# EXOTIC BARYONS IN TOPOLOGICAL SOLITON MODELS.

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The status and properties of pentaquarks discovered recently are discussed within topological soliton and simplistic quark model.

## 1 Discovery of pentaquarks

One of striking events in elementary particle physics after latest Quarks conference was discovery of baryon resonances with unusual properties (end of 2002 - 2004): $\Theta^+(1540)$, strangeness $S=+1$, isospin $I=0$ (most likely), width $\Gamma_\Theta < 10\,Mev$, seen by different collaborations in Japan, Russia, USA, FRG, CERN;
$\Xi^{--}_{3/2}(1862)$, $S=-2$ , $I=3/2$ (?), $\Gamma < 18\,Mev$ observed by NA49 Collab. at CERN;
$\Theta_c^0(3099)$, charm $C=-1$, $\Gamma < 15\,Mev$ seen by H1 Collab., DESY. Spin-parity $J^P$ of these states is not measured yet.

These states are manifestly exotic because they cannot be made of 3 valence quarks only. There are different possibilities to have exotic baryon states:
a) positive strangeness $S > 0$ (or negative charm $C < 0$, or positive beauty), since $s$-quark has $S=-1$ and $c$-quark $C=+1$,
b) large (in modulus) negative strangeness $S < -3B$, $B$ - baryon number; similar for charm or beauty,
c) large enough isospin $I > (3B+S)/2$ , if $-3B \le S \le 0$, or charge $Q > 2B+S$ or $Q < -B$ in view of Gell-Mann - Nishijima relation $Q = I_3 + Y/2$.

The pentaquarks $\Theta^+(1540)$ and $\Theta_c(3099)$, if it is confirmed, are just of the type a), the possibility b) is difficult to be realized in practice, since large negative strangeness of produced baryon should be balanced by corresponding amount of positively strange kaons. The state $\Xi^{--}_{3/2}$ is of the type c). The minimal quark contents of these states are: $\Theta^+ = (dduu\bar{s})$; $\Xi^{--} = (ssdd\bar{u})$; $\Theta_c^0 = (dduu\bar{c})$, and by this reason they are called pentaquarks.

<u>Chronology of pentaquarks discovery.</u>

$\Theta^+$, $S=+1$ baryon was observed first at SPring-8 installation (RCNP, Japan)[1] in reaction $\gamma^{12}C \to K^+n+....$ The reported mass is $1540\pm10$ $Mev$ and width $\Gamma < 25\,Mev$, confidence level (CL) $4.6\sigma$. Soon after this and independently DIANA collaboration at ITEP, Moscow [2] observed $\Theta^+$ in interactions of $K^+$ in $Xe$ bubble chamber. The mass of the bump in $K^0p$ invariant mass distribution is $1539 \pm 2$ $Mev$, $\Gamma < 9\,Mev$, confidence level a bit lower, about $4.4\sigma$. Confirmation of this result came also from several other experiments [3, 4, 5, 6, 7, 8, 9] mostly in reactions of photo-(electro)-production. The CLAS Collaboration [10] provided recently evidence for two states in $\Theta$-region of the $K^+n$ invariant mass distribution at $1523 \pm 5\,Mev$ and $1573 \pm 5\,Mev$.

The nonobservation of $\Theta^+$ in old kaon-nucleon scattering data provided restriction on the width of this state. Phase shift analysis of $KN$-scattering in the energy interval $1520 - 1560\,Mev$ gave a restriction $\Gamma < 1\,Mev$ [11]. Later analysis of total cross sections of kaon-deuteron interactions allowed to get the estimate for the width of $\Theta^+$: $\Gamma \simeq 0.9 \pm 0.2\,Mev$ [12].

The doubly strange cascade hyperon $\Xi_{3/2}$, $S=-2$, probably with isospin $I=3/2$ is observed in one experiment at CERN, only, in proton-proton collisions at $17Gev$[13]. The mass of resonance in $\Xi^-\pi^-$ and $\bar{\Xi}^+\pi^+$ systems is $1862 \pm 2$ $Mev$ and mass of resonance in $\Xi^-\pi^+$, $\bar{\Xi}^+\pi^-$ systems is $1864 \pm 5$ $Mev$, width $\Gamma < 18\,Mev$, and $CL = 4.0\sigma$. The fact makes this result more reliable that resonance $\Xi^{--}$ was observed in antibaryon channel as well. However, this resonance is not confirmed by HERA-B, ZEUS, CDF, WA-89 collaborations (see e.g. [14]), although there is no direct contradiction with NA49 experiment: upper bounds on the production cross sections of $\Xi_{3/2}$ are obtained in this way.

The anticharmed pentaquark $\Theta_c^0$, $C = -1$ was observed at H1, HERA, Germany, in $ep$ collisions. The mass of resonance in $D^{*-}p$, $D^{*+}\bar{p}$ systems is $3099 \pm 3 \pm 5\ Mev$, $\Gamma < 15\, Mev$, $CL = 6.2\sigma$. ZEUS collaboration at HERA [16] did not confirm the existence of $\Theta_c^0$ with this value of mass, and this seems to be already serious contradiction, see again [14].

