EXOTIC INTERPRETATION OF $\Omega_c$ EXCITED STATES

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We use the chiral quark-soliton model to interpret five excited $\Omega_c$ states recently reported by the LHCb collaboration and confirmed by Belle. We briefly recapitulate the model and its application to light baryons. We then show how the model can be extended to the case of baryons with one heavy quark. We test the model against ground state heavy baryons and then examine possible excitations. We argue that it is not possible to accommodate all five $\Omega_c$’s within five parity minus excitations predicted by the model and propose to interpret two narrowest states split by 70 MeV as pentaquarks belonging to the SU(3) representation $\overline{15}$.

1 Chiral Quark Soliton Model ($\chi$QSM)

$\chi$QSM$^1$ (for review see Ref. [2] and references therein) is based on an old argument by Witten, which says that in the limit of a large number of colors ($N_c \rightarrow \infty$), $N_c$ 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 the Dirac equation for the constituent quarks (with gluons integrated out) in the mean-field approximation, where pseudoscalar mean fields respect so called hedgehog symmetry, since it is impossible to construct a pseudoscalar field that changes sign under inversion of coordinates, which would be compatible with the SU(3)$_{flav} \times$SO(3) space symmetry. This means that neither spin ($S$) nor isospin ($T$) are good quantum numbers. Instead a grand spin $K = S + T$ is a good quantum number.

The ground state configuration corresponds to the fully occupied $K^P = 0^+$ valence level, as shown in Fig. 1.a. Therefore the soliton does not carry definite quantum numbers except for the baryon number resulting from the valence quarks. Spin and isospin appear when the rotations in space and flavor are quantized and the resulting collective hamiltonian is analogous to the one of a symmetric top. There are two conditions that the collective wave functions have to satisfy:

- allowed SU(3) representations must contain states with hypercharge $Y' = N_c/3$,
- the isospin $T'$ of the states with $Y' = N_c/3$ couples with the soliton spin $J$ to a singlet: $T' + J = 0$.

As a result, the lowest parity ($+$) baryons belong to the SU(3)$_{flavor}$ octet of spin 1/2 and decuplet of spin 3/2. The first exotic representation is $\overline{10}$ of spin 1/2 with the lightest state corresponding
Figure 1 – Schematic pattern of light quark levels in a self-consistent soliton configuration. In the left panel all sea levels are filled and $N_c (=3$ 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.

to the putative $\Theta^+$ (1540) (see e.g. Moriond proceedings $^4$ 2005). The model has been successfully tested in the light baryon sector.

2 $\chi$QSM and heavy baryons

Recently we have proposed $^5$, following Ref. [6] 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. In the large $N_c$ limit both systems: light and heavy baryons are described essentially by the same mean field, and the only difference is now in the quantization condition:

- allowed SU(3) representations must contain states with hypercharge $Y' = (N_c - 1)/3$.

The lowest allowed SU(3) representations are in this case $\bar{3}$ of spin 0 and to 6 of spin 1 shown in Fig. 2.

Figure 2 – 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 $\bar{15}$ of spin 1 or 0. Heavy quark has to be added.

An important feature of this approach is that both $6 - \bar{3}$ splitting and the splittings inside these multiplets due to the strange quark mass are predicted using as an input the light sector spectrum and are in good agreement with experiment $^5$. The new ingredient is a hyperfine splitting due to the spin-spin interaction of a soliton and a heavy quark, which can be parametrized phenomenologically. Moreover, the decay widths can be calculated within the same approach, and the results for the charm baryons are shown in Fig. 3.
3 Excitations of heavy baryons

Two possible kinds of excitations are present in the $\chi$QSM. 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 $15$ of positive parity and spin 1 ($15$ of spin 0 is heavier) depicted in Fig. 2. Second possibility corresponds to the excitation of the sea quark from the $K^P = 1^-$ sea level to the valence level $6$ shown in Fig. 1.b (or alternatively valence quark excitation to the first excited level $a$ of $K^P = 1^-$). In this case the parity is negative but the rotational band is the same (see Fig. 2) with, however, different quantization condition:

- the isospin $T'$ of the states with $Y' = (N_c - 1)/3$ couples with the soliton spin $J$ as follows:

  $T' + J = F$, where $F$ is the grand spin of the excited level.

We have shown that the model describes well the only fully known spectrum of negative parity antitriplets of spin 1/2 and 3/2. There has been no experimental evidence for the sextet until recent report of five $\Omega_c^0$ states reported by the LHCb and confirmed by BELLE. In the sextet case the above mentioned condition predicts that the soliton spin can be quantized as $F = 0, 1, 2$. 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, it is not possible to accommodate all five $\Omega_c^0$ states within the constraints imposed by the $\chi$QSM. We have therefore forced model constraints (note that in the 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 $\chi$QSM states (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 $\Xi_c^0 + K^-$ final state analyzed by the LHCb. Two remaining states indicated by dark-blue arrows 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 $15$ of positive parity shown as a red dot in Fig. 2. This interpretation

\[ \text{Figure 3 – Decay widths of the charm baryons. Red full circles correspond to our theoretical predictions. Dark green triangles correspond to the experimental data. Data for decays 4 – 6 of } \Sigma_c^0(6_1, 3/2) \text{ have been divided by a factor of 5 to fit within the plot area. Widths of two LHCb } \Omega_c \text{ states that we interpret as pentaquarks are plotted as black full squares with theoretical values shown as red full circles.} \]

\[ \begin{align*}
1. \Sigma_c^+(1/2) &\rightarrow \Lambda_c^+ + \pi^+ \\
2. \Sigma_c^0(1/2) &\rightarrow \Lambda_c^0 + \pi^0 \\
3. \Sigma_c^0(1/2) &\rightarrow \Lambda_c^0 + \pi^- \\
4. \Sigma_c^+(3/2) &\rightarrow \Lambda_c^+ + \pi^+ \\
5. \Sigma_c^0(3/2) &\rightarrow \Lambda_c^0 + \pi^0 \\
6. \Sigma_c^0(3/2) &\rightarrow \Lambda_c^0 + \pi^- \\
7. \Xi_c^+(3/2) &\rightarrow \Xi_c^+ + \pi \\
8. \Xi_c^0(3/2) &\rightarrow \Xi_c^0 + \pi \\
9. \Omega_c^0(1/2) &\rightarrow \text{total} \\
10. \Omega_c^0(3/2) &\rightarrow \text{total}
\end{align*} \]

\[ ^a \text{We thank Victor Petrov for pointing out this possibility.} \]
is reinforced by the decay widths, 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 $N_c$ terms of the relevant couplings cancel in the non-relativistic limit.

![Figure 4 – Spectrum of the $\Omega_0^-$ states (from Ref. [8]) with theoretical predictions of the present model](image)

The simplest way to falsify or to confirm our identification is to search for the isospin partners of $\Omega_0^-$ from the $\mathbf{T}^5$. They can be searched in the mass distribution of $\Xi_0^0 + K^-$ or $\Xi_c^- + \bar{K}^0$: the $\Omega_0^-$’s from the sextet do not decay into these channels. Our model applies also to the bottom sector, and – where the data is available – it describes very well both masses and decay widths.

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