ON A POSSIBILITY OF BARYONIC EXOTICA*

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Models based on chiral symmetry predict pentaquarks that have relatively low masses. We briefly review both theoretical and experimental status of exotica in the light sector. Next, we shall show how to extend chiral models to baryons with one heavy quark and show that one expects exotica also in this case. Finally, we interpret recently discovered by the LHCb Collaboration five Ω_c^* resonances in terms of regular and exotic excitations of the ground state Ω_c.

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1. Introduction: Chiral Quark–Soliton Model

The Chiral Quark–Soliton Model (χQSM) is based on an old argument by Witten [1], which says that in the $N_{\rm c} \to \infty$ limit ($N_{\rm c}$ stands for number of colors), $N_{\rm c}$ relativistic valence quarks generate chiral mean fields represented by a distortion of a Dirac sea that, in turn, interact with the valence quarks themselves (for a review, see Ref. [2]). In this way, a self-consistent configuration called a *soliton* is formed. In Fig. 1 (a), we plot schematic pattern of light quark energy levels corresponding to this scenario. It is assumed that the mean fields exhibit the so-called *hedgehog* symmetry, which means that neither quark spin ($\boldsymbol{S_q}$) nor quark isospin ($\boldsymbol{T_q}$) are "good" quantum numbers. Instead, a *grand spin* $\boldsymbol{K} = \boldsymbol{S_q} + \boldsymbol{T_q}$ is a "good" quantum number. The lowest valence level has $K^P = 0^+$.

In order to project out spin and isospin, one has to rotate the soliton, both in flavor and configuration spaces. These rotations are then quantized semiclassically and the collective Hamiltonian is computed. The model predicts rotational baryon spectra that satisfy the following selection rules:

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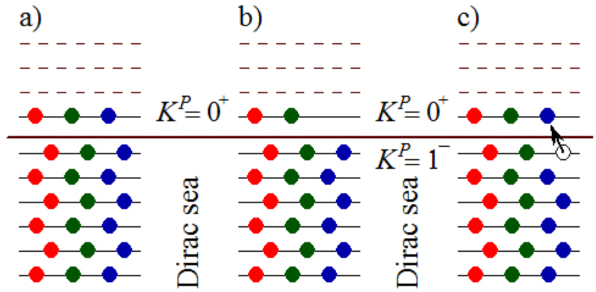

Fig. 1. Schematic pattern of light (u and d) quark levels in a self-consistent soliton configuration. In the left panel, all sea levels are filled and N_c (= 3 in the figure) valence quarks occupy the $K^P = 0^+$ lowest positive energy level. In the middle panel, one valence quark has been stripped off, 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. Levels for strange quarks that exhibit different filling pattern are not shown.

— allowed SU(3) representations must contain states with hypercharge $Y' = N_c/3$,

— the isospin $\boldsymbol{T}'$ of the states with $Y' = N_c/3$ couples with the soliton spin $\boldsymbol{J}$ to a singlet: $\boldsymbol{T}' + \boldsymbol{J} = 0$.

In the case of light positive parity baryons, the lowest allowed representations are **8** of spin 1/2, **10** of spin 3/2, and also exotic $\overline{\mathbf{10}}$ of spin 1/2 with the lightest state corresponding to the putative $\Theta^+(1540)$. They are shown in Fig. 2. Chiral models in general predict that pentaquarks are light [3, 4] and — in some specific models — narrow [4].

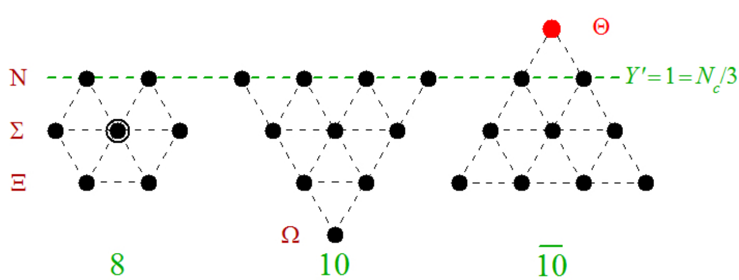

Fig. 2. The lowest lying SU(3) flavor representations allowed by the constraint $Y' = 1$. The first *exotic* representation, $\overline{\mathbf{10}}$, contains the explicitly exotic pentaquark states Θ^+, Ξ^+ and Ξ^{--}, and non-exotic nucleon- and sigma-like states.