There is also some evidence for existence of other baryon states, probably exotic, e.g. nonstrange state decaying into nucleon and two pions [17] or resonance in $\Lambda K_S^0$ system with mass $1734 \pm 6\, Mev$, $\Gamma < 6\, Mev$ at $CL = (3-6)\sigma$ which is $N^{*0}$ or $\Xi^*_{1/2}$, observed by STAR collaboration at RHIC [18] in reaction $Au+Au$ at $\sqrt{s_{NN}} \sim 200\, Gev$.

Already after the Quarks-04 conference the negative results on $\Theta^+$ observation have been reported by several groups. If high statistics experiments will not confirm existence of $\Theta^+$, it would be interesting then to understand why about 10 different experiments, although each of them with not high statistics, using different installations and incident particles, provided similar positive results. Information about status of higher statistics experiments performed or to be performed at JLAB (CLAS Collab.) can be found in [19].

# 2 Early predictions

From theoretical point of view the existence of such exotic states by itself was not unexpected. Such states have been discussed first within MIT quark-bag model [20]. The mass of these states was found considerably higher than that reported now: $M_\Theta \simeq 1700\ Mev$, $J^P = 1/2^-$. These studies were continued by other authors [21]: $M_\Theta \simeq 1900\, Mev$, $J^P = 1/2^-$ and [22]. From analysis of existed that time data on $KN$ interactions the estimate was obtained in [23] $M_\Theta \simeq 1705\, Mev\ (I=0), 1780\, Mev\ (I=1)$ with very large width.

In the context of chiral soliton model the $\{\overline{10}\}$ and $\{27\}$ -plets of exotic baryons were mentioned first in [24], without any mass estimates, however. Rough estimate within the "toy" model, $M_{\overline{10}} - M_8 \simeq 600\, Mev$, was made a year later in [25]. A resonance-like behaviour of $KN$ scattering phase shift in $\Theta$ channel was obtained in [26] in a version of Skyrme model (in the limit $M_K = M_\pi$).

Numerical estimate $M_\Theta \simeq 1530\ Mev$ was obtained by M.Praszalowicz [27], but it was no serious grounds for this since mass splittings within octet and decuplet of baryons was not described here satisfactorily ("accidental" prediction).

Extension of quantization condition [28] to "exotic" case was made in [29] where masses of exotic baryonic systems ($B$ arbitrary, $N_c = 3$) were estimated as function of the number of additional quark-antiquark pairs, or "exoticness number m": $\Delta E \sim m/\Theta_K,\ m^2/\Theta_K$. But here it was no mass splittings estimates inside of multiplets, no discussion of masses of particular baryons.

First calculation with configuration mixing due to flavor symmetry breaking ($m_K \neq m_\pi$) was made in [30] where mass splittings within the octet and decuplet of baryons were well described, and estimate obtained $M_\Theta \simeq 1660\ Mev$. "Strange" or kaonic inertia $\Theta_K$ was underestimated in this work, as it is clear now.

The estimate $M_\Theta \simeq 1530\ Mev$, coinciding with [27], and first estimate of the width, $\Gamma_\Theta < 30\, Mev$ were made 5 years later in [31]. It was "a luck", as stated much later by same authors (hep-ph/0404212): mass splitting inside of $\overline{10}$ was obtained greater than for decuplet of baryons, 540 $Mev$, and it was supposed that resonance $N^*(1710) \in \{\overline{10}\}$, i.e. it is the nonstrange component of antidecuplet. The above mass value was a result of subtraction, $1530 = 1710 - 540/3$. [31] is instructive example of a paper which, strictly speaking, is not quite correct, but being in right direction, stimulated successful searches for $\Theta^+$ in RCNP (Japan) and ITEP (Russia).

Skyrme-type model with vibrational modes included was studied first in [32] with a result $M_\Theta \simeq 1570\, Mev$, $\Gamma_\Theta \sim 70\, Mev$. A mistake (or misprint?) in paper's [31] width estimate was noted here.

<ins>Developements after $\Theta^+$ discovery.</ins>

After discovery of pentaquarks there appeared big amount of papers on this subect which develop theoretical ideas in different directions: within chiral soliton models [33, 34] and many other, phenomenological correlated quark models [35, 36, 37] and other, QCD sum rules [38], by means of lattice calculations [39], etc. It is not possible to describe all of them within restricted framework of this talk (reviews of that topic from different sides can be found, e.g. in [42, 46]). Quite sound criticism concerning chiral soliton models was developed in [40, 41], but it should be kept in mind that the drawbacks of soliton approach should be compared with uncertainces and drawbacks of other models. There is no regular way of solving relativistic many-body problem of finding bound states or resonances in 3-,5-, etc. quark system, and the chiral soliton approach, in spite of its drawbacks, provides a way to circumwent some of difficulties. The correlated quark models, diquark-triquark model [35], or diquark-diquark-antiquark model [36], being interesting and predictive, contain good amount of phenomenological guess.

# 3 Topological soliton model

In spite of some uncertainties and discrepances between different papers, the chiral soliton approach provided predictions for the masses of exotic states near the value observed later, considerably more near than quark or quark-bag models. Here I will be restricted with this model, mainly. Situation is somewhat paradoxical: it is easier to estimate masses of exotic states within chiral soliton models, whereas interpretation is more convenient in terms of simplistic quark model.

