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Spectroscopy of heavy baryons*

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Abstract. We report first results from a study of heavy-baryon spectroscopy within a relativistic constituent-quark model whose hyperfine interaction is based on Goldstone-boson-exchange dynamics.

1 Introduction

The relativistic constituent-quark model (RCQM) has become quite successful for the description of hadron properties at low energies. This is especially true for the RCQM based on Goldstone-boson-exchange (GBE) dynamics [1] with regard to baryons (for a short review see ref. [2]). So far the GBE RCQM has been restricted to baryons consisting of constituent quarks Q with flavors u, d, and s only, as it has been argued that their hyperfine interaction should be governed by GBE dynamics due to the spontaneous breaking of chiral symmetry (SBχS) of low-energy quantum chromodynamics (QCD) [3]. Regarding the other known baryons, i.e. the ones with flavors c and b, we still face the interesting questions after the light-heavy and heavy-heavy Q-Q interactions. It remains to be clarified, which kind of dynamics, gluon exchange and/or Goldstone-boson exchange, is dominant.

We have looked into these problems within the framework of the RCQM. Accepting the GBE RCQM in the $SU(3)_F$ sector, there are in principle three ways to add interactions for the light-heavy and heavy-heavy Q-Q interactions:

- employ GBE dynamics throughout,
- extend the $SU(3)_F$ GBE RCQM with one-gluon exchange (OGE) for the c and b flavors, and
- use a superposition of both the GBE and OGE hyperfine interactions beyond $SU(3)_F$.

According to our present experience the best performance of a universal RCQM for all $SU(5)_F$ baryons is achieved by the first way [4]. Here, we thus report results of a $SU(5)_F$ RCQM that is based on GBE dynamics for baryons of all five quark flavors.

* Talk delivered by J. Day

2 Theory

Our theoretical framework is relativistic quantum mechanics (RQM), which assumes a fixed number of relevant degrees of freedom and relies on an invariant mass operator $\hat{M} = \hat{M}_{\text{free}} + \hat{M}_{\text{int}}$ fulfilling all symmetry requirements of the Poincaré group. Here, the free and interaction parts of the mass operator are expressed in the rest frame of the baryon (i.e. for $\mathbf{P} = \sum_i^3 \mathbf{k}_i^2 = 0$) by

$$\hat{M}_{\text{free}} = \sum_{i=1}^{3} \sqrt{\hat{m}_i^2 + \hat{\mathbf{k}}_i^2} \,, \qquad \hat{M}_{\text{int}} = \sum_{i<j}^{3} \hat{V}_{ij} = \sum_{i<j}^{3} \left(\hat{V}_{ij}^{\text{conf}} + \hat{V}_{ij}^{\text{hf}} \right) \,, \tag{1}$$

where $\mathbf{k}_i$ represent the three-momenta of the individual quarks with rest masses m_i and the Q-Q potentials $\hat{V}_{ij}$ are composed of confinement and hyperfine interactions. By employing such a mass operator $\hat{M}^2 = \hat{P}^\mu \hat{P}_\mu$, with baryon four-momentum $\hat{P}_\mu = (\hat{H}, \hat{\mathbf{P}})$, the Poincaré algebra of all ten generators $\{\hat{H}, \hat{P}_i, \hat{J}_i, \hat{K}_i\}$, for $i = 1, 2, 3$,

$$\begin{array}{lll}
[\hat{P}_i, \hat{P}_j] = 0, & [\hat{J}_i, \hat{H}] = 0, & [\hat{P}_i, \hat{H}] = 0, \\
[\hat{K}_i, \hat{H}] = i\hat{P}_i, & [\hat{J}_i, \hat{J}_j] = i\epsilon_{ijk}\hat{J}_k, & [\hat{J}_i, \hat{K}_j] = i\epsilon_{ijk}\hat{K}_k, \\
[\hat{J}_i, \hat{P}_j] = i\epsilon_{ijk}\hat{P}_k, & [\hat{K}_i, \hat{K}_j] = -i\epsilon_{ijk}\hat{J}_k, & [\hat{K}_i, \hat{P}_j] = i\delta_{ij}\hat{H}.
\end{array}$$

is guaranteed.

