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HEAVY BARYONS IN THE CHIRAL QUARK–SOLITON MODEL: A POSSIBILITY FOR EXOTICA?*

Michal Praszalowicz

M. Smoluchowski Institute of Physics, Jagiellonian University
Łojasiewicza 11, 30-348 Kraków, Poland

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We discuss possible interpretation of five excited Ω_c^0 states within the Chiral Quark–Soliton Model. We show that it is not possible to interpret all five Ω_c^0s as parity minus excitations and argue that two narrowest states are pentaquarks belonging to the SU(3) representation $\overline{15}$.

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1. Chiral Quark–Soliton Model

In this report, we summarize our recent works on heavy baryons [1–4] where we have applied the Chiral Quark–Soliton Model (χQSM) to the baryonic systems with one heavy quark. An expanded version of this report has been published in Ref. [5] where a complete list of references can be found. There are two other contributions based on [1–4] that have been already published elsewhere [6, 7].

The χQSM [8] (for review, see Ref. [9] and references therein) is based on an old argument by Witten [10] that in the limit of a large number of colors ($N_{\rm c} \to \infty$), $N_{\rm val} = N_{\rm c}$ relativistic valence quarks generate chiral mean fields represented by a distortion of a Dirac sea that, in turn, interacts with the valence quarks themselves. The soliton configuration corresponds to the solution of a pertinent Dirac equation for the constituent quarks (with gluons integrated out) in the mean-field approximation, where the mean fields respect the so-called *hedgehog* symmetry. This means that neither spin ($\boldsymbol{S}$) nor isospin ($\boldsymbol{T}$) are *good* quantum numbers. Instead, a *grand spin* $\boldsymbol{K} = \boldsymbol{S} + \boldsymbol{T}$ is a *good* quantum number. In Ref. [1], following [11], we have observed that the same argument holds for $N_{\rm val} = N_{\rm c} - 1$, which allows to replace one light valence quark by a heavy quark $Q = c$ or b.

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For light baryons, the ground state soliton configuration corresponds to the occupied $K^P = 0^+$ valence level (with $N_{\rm val} = N_{\rm c}$), as shown in Fig. 1 (a). Therefore, the soliton does not carry definite quantum numbers

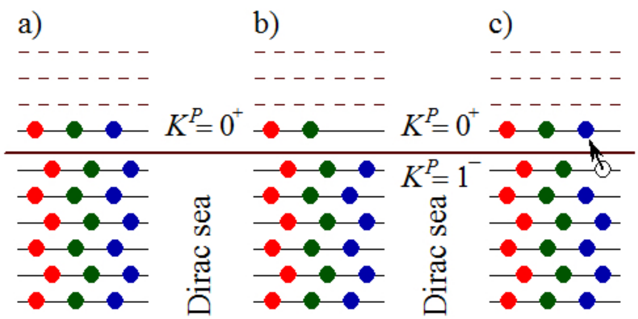

Fig. 1. Schematic pattern of light quark levels in a self-consistent soliton configuration. In the left panel, all sea levels are filled and $N_{\rm c}$ (= 3 in the figure) valence quarks occupy the $K^P = 0^+$ lowest positive energy level. Unoccupied positive energy levels are depicted by dashed lines. In the middle panel, one valence quark has been stripped off, and the soliton has to be supplemented by a heavy quark not shown in the figure. In the right panel, a possible excitation of a sea level quark, conjectured to be $K^P = 1^-$, to the valence level is shown, and again the soliton has to couple to a heavy quark. Strange quark levels that exhibit different filling pattern are not shown.

except for the baryon number resulting from the valence quarks. It is also possible that one of the valence quarks gets excited to some $K > 0$ level (see *e.g.* [12]), which influences the quantization of the soliton spin emerging when the rotations in space and flavor are quantized. The resulting *collective* Hamiltonian is analogous to the one of a symmetric top with the following constraints:

1. allowed SU(3) representations must contain states with hypercharge $Y' = N_{\rm val}/3$,

2. the isospin $\boldsymbol{T}'$ of the states with $Y' = N_{\rm val}/3$ couples with the soliton spin $\boldsymbol{J}$ to $\boldsymbol{K}$, which is 0 for the ground state configuration but may be non-zero for an excited state: $\boldsymbol{T}' + \boldsymbol{J} = \boldsymbol{K}$.