In topological (chiral) soliton models the baryons and baryonic systems appear as classical configurations of chiral ("pionic" in simplest $SU(2)$ version) fields which are characterized by the topological or winding number identified with the baryon number of the system [43]. This baryon number is the 4-th component of the Noether current generated by the Wess-Zumino term in the action written in a compact form by Witten [44], I shall not reproduce it here. In other words, the B-number is degree of the map $R^3 \to SU(2)$, or $R^3 \to S^3$, since $SU(2)$ is homeomorphic to 3-dimensional sphere $S^3$:

$$B = \frac{-1}{2\pi^2} \int s_f^2 s_\alpha I\Big[\frac{(f,\alpha,\beta)}{(x,y,z)}\Big] d^3r \tag{1}$$

where functions $f, \alpha, \beta$, describing $SU(2)$ skyrmion, define the direction of unit vector $\vec{n}$ on 3-dimensional sphere $S^3$ and $I[(f,\alpha,\beta)/(x,y,z)]$ is Jacobian of corresponding transformation. More details can be found, e.g. in [44, 33, 46]. It is important that the number of dimensions of the ordinary space, equal to 3, coincides with the number of degrees of freedom (or generators) of the $SU(2)$ group, and this makes possible the mapping ordinary space onto isospace. This can be explanation why the isospin symmetry takes place in hadronic world.

For each value of baryon number one should find the classical field configuration of minimal energy (mass) - this is done often by means of variational minimization numerical codes. For $B = 1$ configuration of minimal energy is of so called "hedgehog" type, where chiral field at each space point can be directed along radius vector drawn from center of soliton, for $B = 2$ it has torus-like form, for $B = 3$ it has topology of tetrahedron, etc. The next step is quantization of these configurations to get spectrum of states with definite quantum numbers, isospin $I$, strangeness $S$ or hyperchrge $Y$. In the collective coordinates quantization procedure [48, 28] one introduces the angular velocities of rotation of skyrmion in the $SU(3)$ configuration space, $\omega_k$, $k = 1,...8$: $A^\dagger(t)\dot{A}(t) = -i\omega_k\lambda_k/2$, $\lambda_k$ being Gell-Mann matrices, the collective coordinates matrix $A(t)$ is written usually in the form $A = A_{SU2}\, exp(i\nu\lambda_4)A'_{SU2}\, exp(i\rho\lambda_8/\sqrt{3})$. The Wess-Zumino term contribution into lagrangian can be calculated explicitly for this ansatz, $L_{WZ} = -\omega_8 N_c B/2\sqrt{3}$, and so called "right" hypercharge, or hypercharge in the body-fixed system equals $Y_R = -2\partial L/\partial\omega_8/\sqrt{3} = N_c B/3$. For any $SU(3)$ multiplet $(p, q)$ the maximal hypercharge $Y_{max} = (p + 2q)/3$, and obviously, inequality should be fulfilled $p + 2q \geq N_c B$, or

$$p + 2q = 3(B + m) \tag{2}$$

for $N_c = 3$, with $m$ positive integer. States with $m = 0$ can be called, naturally, minimal multiplets. For $B = 1$ they are well known octet $(1, 1)$ and decuplet $(3, 0)$ [28].

States with $m = 1$ should contain at least one $q\bar{q}$ pair, since they contain the $S = +1$, $Y = 2$ hyperon. They are pentaquarks antidecuplet $(p, q) = (0, 3)$, 27-plet $(2, 2)$, 35-plet $(4, 1)$. 28-plet $(6, 0)$ should contain already 2 quark-antiquark pairs, as it follows from analysis of its isospin content, so it is septuquark (or heptaquark) [46]. The pentaquark multiplets are presented at Fig. 1. The minimal value of hypercharge is $Y_{min} = -(2p + q)/3$, the maximal isospin $I_{max} = (p + q)/2$ at $Y = (p - q)/3$. Such multiplets as $\{27\}$, $\{35\}$ for $m = 1$ and multiplets for $m = 2$ in their internal points contain 2 or more states (shown by double or triple circles in **Fig.1**). The 28-plet ($p = 6$, $q = 0$) should contain at least two quark-antiquark pairs, so, it is septuquark (or heptaquark) although it has $m = 1$, and it is not shown in **Fig. 1**.

# 4 The mass formula

The lagrangian describing baryons or baryonic system is quadratic form in angular velocities defined above, with momenta of inertia, isotopical (pionic) $\Theta_\pi$ and flavor, or kaonic $\Theta_K$ as coefficients [28]:

$$L_{rot} = \frac{1}{2}\Theta_\pi(\omega_1^2 + \omega_2^2 + \omega_3^2) + \frac{1}{2}\Theta_K(\omega_4^2 + ... + \omega_7^2) - \frac{N_c B}{2\sqrt{3}}\omega_8. \tag{3}$$

The expressions for these moments of inertia as functions of skyrmion profile are well known [48, 28] and presented in many papers, see e.g. [46]. The quantization condition (1) discussed above follows from the presence of linear in angular velocity $\omega_8$ term in (3) originated from the Wess-Zumino-Witten term in the action of the model [44, 28].