3 The GBE RCQM

3.1 The $SU(3)_F$ Sector

The hyperfine interaction of the GBE RCQM for constituent quarks with flavors u, d, and s, confined by a linear potential $V_{ij}^{\text{conf}}(\mathbf{r}) = Cr$, reads

$$V^{\text{hf}}(\mathbf{r}) = \left[V_\pi(\mathbf{r}) \sum_{a=1}^{3} \lambda_i^a \lambda_j^a + V_K(\mathbf{r}) \sum_{a=4}^{7} \lambda_i^a \lambda_j^a + V_\eta(\mathbf{r}) \lambda_i^8 \lambda_j^8 + V_{\eta'}(\mathbf{r}) \lambda_i^0 \lambda_j^0 \right] \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j \,, \tag{2}$$

where $\mathbf{r}$ is the relative vector between constituent quarks i and j. The λ_i^a represent the $SU(3)_F$ Gell-Mann matrices of flavor a and the $\boldsymbol{\sigma}_i$ the $SU(2)$ Pauli spin matrices of the individual constituent quarks. The GBE is described by the exchange of the octet of pseudoscalar mesons π, K, and η, where due to the $U(1)$ anomaly also the singlet exchange η' is added. The corresponding regularized meson-exchange potentials, derived in instantaneous approximation, are expressed by

$$V_\gamma(\mathbf{r}) = \frac{g_\gamma^2}{2\pi} \frac{1}{12 m_i m_j} \left[\mu_\gamma^2 \frac{e^{-\mu_\gamma r}}{r} - \Lambda_\gamma^2 \frac{e^{-\Lambda_\gamma r}}{r} \right] \,, \qquad \gamma = \pi, K, \eta, \eta' \,, \tag{3}$$

with g_γ the quark-meson coupling constant, μ_γ the exchanged meson mass, and Λ_γ a cut-off parameter. The complete parameterization of the GBE RCQM can be found in ref. [1]. An extended version of it, including beyond spin-spin forces also all other interaction components stemming from GBE dynamics, was published in ref. [5].

3.2 Generalization to $SU(5)_F$

In the spirit of the ansatz (3) we have generalized the GBE RCQM to $SU(5)_F$ in order to cover also heavy baryons, containing the flavors c and b, in a universal model. Keeping the confinement potential unaltered, the extended hyperfine interaction is proposed to be

$$V^{hf}(\mathbf{r}) = \Big[V_\pi(\mathbf{r}) \sum_{a=1}^{3} \lambda_i^a \lambda_j^a + V_K(\mathbf{r}) \sum_{a=4}^{7} \lambda_i^a \lambda_j^a + V_{\eta_8}(\mathbf{r}) \lambda_i^8 \lambda_j^8 + \frac{2}{5} V_{\eta_0}(\mathbf{r}) +$$
$$V_D(\mathbf{r}) \sum_{a=9}^{12} \lambda_i^a \lambda_j^a + V_{D_s}(\mathbf{r}) \sum_{a=13}^{14} \lambda_i^a \lambda_j^a + V_{\eta_{15}}(\mathbf{r}) \lambda_i^{15} \lambda_j^{15} +$$
$$V_B(\mathbf{r}) \sum_{a=16}^{19} \lambda_i^a \lambda_j^a + V_{B_s}(\mathbf{r}) \sum_{a=20}^{21} \lambda_i^a \lambda_j^a + V_{B_c}(\mathbf{r}) \sum_{a=22}^{23} \lambda_i^a \lambda_j^a +$$
$$V_{\eta_{24}}(\mathbf{r}) \lambda_i^{24} \lambda_j^{24}\Big] \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j \ .$$

It contains the GBE in $SU(5)_F$, which is represented by the exchange of the 24-plet of pseudoscalar mesons plus the singlet η_0. The various regularized meson-exchange potentials have the same functional dependence as in Eq. (3). The detailed parameterization is given in a forthcoming paper [6].

