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Universal Constituent-Quark Model for All Baryons

W. Plessas

Theoretical Physics, Institute of Physics, University of Graz, A-8010 Graz, Austria

Abstract. We discuss the performance of a relativistic constituent-quark model that has been constructed in order to provide a universal framework for the description of all known baryons. After recalling some decisive properties of light-flavor baryons we concentrate on the spectroscopy of baryons containing charm and beauty.

It has become quite evident that modern constituent-quark models serve as an effective tool for accessing quantum chromodynamics (QCD) at low energies. Essential prerequisites are the observations of Poincaré invariance and the spontaneous breaking of chiral symmetry (SBχS). A model constructed in this spirit has been presented now already 20 years ago [1,2]. It assumes constituent quarks with dynamical masses in a linear confinement according to the string tension of QCD and a hyperfine interaction deriving from Goldstone-boson exchange (GBE), where the latter is cast into pseudoscalar meson exchange. The original version covered all baryons with u, d, and s flavors. Their spectroscopy is well described in agreement with phenomenology, yielding in particular the inverse level orderings of the first positive- and negative-parity excitations of the nucleon (N), the $J^P = \frac{1}{2}^+$ Roper resonance N(1440) and the $J^P = \frac{1}{2}^-$ N(1535), respectively.

By solving the eigenvalue problem of the pertinent relativistically invariant mass operator one has beyond the eigenvalues (baryon masses) also access to the wave functions of the baryons. Thereby their structures can be tested as revealed under electromagnetic, weak, strong, and gravitational interactions. All of these types of investigations have been carried out with respect to the N over the past. The elastic N electromagnetic form factors calculated in point form - strictly observing Poincaré invariance - have immediately been found in good agreement with experimental data for momentum transfers up to $Q^2 \sim 4$ GeV^2 [3,4]. Even the detailed phenomenological insights into the flavor contents of the N electromagnetic form factors are explained correctly, advocating only $\{QQQ\}$ degrees of freedom [5,6].

Similarly, the covariant axial and induced pseudoscalar N form factors have been described in accordance with phenomenology [7,8]. By the same constituent-quark model a microscopic explanation of the strong πNN and $\pi N\Delta$ vertex form factors has been provided on the quark level [9]. It largely justifies the phenomenological parameterizations traditionally employed in dynamical models on the hadronic level. Finally the gravitational form factor $A(Q^2)$ of the N has been studied yielding results in accordance with other QCD models, see, e.g., Ref. [10].

This kind of structure studies have also been extended to baryon states other than the N, namely to all of the octet and decuplet baryon ground and some of the resonant states. Of course, in these cases comparisons to experimental data are possible only in a few cases, e.g., for electric radii and magnetic moments [4]. In general, very reasonable results have been found, largely also in good agreement with modern lattice-QCD calculations [11–14].

In view of these results it has come up as an interesting question, if the dynamics of GBE can also be extended to all quark flavors, i.e. all baryon states observed so far. This problem has been answered satisfactorily by the universal relativistic constituent-quark model (URCQM) [10, 15, 16]. It was constructed in the same spirit as its antecessor, the GBE relativistic constituent-quark model (RCQM) of Refs. [1,2], i.e. with the same linear confinement, but now with a pseudoscalar boson exchange of a 24-plet and a singlet, thereby including u, d, s, c, and b quark flavors. For the 24-plet GBE only a single mass and a single cut off had to be foreseen with the Goldstone-boson mass equal to the π mass and a π-Q coupling constant derived from the phenomenological π-N coupling constant using the Goldberger-Treiman relation. The two open parameters inherent in the singlet GBE (the η_0-Q coupling and the corresponding cut off) were adjusted by fitting the baryon spectra. For more details on the parameter values see Refs. [10] or [16].

Since the 2018 Bled Mini-Workshop concentrated on double-charm baryons, we discuss in this contribution only the description of heavy-flavor baryons by the URCQM [1]. We start with the single-charm spectra in Fig. 1. It is immediately evident that all of the ground states are well reproduced. The same is true with the experimentally established excitations. For the levels in the Λ_c and Σ_c spectra, where J^P is not definitely known, the URCQM offers nearby levels.