The hamiltonian of the model can be obtained from (3) by means of canonical quantization procedure [28]:

$$H = M_{cl} + \frac{1}{2\Theta_\pi}\vec{R}^2 + \frac{1}{2\Theta_K}\left[C_2(SU_3) - \vec{R}^2 - \frac{N_c^2 B^2}{12}\right], \tag{4}$$

where the second order Casimir operator for the $SU(3)$ group, $C_2(SU_3) = \sum_{a=1}^{8} R_a^2$, with eigenvalues for the $(p, q)$ multiplets $C_2(SU_3)_{p,q} = (p^2 + pq + q^2)/3 + p + q$, for the $SU(2)$ group, $C_2(SU2) = \vec{R}^2 = R_1^2 + R_2^2 + R_3^2 = J(J + 1) = I_R(I_R + 1)$.

The operators $R_\alpha = \partial L/\partial\omega_\alpha$ satisfy definite commutation relations which are generalization of the angular momentum commutation relations to the $SU(3)$ case [28]. Evidently, the linear in $\omega$ terms in lagrangian (3) are cancelled in hamiltonian (4). The equality of angular momentum (spin) $J$ and the so called right or body fixed isospin $I_R$ used in (4) takes place only for configurations of the "hedgehog" type when usual space and isospace rotations are equivalent. This equality is absent for configurations which provide the minimum of classical energy for greater baryon numbers, $B \geq 2$.

For minimal multiplets ($m = 0$) the right isospin $I_R = p/2$, and it is easy to check that coefficient of $1/2\Theta_K$ in (5) equals to

$$K = C_2(SU_3) - \vec{R}^2 - N_C^2 B^2/12 = N_C B/2, \qquad (5)$$

for arbitrary $N_C$ [1]. So, $K$ is the same for all multiplets with $m = 0$ [29], see **Table 1**- the property known long ago for the $B = 1$ case [28]. For nonminimal multiplets there are additional contributions to the energy proportional to $m/\Theta_K$ and $m^2/\Theta_K$, according to (4)[29]. It means that in the framework of chiral soliton approach the "weight" of quark- antiquark pair is defined by parameter $1/\Theta_K$, and this property of such models deserves better understanding.

| $(p,q)$ | $N(p,q)$ | m | $C_2(SU_3)$ | $J = I_R$ | $K(J_{max})$ | $K(J_{max}-1)$ |
|---|---|---|---|---|---|---|
| $(1,1)$ | $\{8\}$ | 0 | 3 | 1/2 | 3/2 | |
| $(3,0)$ | $\{10\}$ | 0 | 6 | 3/2 | 3/2 | |
| $(0,3)$ | $\{\overline{10}\}$ | 1 | 6 | 1/2 | 3/2+3 | |
| $(2,2)$ | $\{27\}$ | 1 | 8 | 3/2; 1/2 | 3/2+2 | 3/2+5 |
| $(4,1)$ | $\{35\}$ | 1 | 12 | 5/2; 3/2 | 3/2+1 | 3/2+6 |
| $(6,0)$ | $\{28\}$ | 1 | 18 | 5/2 | 3/2+7 | |
| $(1,4)$ | $\{\overline{35}\}$ | 2 | 12 | 3/2; 1/2 | 3/2+6 | 3/2+9 |
| $(3,3)$ | $\{64\}$ | 2 | 15 | 5/2; 3/2; 1/2 | 3/2+4 | 3/2+9 |
| $(5,2)$ | $\{81\}$ | 2 | 20 | 7/2; 5/2; 3/2 | 3/2+2 | 3/2+9 |
| $(7,1)$ | $\{80\}$ | 2 | 27 | 7/2; 5/2 | 3/2+9 | 3/2+16 |
| $(9,0)$ | $\{55\}$ | 2 | 36 | 7/2 | 3/2+18 | |

**Table 1.**The values of $N(p,q)$, Casimir operator $C_2(SU_3)$, spin $J = I_R$, coefficient $K$ for first two values of $J$ for minimal $(m = 0)$ and nonminimal $(m = 1,\ 2)$ multiplets of baryons.

It follows from **Table 1** [46] that for each nonzero $m$ the coefficient $K(J_{max})$ decreases with increasing $N(p,q)$, e.g. $K_{5/2}(35) < K_{3/2}(27) < K_{1/2}(\overline{10})$. The following differences of the rotation energy can be obtained easily:

$$M_{10} - M_8 = \frac{3}{2\Theta_\pi}, \qquad M_{\overline{10}} - M_8 = \frac{3}{2\Theta_K}, \qquad (6)$$

obtained in [28, 31],

$$M_{27,J=3/2} - M_{10} = \frac{1}{\Theta_K}, \quad M_{27,J=3/2} - M_{\overline{10}} = \frac{3}{2\Theta_\pi} - \frac{1}{2\Theta_K}, \qquad (7)$$

$$M_{35,J=5/2} - M_{27,J=3/2} = \frac{5}{2\Theta_\pi} - \frac{1}{2\Theta_K}. \qquad (8)$$

If the relation took place $\Theta_K \ll \Theta_\pi$ then $\{27\}$-plet would be lighter than antidecuplet, and $\{35\}$-plet would be lighter than $\{27\}$. In realistic case $\Theta_K$ is approximately twice smaller than $\Theta_\pi$ (see **Table 2**, next section), and therefore the components of antidecuplet are lighter than components of $\{27\}$ with same values of strangeness. Beginning with some values of $N(p,q)$ coefficient $K$ increases strongly, as can be seen from **Table 1**, and this corresponds to the increase of the number of quark-antiquark pairs by another unity. The states with $J < J_{max}$ have the energy considerably greater than that of $J_{max}$ states, by this reason they could contain also greater amount of $q\bar{q}$-pairs.

