boldsymbol{\Xi_b}$ and $\boldsymbol{\Omega_b}$ masses: The Ξ_b (bsq) and Ω_b (bss) are analogues of the above-discussed Σ_b (bqq). In the ground state of Ξ_b, the (sq) diquark has spin zero. Consequently, the Ξ_b mass is given by: $\Xi_b = m_b + m_s + m_u - 3v\langle\delta(r_{us})\rangle/m_u m_s$ and can be predicted from the Ξ_c mass from the mass differences and HFI

$$\Xi_b = \Xi_c + (m_b - m_c) - 3v\left(\langle\delta(r_{us})\rangle_{\Xi_b} - \langle\delta(r_{us})\rangle_{\Xi_c}\right)/(m_u m_s)\,. \tag{5}$$

Since the Ξ_b and Ξ_c baryons contain a strange quark, the optimal estimate of $(m_b - m_c)$ comes from mesons which contain both s and b or c quarks: $m_b - m_c = \frac{1}{4}(3B_s^* + B_s) - \frac{1}{4}(3D_s^* + D_s) = 3324.6 \pm 1.4$ MeV, yielding the prediction [7] $M(\Xi_b) = 5795 \pm 5$ MeV, soon confirmed by CDF [9], $M(\Xi_b) = 5792.9 \pm 2.5 \pm 1.7$ MeV, following up on an earlier D0 measurement, $M(\Xi_b) = 5774 \pm 11 \pm 15$ MeV [8]. Later, CDF discovered Ξ_b^0, *i.e.* (usb) with mass $5787.8 \pm 5.0(\text{stat.}) \pm 1.3(\text{sys.})$ MeV [10], to be compared with our prediction 5786.7 ± 3.0 MeV. In early 2012, LHCb provided an independent measurement of Ξ_b^- mass: $5796.5 \pm 1.2 \pm 1.2$ MeV [11], in excellent agreement with CDF and with our prediction.

In 2012, CMS discovered a new, excited Ξ_b baryon of mass $5945.0 \pm 0.7(\text{stat.}) \pm 0.3(\text{sys.}) \pm 2.7(\text{PDG})$ MeV, decaying into $\Xi_b^-\pi^+$ [12]. *A priori*, there are two excited Ξ_b states: one is called Ξ_b' and has spin 1/2 with qs

coupled to spin 1. The other is called Ξ_b^* and has spin 3/2. CMS has not measured the spin of the excited Ξ_b baryon, but still identified it as Ξ_b^*, since according to theory Ξ_b' lies below the $\Xi_b^- \pi^+$ threshold. The mass of Ξ_b^* is close to our prediction 5959 ± 4 MeV [13].

For the spin-averaged Ω_b mass, we have

$$\frac{2M(\Omega_b^*)+M(\Omega_b)}{3} = \frac{2M(\Omega_c^*)+M(\Omega_c)}{3} + (m_b - m_c)_{B_s - D_s} = 6068.9 \pm 2.4 \text{ MeV} . \tag{6}$$

And for the HF splitting, we obtain

$$M(\Omega_b^*) - M(\Omega_b) = (M(\Omega_c^*) - M(\Omega_c)) \frac{m_c}{m_b} \frac{\langle \delta(r_{bs}) \rangle_{\Omega_b}}{\langle \delta(r_{cs}) \rangle_{\Omega_c}} = 30.7 \pm 1.3 \text{ MeV} \tag{7}$$

leading to the following predictions [13]:

$$M(\Omega_b) = 6052.1 \pm 5.6 \text{ MeV} ; \qquad M(\Omega_b^*) = 6082.8 \pm 5.6 \text{ MeV} . \tag{8}$$

The D0 Collaboration published the first measurement of the Ω_b mass [14]: $M(\Omega_b)_{\mathrm{D0}} = 6165 \pm 10(\text{stat.}) \pm 13(\text{syst.})$ MeV deviating from our prediction by 113 MeV. Fortunately, later CDF found [15]: $M(\Omega_b)_{\mathrm{CDF}} = 6054 \pm 6.8(\text{stat.}) \pm 0.9(\text{syst.})$ MeV, recently confirmed by LHCb [11]: $M(\Omega_b)_{\mathrm{LHCb}} = 6050.3 \pm 4.5 \pm 2.2$ MeV. Figure 1 shows a comparison of our predictions for the masses of Σ_b, Ξ_b and Ω_b baryons with the experimental data from CDF, LHCb and CMS. Additional predictions can be found in Ref. [7, 13].