3.3 Consistency of the Universal GBE RCQM

Since $SU(3) \subset SU(4) \subset SU(5)$, the generalized GBE RCQM should perform with similar or even better success as the corresponding $SU(3)_F$ model specifically for u-, d-, and s-flavor baryons. This is not immediately obvious, as the light- and strange-baryon sectors are now influenced by an altered singlet exchange, namely, η_0 that corresponds to $SU(5)_F$ rather than to $SU(3)_F$. In addition the exchanges of η_{15} and η_{24} come into play.

We thus present in Figs. 1 and 2 first a comparison of the spectroscopy of light and strange baryons, as yielded by the original $SU(3)_F$ and the extended $SU(5)_F$ GBE RCQMs. As becomes clearly evident, the $SU(5)_F$ GBE RCQM performs equally well, in some instances even better, than the original $SU(3)_F$ one. In particular, the new model also produces the right level orderings in the N and Λ excitation spectra due to the specific flavor dependence in the hyperfine interaction in Eq. (4).

3.4 Results for Heavy-Baryon Spectra

Next we present the predictions of the $SU(5)_F$ GBE RCQM for the spectra of c- and b-flavor baryons in comparison to experimental data available for states with at least 4- or 3-star status according to the PDG (see Fig. 3). It appears that all experimental results, for which also a definite J^P is known, are reproduced quite well.

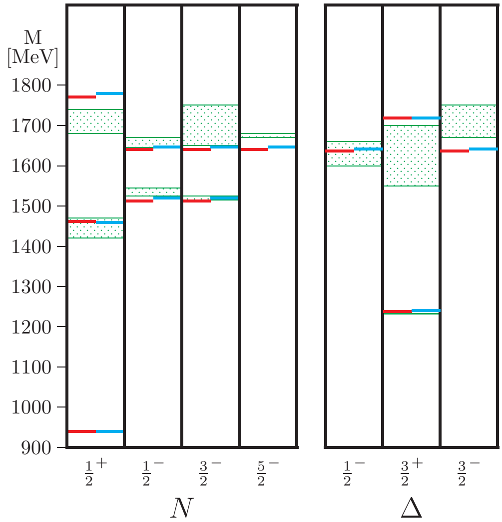

Fig. 1. N and Δ spectra of definite spin and parity J^P produced by the extended $SU(5)_F$ GBE RCQM (left/red levels) in comparison to the ones of the original $SU(3)_F$ GBE RCQM [1, 3] (right/blue levels) and to experimental data with their uncertainties (green boxes) from the PDG [7].

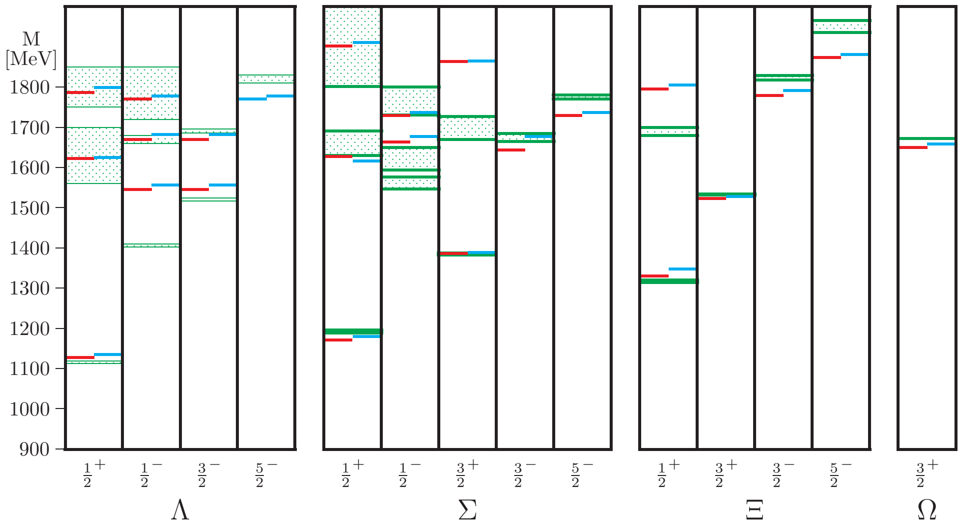

Fig. 2. Same as in Fig. 1 but for strange baryons.