The formula (5) is obtained in the rigid rotator approximation which is valid if the profile function of the skyrmion and therefore its dimensions and other properties are not changed when it is rotated in the configuration space (see, e.g. discussion in [46].

[1]It should be kept in mind that for $N_C$ different from 3 the minimal multiplets for baryons differ from octet and decuplet. They have $(p,q) = (1,(N_C-1)/2),\ (3,(N_C-3)/2), ..., (N_C,0)$.

# 5 Spectrum of baryonic states

Expressions (4), (5) and numbers given in **Table 1** are sufficient to calculate the spectrum of baryons without mass splitting inside of $SU(3)$- multiplets, as it was made e.g. in [25, 29]. The mass splitting due to the presence of flavor symmetry breaking terms plays a very substantial role [30, 31, 33]:

$$H_{SB} = \frac{1 - D^{(8)}_{88}}{2} \Gamma_{SB} \tag{9}$$

where the $SU(3)$ rotation function $D^{8}_{88}(\nu) = 1 - 3s^2_\nu/2$,

$$\Gamma_{SB} = \frac{2}{3}\left[\left(\frac{F_K^2}{F_\pi^2} m_K^2 - m_\pi^2\right)\Sigma + (F_K^2 - F_\pi^2)\tilde{\Sigma}\right] \tag{10}$$

$$\Sigma = \frac{F_\pi^2}{2}\int (1 - c_f) d^3\vec{r}, \qquad \tilde{\Sigma} = \frac{1}{4}\int c_f \left(f'^2 + \frac{2s_f^2}{r^2}\right) d^3 r, \tag{11}$$

kaon and pion masses $m_K$, $m\pi$ are taken from experiment. The quantity $SC =< s^2_\nu > /2 =< 1 - D^{(8)}_{88} > /3$ averaged over the baryon $SU(3)$ wave function defines its strangeness content. Without configuration mixing, i.e. when flavor symmetry breaking terms in the lagrangian are considered as small perturbation, $< s^2_\nu >_0$ can be expressed simply in terms of the $SU(3)$ Clebsh-Gordan coefficients. The values of $< s^2_\nu >_0$ for the octet, decuplet, antidecuplet and some components of higher multiplets are presented in **Table 2**. In this approximation the components of $\{10\}$ and $\{\overline{10}\}$ are placed equidistantly, and splittings of decuplet and antidecuplet are equal.

The spectrum of states with configuration mixing and diagonalization of the hamiltonian in the next order of perturbation theory in $H_{SB}$ is given in **Table 2** (the code for calculation was kindly presented by H.Walliser). The calculation results in the Skyrme model with only one adjustable parameter - Skyrme constant $e$ ($F_\pi = 186\, Mev$ - experimentally measured value) are shown as variants A and B. The values of $< s^2_\nu >$ become lower when configuration mixing takes place, and equidistant spacing of components inside of decuplet and especially antidecuplet is violated, see also **Fig.2**.

It should be stressed here that the chiral soliton approach in its present state can describe the differences of baryon or multibaryon masses [45, 30, 33]. The absolute values of mass are controlled by loop corrections of the order of $N_C^0 \sim 1$ which are estimated now for the case of $B = 1$ only [47]. Therefore, the value of nucleon mass in **Table 2.** and **Fig.2** is taken to be equal to the observed value.

As it can be seen from **Table 2**, the agreement with data for pure Skyrme model with one parameter is not so good, but the observed mass of $\Theta^+$ is reproduced with some reservation. To get more reliable predictions for masses of other exotic states the more phenomenological approach was used in [33] where the observed value $M_\Theta = 1.54\, Gev$ was included into the fit, and $\Theta_K$, $\Gamma_{SB}$ were the variated parameters (variant C in **Table 2** and **Fig.2**). The position of some components of $\{27\}$, $\{35\}$ and $\{28\}$ plets is shown as well.

It looks astonishing at first sight that the state $\Theta^+$ containing strange antiquark is lighter than nonstrange component of antidecuplet, $N^*(I = 1/2)$. But it is easy to understand if we recall that all antidecuplet components contain $q\bar{q}$ pair: $\Theta^+$ contains 4 light quarks and $\bar{s}$, $N^*$ contains 3 light quarks and $s\bar{s}$ pair with some weight, $\Sigma^* \in \{\overline{10}\}$ contains $u, d, s$ quarks and $s\bar{s}$, etc.