After the first enthusiastic announcements of the discovery of pentaquarks in 2003 by LEPS [5] and DIANA [6] collaborations, the experimental evidence for the light exotica has been questioned (see *e.g.* [7]). Nevertheless, both DIANA [8] and LEPS [9] upheld their original claims after performing higher statistics analyses. The report on exotic Ξ states (see Fig. 2) by NA49 [10] from 2004, to the best of my knowledge, has not been questioned so far, however the confirmation is still strongly needed.

Another piece of information on $\overline{\mathbf{10}}$ comes from the η photo-production off the nucleon. Different experiments confirm the narrow structure at the c.m.s. energy $W \sim 1.68$ GeV observed in the case of the neutron, whereas no structure is observed on the proton (see Fig. 27 in the latest report by CBELSA/TAPS Collaboration [11] and references therein). The natural interpretation of this "neutron puzzle" was proposed already in 2003 in Ref. [12]. There one assumes that the narrow excitation at $W \sim 1.68$ GeV corresponds to the non-exotic penta-nucleon resonance belonging to $\overline{\mathbf{10}}$. Indeed, the SU(3) symmetry forbids photo-excitation of the proton member of $\overline{\mathbf{10}}$, while the analogous transition on the neutron is possible. This is due to the fact that photon is an SU(3) U-spin singlet, and the U-spin symmetry is exact in the SU(3) symmetric limit. An alternative interpretation is based on a partial wave analysis in terms of the Bonn–Gatchina approach [13]. There is an ongoing dispute on the interpretation of the "neutron puzzle" (for the latest arguments, see Ref. [14]).

2. Heavy baryons in the Chiral Quark–Soliton Model

In a recent paper [15] following [16], we have extended the χQSM to baryons involving one heavy quark. In this case, the valence level is occupied by $N_{\rm c}-1$ light quarks (see Fig. 1 (b)) that couple with a heavy quark Q to form a color singlet. The lowest allowed SU(3) representations are shown in Fig. 3. They correspond to the soliton in representation in $\overline{\mathbf{3}}$ of spin 0 and to $\mathbf{6}$ of spin 1. Therefore, the baryons constructed from such a soliton and a heavy quark form an SU(3) antitriplet of spin 1/2, and two sextets of spin 1/2 and 3/2 that are subject to a hyper-fine splitting. The next allowed representation of the rotational excitations corresponds to the exotic $\overline{\mathbf{15}}$ of spin 0 or spin 1 [17]. The spin 1 soliton has a lower mass and when it couples with a heavy quark, it forms spin 1/2 or 3/2 exotic multiplets that should be hyper-fine split similarly to the ground state sextets by ~ 70 MeV.

The rotational states described above correspond to positive parity and are clearly seen in the data [17]. Negative parity states are generated by soliton configurations with one light quark excited to the valence level from the Dirac sea (Fig. 1 (c)). The selection rules for excited quark solitons can be summarized as follows [18]:

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

— the isospin $\boldsymbol{T}'$ of the states with $Y' = (N_c - 1)/3$ couples with the soliton spin $\boldsymbol{J}$ as follows: $\boldsymbol{T}' + \boldsymbol{J} = \boldsymbol{K}$, where $\boldsymbol{K}$ is the grand spin of the excited level.

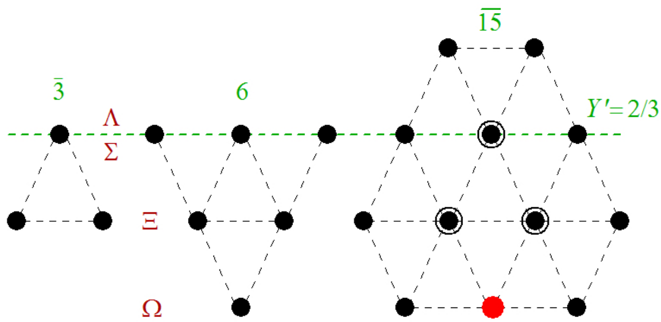

Fig. 3. (Color online) The lowest lying SU(3) flavor representations allowed by the constraint $Y' = 2/3$. The first *exotic* representation, $\overline{\mathbf{15}}$, contains the putative pentaquark states Ω_c with Ω_c^0 marked in gray/red.