In Fig. 4 we also present the predictions of the $SU(5)_F$ GBE RCQM for double-charm baryons. Here, there is only one measurement reported by the PDG, namely, the ground state of Ξ_{cc}. As can be seen from Fig. 4 and also the Table below, the theoretical level produced by the GBE RCQM remains at variance with the experimental data. For this comparison, however, one should bear in mind that the

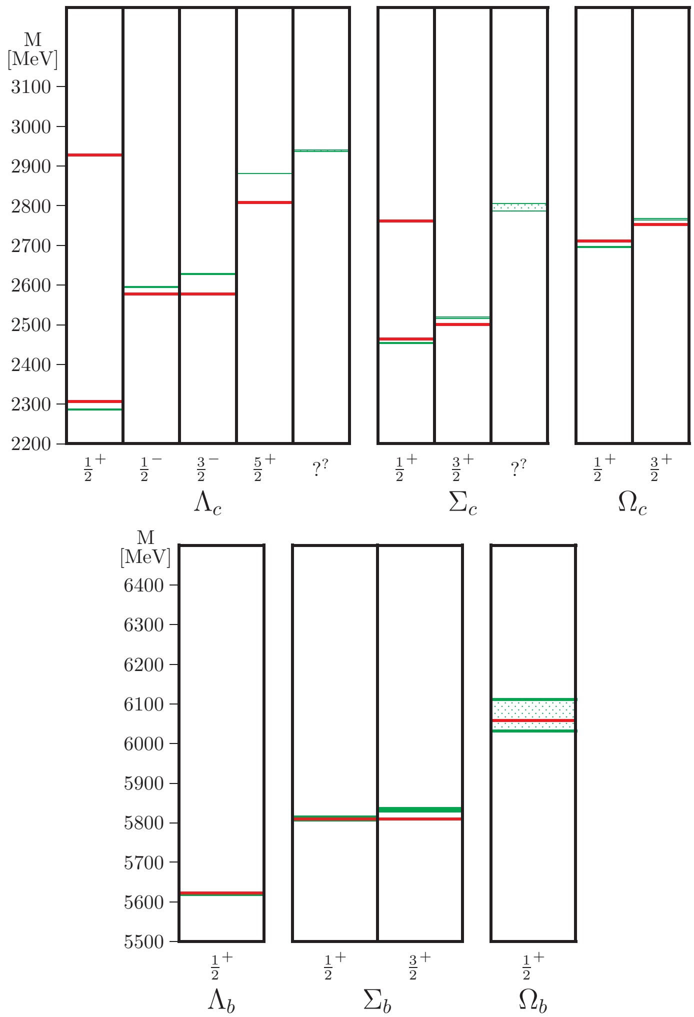

Fig. 3. Heavy-baryon spectra of definite J^P as produced by the extended $SU(5)_F$ GBE RCQM (solid/red levels) in comparison to experimental data with their uncertainties (dotted/green levels resp. boxes) reported by the PDG [7].

lowest Ξ_{cc} state with $J^P = \frac{1}{2}^+$ is only rated by 1 star by the PDG. Its measurement was only made once in 2002 by the SELEX collaboration [8], and since then has never been reproduced independently. In view of other theoretical works having investigated double-charm baryons, one may have some doubt about the measured mass of Ξ_{cc}. As is evident from the comparison in the Table below, for instance, the theoretical results from the RCQM of the Bonn group [11] and also the ones from the Bhaduri-Cohler-Nogami one-gluon-exchange model [9], reported in 2005 by Stancu and Richard [10] at the Bled Workshop, give mass values for the Ξ_{cc} ground state quite similar to the one we have achieved. Further measurements of double-charm baryons would thus be highly welcome.