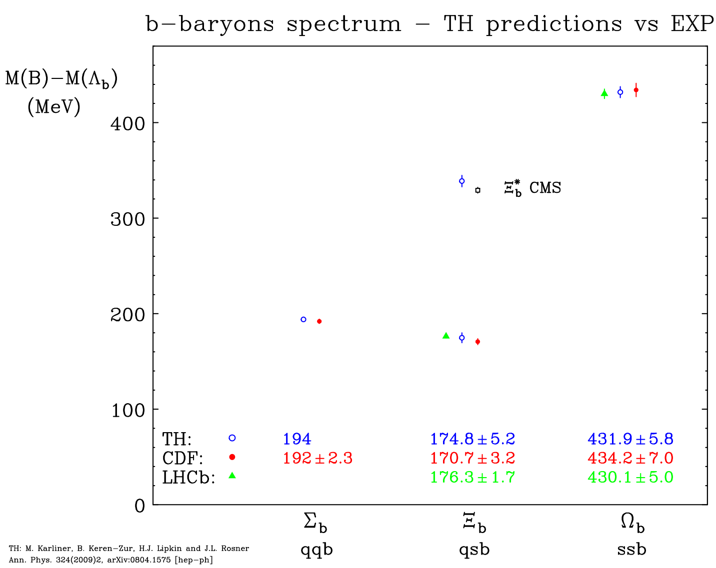

Fig. 1. Masses of b-baryons — theoretical predictions [7, 13] *versus* experiment.

The prediction $M(\Sigma_b^*) - M(\Sigma_b) < M(\Omega_b^*) - M(\Omega_b)$ appears to be counterintuitive, since HFI $\sim 1/m_q$. This is also seen in the charm data, $M(\Sigma_c^*) - M(\Sigma_c) = 64.3 \pm 0.5$ MeV $< M(\Omega_c^*) - M(\Omega_c) = 70.8 \pm 1.5$ MeV, and is not predicted by other recent approaches [16–18].

5. Heavy exotics

Exotic hadrons such as $q\bar{q}q\bar{q}$ or $q\bar{q}Q\bar{Q}$ tetraquarks, *etc.*, can have novel color structures that are completely absent in ordinary mesons and baryons [19]. Until May 2011, the leading candidate for a non $\bar{Q}Q$ exotic state has been the $X(3872)$, which is most likely either a $c\bar{c}q\bar{q}$ or a threshold bound state of D and $\bar{D}^*$.

General considerations suggest that the analogue $c \to b$ states should be more strongly bound, since the kinetic energy $\sim \frac{1}{2}p^2/m_Q$ is smaller. We have, therefore, suggested that $b\bar{b}q\bar{q}$ might be below the $B\bar{B}$ threshold and $b\bar{c}q\bar{q}$ might be below the $B\bar{D}$ threshold. Some of these states have exotic electric charge, *e.g.* $bd\bar{c}\bar{u} \to J/\psi\pi^-\pi^-$, and their decays have striking experimental signatures: monoenergetic photons and/or pions, *e.g.* $bq\bar{c}\bar{q}$ with $I = 0$ above $B_c\pi$ threshold can decay into $B_c\pi$ via isospin violation, or electromagnetically into $B_c\gamma$, keeping a very narrow state.

Hadrons containing two b quarks, such as double-bottom baryons bbq or $b\bar{b}q\bar{q}$ and $bb\bar{q}\bar{q}$ tetraquarks have a unique and a spectacular decay mode with two J/ψ's in the final state. It is mediated by both b quarks decaying via $b \to \bar{c}cs \to J/\psi s$ and yields $(bbq) \to J/\psi J/\psi(ssq) \to J/\psi J/\psi\,\Xi$, $(b\bar{b}q\bar{q}) \to J/\psi\, J/\psi(\bar{s}s\bar{q}q) \to J/\psi\, J/\psi\, K\, K$, *etc.*, with all final state hadrons coming from the same vertex. This unique signature is, however, hampered by a very low rate. It is both challenge and a opportunity for LHCb [19].