| | | A | B | C | |
|---|---|---|---|---|---|
| $\Theta_\pi\,(Gev^{-1})$ | — | 6.175 | 5.556 | 5.61 | - |
| $\Theta_K\,(Gev^{-1})$ | — | 2.924 | 2.641 | 2.84 | - |
| $\Gamma_{SB}\ (Gev)$ | — | 1.369 | 1.244 | 1.45 | - |
| $Baryon\|N,Y,I,J>$ | $< s_\nu^2 >_0$ | A | B | C | $Data$ |
| $\Lambda\,\|8,0,0,1/2>$ | 0.60 | 1094 | 1078 | 1103 | 1116 |
| $\Sigma\,\|8,0,1,1/2>$ | 0.73 | 1202 | 1182 | 1216 | 1193 |
| $\Xi\,\|8,-1,1/2,1/2>$ | 0.80 | 1310 | 1274 | 1332 | 1318 |
| $\Delta\,\|10,1,3/2,3/2>$ | 0.58 | 1228 | 1258 | 1253 | 1232 |
| $\Sigma^*\|10,0,1,3/2>$ | 0.67 | 1357 | 1372 | 1391 | 1385 |
| $\Xi^*\|10,-1,1/2,3/2>$ | 0.75 | 1483 | 1484 | 1525 | 1530 |
| $\Omega\,\|10,-2,0,3/2>$ | 0.83 | 1604 | 1587 | 1654 | 1672 |
| $\Theta^+\,\|\overline{10},2,0,1/2>$ | 0.50 | 1520 | 1564 | 1539 | 1540 |
| $N^*\,\|\overline{10},1,1/2,1/2>$ | 0.58 | 1663 | 1664 | 1661 | 1710? |
| $\Sigma^*\,\|\overline{10},0,1,1/2>$ | 0.67 | 1731 | 1749 | 1764 | 1770? |
| $\Xi^*_{3/2}\|\overline{10},-1,3/2,1/2>$ | 0.75 | 1753 | 1781 | 1786 | 1862? |
| $\Theta_1^*\,\|27,2,1,3/2>$ | 0.57 | 1646 | 1697 | 1688 | |
| $\Sigma_2^*\,\|27,0,2,3/2>$ | 0.61 | 1675 | 1724 | 1718 | |
| $\Xi^*_{3/2}\|27,-1,3/2,3/2>$ | 0.71 | 1798 | 1835 | 1850 | 1862? |
| $\Omega_1^*\,\|27,-2,1,3/2>$ | 0.82 | 1928 | 1950 | 1987 | |
| $\Theta_2^*\,\|35,2,2,5/2>$ | 0.71 | 1979 | 2055 | 2061 | |
| $\Delta_{5/2}\|35,1,5/2,5/2>$ | 0.44 | 1723 | 1817 | 1792 | |
| $\Sigma_2^*\,\|35,0,2,5/2>$ | 0.54 | 1842 | 1924 | 1918 | |
| $\Xi^*_{3/2}\|35,-1,3/2,5/2>$ | 0.65 | 1963 | 2032 | 2046 | |
| $\Omega_1^*\,\|35,-2,1,5/2>$ | 0.75 | 2085 | 2141 | 2175 | |
| $\|35,-3,1/2,5/2>$ | 0.85 | 2208 | 2251 | 2306 | |

**Table 2.** Values of masses of the octet, decuplet, antidecuplet and manifestly exotic components of higher multiplets. A: $e = 3.96$; B: $e = 4.12$; C: fit with parameters $\Theta_K$, $\Theta_\pi$ and $\Gamma_{SB}$ [33], which are shown in the upper 3 lines.

The mass splitting inside of decuplet is influenced essentially by its mixing with $\{27\}$-plet components [33], see **Fig.1**, which increases this splitting considerably - the effect ignored in [31]. The mixing of antidecuplet with the octet of baryons has some effect on the position of $N^*$ and $\Sigma^*$, the position of $\Xi^*_{3/2}$ is influenced strongly by mixing with $\{27\}$-plet ($J = 1/2$) and $\{\overline{35}\}$-plet. As a result of mixing, the mass splitting of antidecuplet decreases. Position of $\Theta^* \in \{27\}$ is influenced by mixing with higher multiplets [33], the components of $\{35\}$-plet mix mainly with corresponding components of septuquark $\{64\}$-plet.

It should be noted that predictions of the mass of $\Xi^*_{3/2}$ made in [33] half a year before its observation at CERN [13] were quite close to the reported value $1862\,Mev$: $1786\,Mev$ for the component of antidecuplet, and $1850\,Mev$ for the $\{27\}$ component, variant C of **Table 2**. The component of $\{35\}$-plet with zero strangeness and $I = J = 5/2$ is of special interest because it has the smallest strangeness content (or $s_\nu^2$) - smaller than nucleon and $\Delta$. It is the lightest component of $\{35\}$-plet, and this remarkable property has explanation in simplistic pentaquark model, see Section 6 below. As a consequence of isospin conservation by strong interactions it can decay into $\Delta\pi$, but not to $N\pi$ or $N\rho$. According to **Table 1**, the components of $\{28\}$ plet containing 2 $q\bar{q}$ pairs at least, have the mass considerably greater than that of other multiplets of **Fig.1**.

All baryonic states considered here are obtained by means of quantization of soliton rotations in $SU(3)$ configuration space, therefore they have positive parity. A qualitative discussion of the influence of other (nonzero) modes - vibration, breathing

- as well as references to corresponding papers can be found in [33, 32]. The realistic situation can be more complicated than somewhat simplified picture presented here, since each rotation state can have vibrational excitations with characteristic energy of hundreds of $Mev$.