For light baryons $N_{\rm val} = N_{\rm c}$, $K^P = 0^+$, and as a result, the lowest lying positive parity baryons belong to the $\mathrm{SU(3)_{flavor}}$ octet of spin 1/2 and decuplet of spin 3/2. The first exotic representation is $\overline{\mathbf{10}}$ of spin 1/2 with the lightest state corresponding to the putative $\Theta^+(1540)$ [13]. The model has been successfully tested in the light baryon sector [9].

2. χQSM and heavy baryons

Recently [1], following Ref. [11], we have made a proposal how to generalize the above approach to heavy baryons, by stripping off one valence quark from the $K^P = 0^+$ level, as shown in Fig. 1 (b), and replacing it by a heavy quark to neutralize the color. The only difference to the previous case is the quantization condition, since $N_{\rm val} = N_{\rm c} - 1$. The lowest allowed SU(3) representations are in this case $\overline{\mathbf{3}}$ of spin 0 and $\mathbf{6}$ of spin 1 shown in Fig. 2.

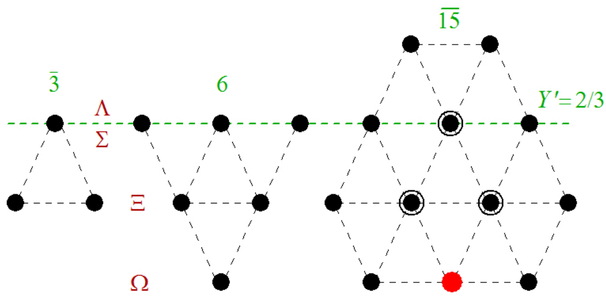

Fig. 2. (Color online) Rotational band of a soliton with one valence quark stripped off. Soliton spin corresponds to the isospin T' of states on the quantization line $Y' = 2/3$. We show three lowest allowed representations: antitriplet of spin 0, sextet of spin 1 and the lowest exotic representation $\overline{\mathbf{15}}$ of spin 1 or 0. Heavy quark has to be added.

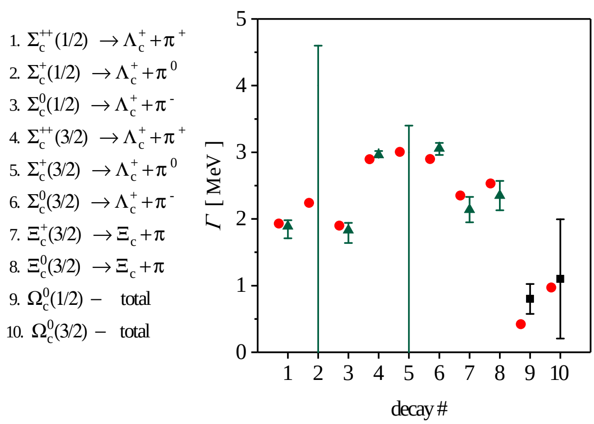

Fig. 3. (Color online) Decay widths of the charm baryons. Full circles (red) correspond to our theoretical predictions. Triangles (dark green) correspond to the experimental data [14]. Data for decays 4–6 of $\Sigma_c(\mathbf{6}_1, 3/2)$ have been divided by a factor of 5 to fit within the plot area. Widths of two LHCb [15] Ω_c states that we interpret as pentaquarks are plotted as full squares (black) with theoretical values shown as full circles (red).

As a result, both $\mathbf{6}$–$\overline{\mathbf{3}}$ splitting and the m_s splittings inside these multiplets are *predicted* using as an input the light sector spectrum [1] except for a hyperfine splitting of $\mathbf{6}$ due to the spin–spin interaction of a soliton and a heavy quark that has been parameterized phenomenologically. Moreover, we have calculated the decay widths [3], which are in surprisingly good agreement with the data (see Fig. 3 for charm baryons decay widths).