5.1. Exotic $\bar{b}b$ hadrons Z_b: theoretical prediction and discovery by Belle

In 2008, Belle reported [20] anomalously large (by two orders of magnitude) branching ratios for the decays $\Upsilon(5S) \to \Upsilon(mS)\pi^+\pi^-$, $m = 1,2$. In [21], we suggested that the enhancement is due to an intermediate state of a tetraquark $T_{\bar{b}b} = (\bar{b}bu\bar{d})$ and a pion, mediating the two-step process $\Upsilon(5S) \to T_{\bar{b}b}^{\pm}\pi^{\mp} \to \Upsilon(mS)\pi^+\pi^-$. We proposed looking for the $(\bar{b}bu\bar{d})$ tetraquark in these decays as peaks in the invariant mass of $\Upsilon(1S)\pi^+$ or $\Upsilon(2S)\pi^+$ systems. Very recently Belle Collaboration confirmed this prediction, announcing [22] the observation of two charged bottomonium-like resonances Z_b as narrow structures in $\pi^\pm\Upsilon(nS)$ $(n = 1,2,3)$ and $\pi^\pm h_b(mP)$ $(m = 1,2)$ mass spectra that are produced in association with a single charged pion in $\Upsilon(5S)$ decays. The measured masses of the two structures averaged over the five final states are $M_1 = 10608.4 \pm 2.0$ MeV,

$M_2 = 10653.2 \pm 1.5$ MeV, both with a width of about 15 MeV. Interestingly enough, the two masses M_1 and M_2 are about 3 MeV above the respective $B^*\bar{B}$ and $B^*\bar{B}^*$ thresholds.

This strongly suggests a parallel with $X(3872)$, whose mass is almost exactly at the $D^*\bar{D}$ threshold. It also raises the possibility that such states might have a complementary description as deuteron-like "molecule" of two heavy mesons quasi-bound by pion exchange [23, 24].

The attraction due to π exchange is 3 times weaker in the $I = 1$ channel than in the $I = 0$ channel. Consequently, in the charm system the $I = 1$ state is far above the $D^*\bar{D}$ threshold and only the $I = 0$ $X(3872)$ is bound by 2 MeV. In the bottom system, the attraction due to π exchange is essentially the same, but the kinetic energy is much smaller by a factor of $\sim m(B)/m(D) \approx 2.8$. Therefore, the net binding is much stronger than in the charm system. This raises two very interesting possibilities:

1. The Z_b states are virtually bound S-wave $B^*\bar{B}$ and $B^*\bar{B}^*$ states, *i.e.* states which analytically are second sheet poles just below the threshold, but which appear as standard Breit–Wigner resonances slightly above threshold, see *e.g.* [25]. The quantum numbers of these states are $I = 1$, $J^P = 1^+$. The neutral members of their isomultiplets have $C = -1$, $G = +1$.

2. Since the binding for $I = 0$ is much stronger than for $I = 1$, *we expect the $I^G = 0^+$, $J^{PC} = 1^{++}$ states to be up to 40–50 MeV <u>below</u> the thresholds* [26], close to the $\Upsilon(4S)$. Their expected decay modes are to $\Upsilon(mS)\pi^+\pi^-$, $\Upsilon(mS)\gamma$, as well as to $B\bar{B}\gamma$ via $B^* \to B\gamma$, $E_\gamma = 46$ MeV. Such processes might well be within the reach of LHCb.

5.2. A $(\Sigma_b^+\Sigma_b^-)$ beauteron dibaryon?

The discovery of the Z_b,s and their interpretation as pion-bound $B^*\bar{B}$ and $B^*\bar{B}^*$, raises an interesting possibility of a *strongly bound $\Sigma_b^+\Sigma_b^-$ deuteron-like state, <u>a beauteron</u>*. The Σ_b is about 500 MeV heavier than B^*. The $\Sigma_b\Sigma_b$ kinetic energy is, therefore, significantly smaller than that of $B\bar{B}^*$ or $B^*\bar{B}^*$. Moreover, Σ_b with $I = 1$ couples more strongly to pions than B and B^* with $I = \frac{1}{2}$. The opposite electric charges of Σ_b^+ and Σ_b^- provide an additional attraction. The heavy dibaryon bound state might be sufficiently long-lived to be observed experimentally. A possible decay mode of the beauteron is $(\Sigma_b^+\Sigma_b^-) \to \Lambda_b\Lambda_b\pi^+\pi^-$, which might be observable in LHCb. It should also be seen in lattice QCD.

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