If the matrix element of the decay $\Theta^+ \to KN$ is written in a form

$$M_{\Theta \to KN} = g_{\Theta KN} \bar{u}_N \gamma_5 u_\Theta \phi_K^\dagger \tag{12}$$

with $u_N$ and $u_\Theta$ - bispinors of final and initial baryons, then the decay width equals to

$$\Gamma_{\Theta \to KN} = \frac{g^2_{\Theta KN}}{8\pi} \frac{\Delta_M^2 - m_K^2}{M^2} p_K^{cm} \simeq \frac{g^2_{\Theta KN}}{8\pi} \frac{(p_K^{cm})^3}{M m_N} \tag{13}$$

where $\Delta_M = M - m_N$, $M$ is the mass of decaying baryon, $p_K^{cm}$ - the kaon momentum in the c.m. frame. For the decay constant we obtain then $g_{\Theta KN} \simeq 4.4$ if we take the value $\Gamma_{\Theta \to KN} = 10\, Mev$ as suggested by experimental data [2],[16]. This should be compared with $g_{\pi NN} \simeq 13.5$. So, suppression of the decay $\Theta \to KN$ takes place, but not large and understandable, according to [31, 35, 36]. It would be difficult, however, to explain the with $\Gamma_\Theta \sim 1\, Mev$ or smaller, as suggested by scattering data [11, 12].

# 6 Comments on wave functions of pentaquarks

Wave functions (WF) of **manifestly** exotic resonances are **unique** within pentaquark approximation, i.e. their quark content is fixed by isospin, strangeness, etc. It is easily to obtain for manifestly exotic components of antidecuplet (see also **Fig. 1**):

$$\Psi_\Theta \sim uudd\bar{s},$$

$$\Psi_{\Xi_{3/2}} \sim ssdd\bar{u},\ \dots,\ \dots,\ ssuu\bar{d},$$

WF of cryptoexotic states are not unique. Within antidecuplet:

$$\Psi_{N^*} \sim udd\,[\alpha_- u\bar{u} + \beta_- d\bar{d} + \gamma_- s\bar{s}],\ uud\,[\alpha_+ u\bar{u} + \beta_+ d\bar{d} + \gamma_+ s\bar{s}],$$

$$\Psi_{\Sigma^*} \sim sdd\,[\mu_- u\bar{u} + \nu_- d\bar{d} + \rho_- s\bar{s}],\ \dots,\ sdd\,[\mu_+ u\bar{u} + \nu_+ d\bar{d} + \rho_+ s\bar{s}],$$

coefficients $\alpha_-$, $\alpha_+$, etc depend on the particular variant of the model.
E.g., for the diquark model with $D_q \sim \bar{3}_F$ [36] $\alpha_- = \sqrt{1/3}$, $\beta_- = 0$, $\gamma_- = \sqrt{2/3}$, etc. Equidistancy within $\overline{10}$ was obtained in [37].

Within $\{27\}$-plet only $S = 0$, $I = 3/2$-state (analog of $\Delta$-isobar) is cryptoexotic. The states with $S = +1, I = 1$ and state with $S = -1, I = 2$ contain one $s$-quark field as depicted in **Fig. 1**, and their masses do not differ much by this reason, as it was obtained in chiral soliton model as well, see **Table 2, Fig. 2**.

Within 35-plet ALL states of maximal isospin are manifestly exotic and have unique quark content. The state with $S = 0$, $I = 5/2$ (it can be called $\Delta_{5/2}$) does not contain strange quarks:

$$\Psi_{\Delta_{5/2}} \sim dddd\bar{u},\ \dots, uuuu\bar{d},$$

neither $s$, nor $\bar{s}$ quarks! Remarkably, that within chiral soliton model this state has minimal strangeness content and has the lowest (within $\{35\}$-plet) mass, see **Table 2**.

Besides flavor antitriplet diquark $D_q \sim \bar{3}_F$ discussed in this context first in [36], the diquarks $D_q \sim 6_F$ are necessary to form $\{27\}$- and $\{35\}$-plets of pentaquarks. The comparison of masses of $\Theta^+ \in \overline{10}$ and $\Theta^* \in 27$ allows to conclude that $6_F$ diquark is heavier that $\bar{3}_F$ by $120 - 150\, Mev$, at least. To conclude this section I note that there is good correspondence between chiral soliton calculations [33] and simplistic pentaquark model, the fact which needs probably deeper understanding.

# 7 Conclusions and prospects

Even if not all reported states are confirmed, one can state that new and interesting branch of hadron (baryon) spectroscopy appeared which will enlarge our knowledge about hadron structure. The following problems and questions can be pointed out:

$*$ High statistics confirmation of existence of narrow pentaquarks seems to be necessary, especially for the resonances $\Xi_{3/2}$ and $\Theta_c$, see [19].

$*$ Width determination is of great importance, $\Gamma \sim 1\,Mev$ is not excluded and suggested by analyses of scattering data, but would be difficult to explain by theory: a special reason is necessary then.

$*$ Several missing components of multiplets remain to be found, for example:
in $\{\overline{10}\}$-plet: $\Xi^+_{3/2} \to \Xi^0\,\pi^+,\;\; \Sigma^+\,\bar{K}^0$;
in $\{27\}$-plet: $\Theta^*_1 \to NK$; $\Sigma_2 \to \Sigma\,\pi$; $\Xi^*_{3/2}$; $\Omega_1 \to \Omega\,\pi, \Xi\bar{K}$;
in $\{35\}$-plet: $\Omega^*_1 \to \Omega\,\pi,\; \Xi\bar{K}$; $\Delta_{5/2} \to N\pi\pi$; $\Xi_{S=-4} \to \Omega\bar{K}$, etc.