3. Excitations of heavy baryons

The χQSM allows for two kinds of excitations [2]. Firstly, higher SU(3) representations, similar to the antidecuplet in the light sector, appear in the rotational band of the soliton of Fig. 1 (b). The lowest possible exotic SU(3) representation is $\overline{\mathbf{15}}$ of positive parity and spin 1 ($\overline{\mathbf{15}}$ of spin 0 is heavier) shown in Fig. 2. Second possibility corresponds to the excitation of the sea quark from the $K^P = 1^-$ sea level to the valence level [11] depicted in Fig. 1 (b) (or, alternatively, valence quark excitation to the first excited level[1] of $K^P = 1^-$). In this case, the parity is negative but the rotational band is the same as in Fig. 2 with, however, different quantization condition, since J and T' have to couple to $K = 1$.

We have shown that the model describes well the only fully known spectrum of negative parity antitriplets of spin $1/2$ and $3/2$ [2]. There has been no experimental evidence for the sextet until recent report of five Ω_c^0 states by the LHCb [15] and later by Belle [16]. In the sextet case, the quantization condition requires the soliton spin to be quantized as $J = 0, 1$ and 2. By adding one heavy quark, we end up with five possible total spin S excitations for $J = 0$: $S = 1/2$, for $J = 1$: $S = 1/2$ and $3/2$, and for $J = 2$: $S = 3/2$ and $5/2$. Although the number of states coincides with the experimental results [15, 16], it is not possible to accommodate all five Ω_c^0 states within the constraints imposed by the χQSM [2]. We have, therefore, *forced* model constraints (note that in the $\mathbf{6}$ case, we cannot predict the mass splittings, since there is a new parameter in the splitting Hamiltonian that corresponds to the transition of Fig. 1 (c), which is not known from the light sector), which allows to accommodate only three out of five LHCb states (see black vertical lines in Fig. 4). Two heaviest χQSM states (gray vertical (green) lines in Fig. 4) lie already above the decay threshold to heavy mesons, and it is quite possible that they have very small branching ratio to the $\Xi_c^+ + K^-$ final state analyzed by the LHCb. Two remaining states indicated by arrows (dark blue) in Fig. 4, which are hyper fine split by 70 MeV (as the ground state sextets that belong to the same rotational band), can be therefore interpreted as the members of exotic $\overline{\mathbf{15}}$ of positive parity shown as a gray (red) dot in Fig. 2. This interpretation is reinforced by the decay widths,

[1] We thank Victor Petrov for pointing out this possibility.

which can be computed in the model. These widths are of the order of 1 MeV and agree with the LHCb measurement (see Fig. 3). Such small widths are, in fact, expected in the present approach, since the leading $N_{\rm c}$ terms of the relevant couplings cancel in the non-relativistic limit [4].

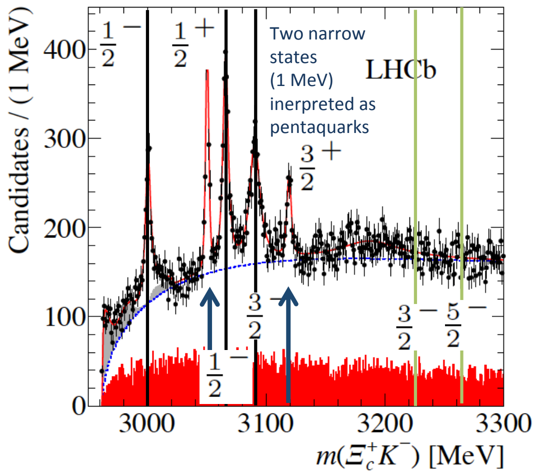

Fig. 4. (Color online) Spectrum of the Ω_c^0 states [15] with theoretical predictions of the present model.

Our identification implies the existence of the *isospin* partners of Ω_c^0 in the $\overline{\mathbf{1}5}$. They can be searched for in the mass distribution of $\Xi_c^0 + K^-$ or $\Xi_c^+ + \bar{K}^0$. Our model applies also to the bottom sector, and — where the data is available — it describes very well both masses and decay widths [1,3].

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