The first allowed SU(3) representation for one quark excited soliton is again $\overline{\mathbf{3}}$, Fig. 3, with $T' = 0$, which for $K = 1$ is quantized as spin 1. The coupling of a heavy quark results in two hyperfine split antitriplets that are indeed seen in the data [17]. The hyperfine splitting parameter is in this case $\kappa'/m_c \sim 30$ MeV. Next possibility is flavor $\mathbf{6}$ with $T' = 1$, which may couple with $K = 1$ to $J = 0, 1$ and 2 resulting in 5 hyperfine split heavy sextets: two $1/2^-$, two $3/2^-$ and one $5/2^-$ (see Table I).

3. Possible interpretation of the LHCb $\boldsymbol{\Omega_c^0}$ resonances

In a very recent paper [19], the LHCb Collaboration announced five Ω_c^0 states with masses in the range of 3–3.2 GeV. The simplest possibility would be to associate them with the five sextets described at the end of Sect. 2. We have shown, however, in [17] that this scenario fails, as can be seen from Table I.

In the second scenario proposed in [17], we have interpreted three LHCb states as quark excitations of the ground state sextets, shown in Fig. 4 as vertical lines. Two remaining sextet excitations have higher mass and are above the threshold for the decays into charm mesons. They can be, therefore, wide and the branching ratio to $\Xi_c^+ + K^-$ final state may be small. This would explain why they are not seen by the LHCb. On the other hand, two remaining Ω_c^0 peaks are in this scenario interpreted as rotational

TABLE I

χQSM scenario where all LHCb Ω_c^0 states are assigned to the excited sextets. This assignment requires hyperfine splitting which is almost two times smaller than in the $\overline{\mathbf{3}}$ case and relation $\Delta_2 = 2\,\Delta_1$ derived in [17] is badly broken. Here, Δ_J is the mass difference between states of given J and $J-1$ before hyper-fine splitting.

J	S^P	M [MeV]	κ'/m_c [MeV]	Δ_J [MeV]
0	$1/2^-$	3000	—	—
1	$1/2^-$ $3/2^-$	3050 3066	16	61
2	$3/2^-$ $5/2^-$	3090 3119	17	47

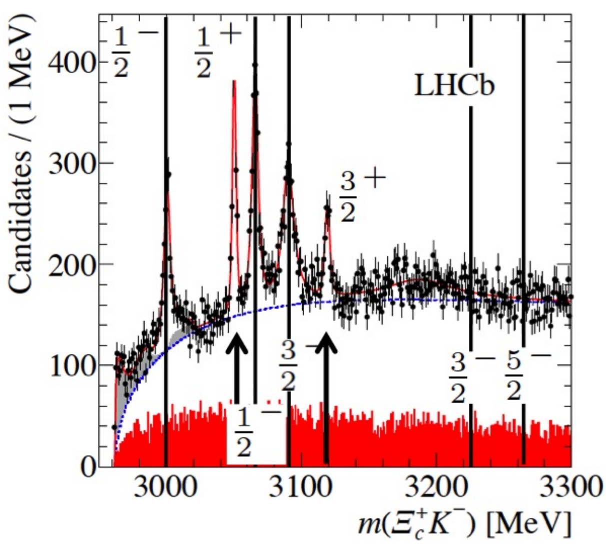

Fig. 4. LHCb spectrum [19] with the assignment described in the text. Two narrow $1/2^+$ and $3/2^+$ states marked with arrows are interpreted as $\overline{\mathbf{15}}$ pentaquarks.

excitations corresponding to the exotic $\overline{\mathbf{15}}$. As such, they are isospin triplets and should decay not only to $\Xi_c^+ + K^-$ but also to $\Xi_c^0 + K^-$ or $\Xi_c^+ + \bar{K}^0$ and $\Omega_c + \pi$ final states. This scenario is, therefore, very easy to confirm or falsify. Moreover, they are very narrow with widths around 1 MeV, and the χQSM provides a mechanism that suppresses pentaquark decays both in the light sector and in the present approach to heavy baryons [4, 17].

Summarizing, let us stress that despite many "null findings", there is still an experimental support for light and narrow pentaquarks. Using the ideas of the χQSM, we have proposed an interpretation of recently discovered Ω_c^0 states in terms of quark and rotational excitations of the ground state charmed baryons, the latter corresponding to the pentaquarks.

This note is based on Refs. [15, 17] where more complete list of references can be found. I would like to thank H.C. Kim, M.V. Polyakov and G.S. Yang for a fruitful collaboration.

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