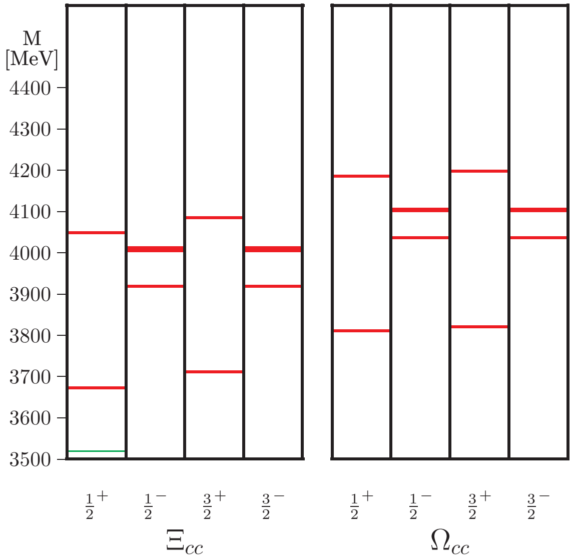

Fig. 4. Ξ_{cc} and Ω_{cc} spectra as produced by the extended $SU(5)_F$ GBE RCQM (solid/red levels) in comparison to experimental data reported only for the Ξ_{cc} ground state (dotted/green level/box) [7,8].

Baryon	J^P	Theory			Experiment [8]
		Ref. [10]	Ref. [11]	GBE RCQM	
Ξ_{cc}	$\frac{1}{2}^+$	3643	3642	3673	3518.9 ± 0.9
Ξ_{cc}	$\frac{3}{2}^+$	3724	3723	3711	-
Ξ_{cc}	$\frac{1}{2}^-$		3920	3919	-
Ξ_{cc}	$\frac{3}{2}^-$		3920	3919	-

Table 1. Comparison of the predictions by the GBE RCQM and other theoretical models for double-charm Ξ_{cc} ground and excited states vis-à-vis the experimental measurement reported by the SELEX collaboration.

4 Conclusion

We have constructed a universal RCQM for all baryons with flavors u, d, s, c, and b. It is based on a relativistically invariant mass operator describing systems of three constituent quarks, confined by a linear potential according to QCD and interacting through hyperfine forces derived from GBE. This RCQM extends the previous GBE RCQM beyond $SU(3)_F$ and reproduces the phenomenologically known spectra with reasonable accuracy. For definitely pinning down the type of hyperfine interaction especially for light-heavy and heavy-heavy Q-Q subsystems more data in the sector of c- and b-flavor baryons would be highly desirable.

In future it will be very interesting, if the universal GBE RCQM discussed here will be able to describe also reactions involving heavy baryons with a similar good performance as has previously been found for the $SU(3)$ GBE RCQM in the cases of light and strange baryons.

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References

1. L. Y. Glozman, W. Plessas, K. Varga, and R. F. Wagenbrunn, Phys. Rev. D **58**, 094030 (1998).
2. W. Plessas, PoS **LC2010**, 017 (2010); arXiv:1011.0156 [hep-ph].
3. L. Y. Glozman, Z. Papp, W. Plessas, K. Varga, and R. F. Wagenbrunn, Phys. Rev. C **57**, 3406 (1998).
4. J. P. Day, K. -S. Choi, and W. Plessas, arXiv:1108.3450 [hep-ph].
5. K. Glantschnig, R. Kainhofer, W. Plessas, B. Sengl, and R. F. Wagenbrunn, Eur. Phys. J. **A23**, 507 (2005).
6. J. P. Day, K. -S. Choi, and W. Plessas, to be published.
7. K. Nakamura *et al.* (Particle Data Group), J. Phys. G **37**, 075021 (2010).
8. M. Mattson *et al.* (SELEX Collaboration), Phys. Rev. Lett. **89**, 112001 (2002).
9. R. K. Bhaduri, L. E. Cohler, and Y. Nogami, Nuovo Cim. **A65**, 376 (1981).
10. J.-M. Richard and F. Stancu, in *Exciting Hadrons* (Proceedings of the Mini-Workshop, Bled, Slovenia, 2005), ed. by B. Golli, M. Rosina, and S. Sirca (DMFA, Zaloznistvo, Ljubljana, 2005), p. 25; [hep-ph/0511043].
11. S. Migura, D. Merten, B. Metsch, and H. -R. Petry, Eur. Phys. J. **A28**, 41 (2006).