The spectra of the double-charm baryons are shown in Fig. 2. Until recently only for the Ξ_{cc} ground state there were experimental data available from a single experiment, namely the one by the SELEX collaboration [18]. The URCQM produces the Ξ_{cc} ground state more than 100 MeV higher than these data, precisely at 3642 MeV. Similarly, other theoretical models such as the RCQM by the Bonn group [19] (shown by the cyan lines in Fig. 2) or the lattice-QCD calculation by Liu et al. [20] (given by the magenta boxes in Fig. 2) obtain a Ξ_{cc} ground-state level by about the same magnitude higher than the SELEX value.

However, there has been a recent measurement of the Ξ_{cc} ground state by LHCb [21] yielding its mass as $m = 3621.40 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.14(\Lambda_c)$ MeV. The predictions by the URCQM as well as by the other theoretical calculations are now quite compatible with this value. It will be interesting to obtain phenomenological data also for Ξ_{cc} resonances. For the sake of future comparisons we give in Tab. 1 the predictions of the UCRQM for the first seven Ξ_{cc} excitations. We remark that certain $J = \frac{1}{2}$ and $J = \frac{3}{2}$ resonances are degenerate, the reason being that the UCRQM does not (yet) contain tensor forces in the GBE hyperfine interaction. However, as has been learned in case of the GBE RCQM, the inclusion of

[1] The light- and strange-baryon spectra of the URCQM are very similar in most cases identical to the ones of the GBE RCQM of Refs. [1, 2]; cf. also Ref. [15].

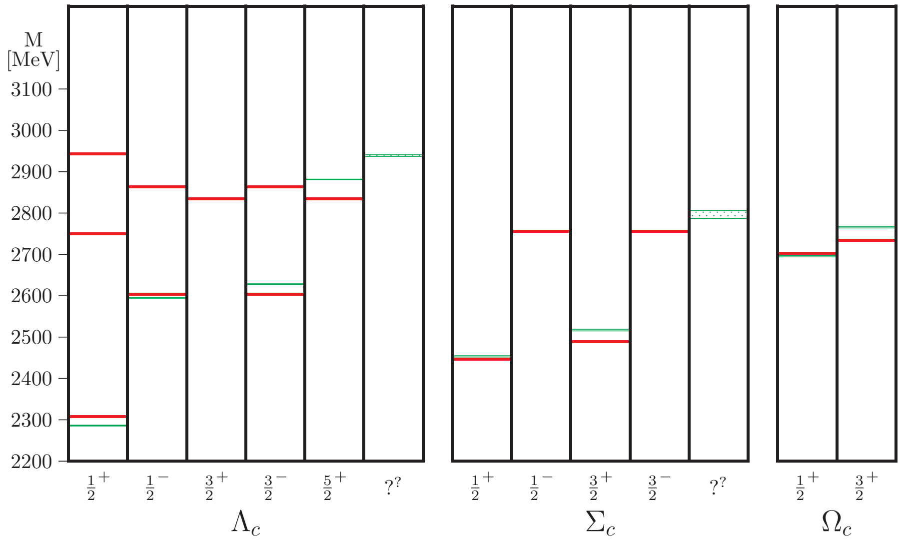

Fig. 1. Single-charm baryon spectra of definite J^P as produced by the URCQM (solid/red levels) in comparison to experimental data with their uncertainties (dotted/green levels resp. boxes) [17].

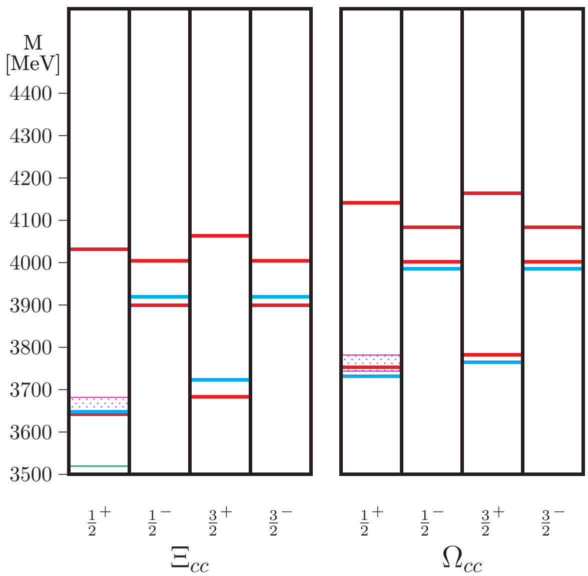

Fig. 2. Same as Fig. 1 but for double-charm baryons. The predictions of the URCQM are the solid/red levels. Here they are compared to several other theoretical results and the SELEX experiment for the Ξ_{cc} ground state (lowest/green level) [18]. For further explanations see the text.

all types of hyperfine forces from GBE does not much change the characteristics of the baryon spectra [22,23].

For completeness of the description of heavy baryons by the URCQM we add the single- and double-b baryons in Figs. 3 and 4. Only for single-b baryons we

Table 1. Ξ_{cc} ground state and its first seven excitations as predicted by the URCQM.

State	J^P	URCQM
Ξ_{cc}	$\frac{1}{2}^+$	3642
Ξ_{cc}	$\frac{3}{2}^+$	3683
Ξ_{cc}	$\frac{1}{2}^-$	3899
Ξ_{cc}	$\frac{3}{2}^-$	3899
Ξ_{cc}	$\frac{1}{2}^-$	4004
Ξ_{cc}	$\frac{3}{2}^-$	4004
Ξ_{cc}	$\frac{1}{2}^+$	4032
Ξ_{cc}	$\frac{3}{2}^+$	4064

may compare to experimental data. In all instances we find good agreement with phenomenology. In case of double-b baryons we are left only with comparisons to other effective models, where we now notice bigger discrepancies.

By the results shown here together with the ones for the light- and strange baryon sectors reported in Refs. [15] and [10] it is certainly evident that a universal relativistic constituent-quark model may be constructed solely on the basis of Goldstone-boson exchange. While beyond the given confinement all of the masses involved in the hyperfine interaction - for constituent quarks u, d, s, c, and b as well as the exchanged Goldstone bosons π and η - may be taken as predetermined, like the 24-plet coupling constant, there remain only three open fit parameters, the 24-plet as well as the singlet cut offs and the singlet coupling constant. This is certainly remarkable, like the fact that the dynamical ingredients

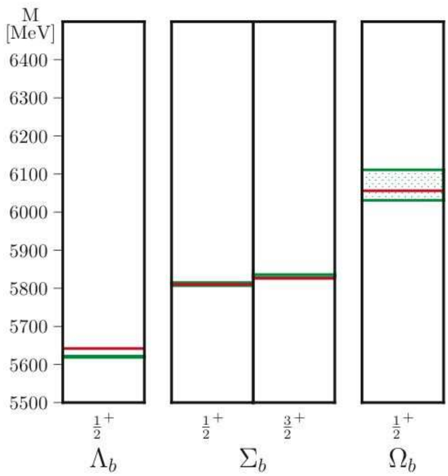

Fig. 3. Single-beauty baryon spectra of definite J^P as produced by the URCQM (solid/red levels) in comparison to experimental data with their uncertainties (dotted/green levels resp. boxes) [17].

in the constituent-quark masses (differences between the current and constituent masses) remain practically independent of the flavor [26, 27].

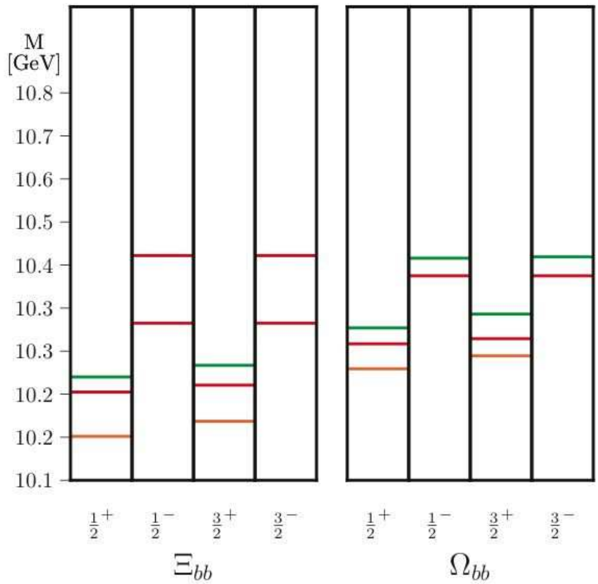

Fig. 4. Double-beauty baryon spectra of definite J^P as produced by the URCQM (solid/red levels) in comparison to a nonrelativistic one-gluon-exchange constituent-quark model by Roberts and Pervin [24] (green/higher-lying levels) and the RCQM by Ebert et al. [25] (brown/lower-lying levels).

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