$*$ Studies of cryptoexotics ($N^*$, $\Delta^*$, $\Xi^*$...) are of interest as well, to complete the picture of pentaquarks.

$*$ Spin and parity are **crucial** for cheking the validity of chiral soliton models predictions. Negative parity of these states would provide big difficulties for their interpretation as quantized topological solitons.

$*$ As a result, better understanding of the structure of baryons wave functions will be reached.

$*$ Other predictions of CSM are of interest, e.g. supernarrow radiatively decaying dibaryon [49] (JINR and INR experiments [50, 51], see, however, [52]); $\Theta^+$ hypernuclei and anti-charmed hypernuclei, e.g. ${}^3H_{\bar{c}} \sim ddddduuuu\bar{c}$, ${}^4He_{\bar{c}}$, etc. [46, 53].

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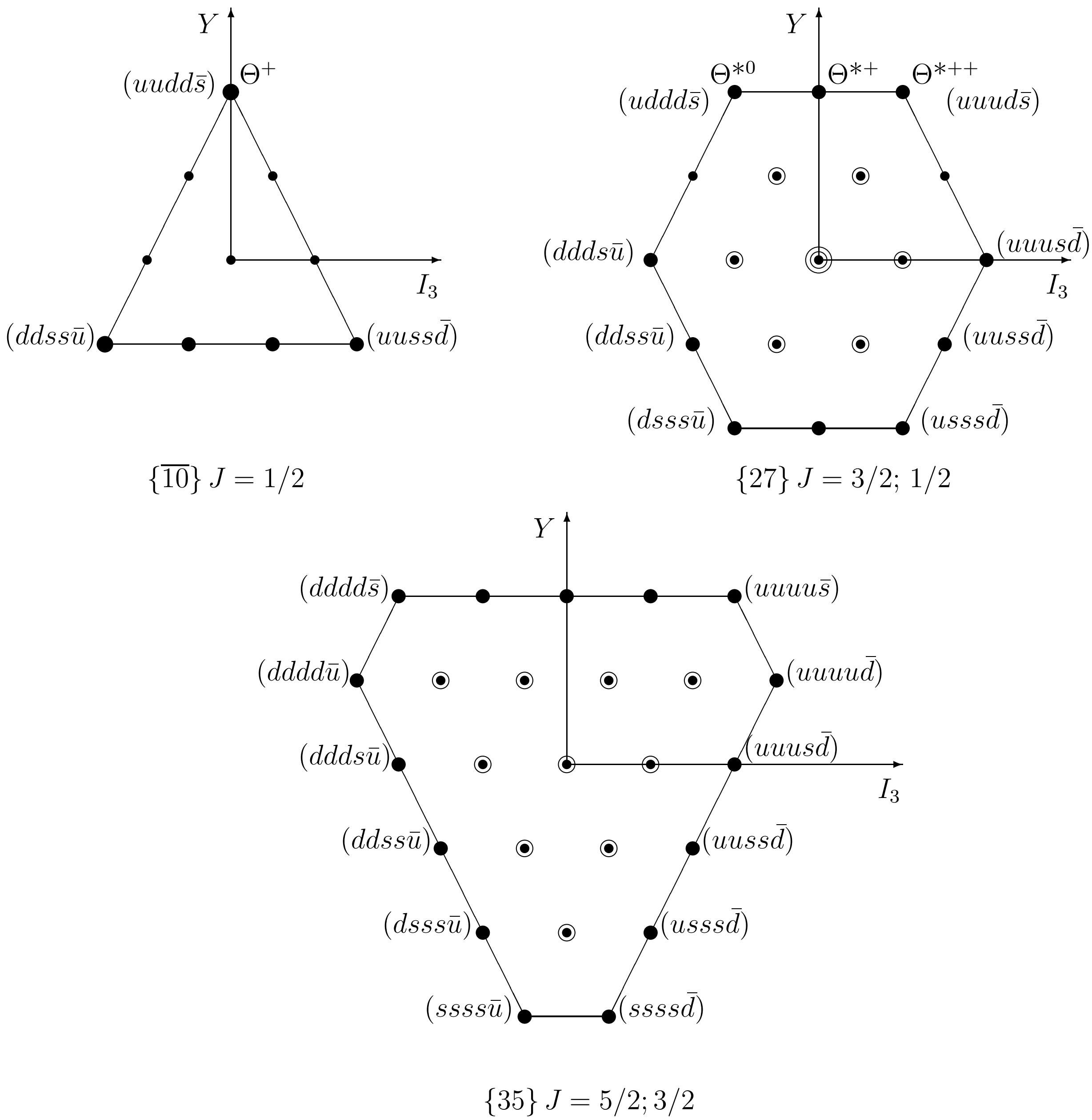


Figure 1: The $I_3 - Y$ diagrams for the multiplets of pentaquarks, $B = 1,\ m = 1$. Large full circles show the exotic states, smaller - the cryptoexotic states which can mix with nonexotic states from octet and decuplet. Manifestly exotic components of pentaquarks have unique quark contents shown in the figure.

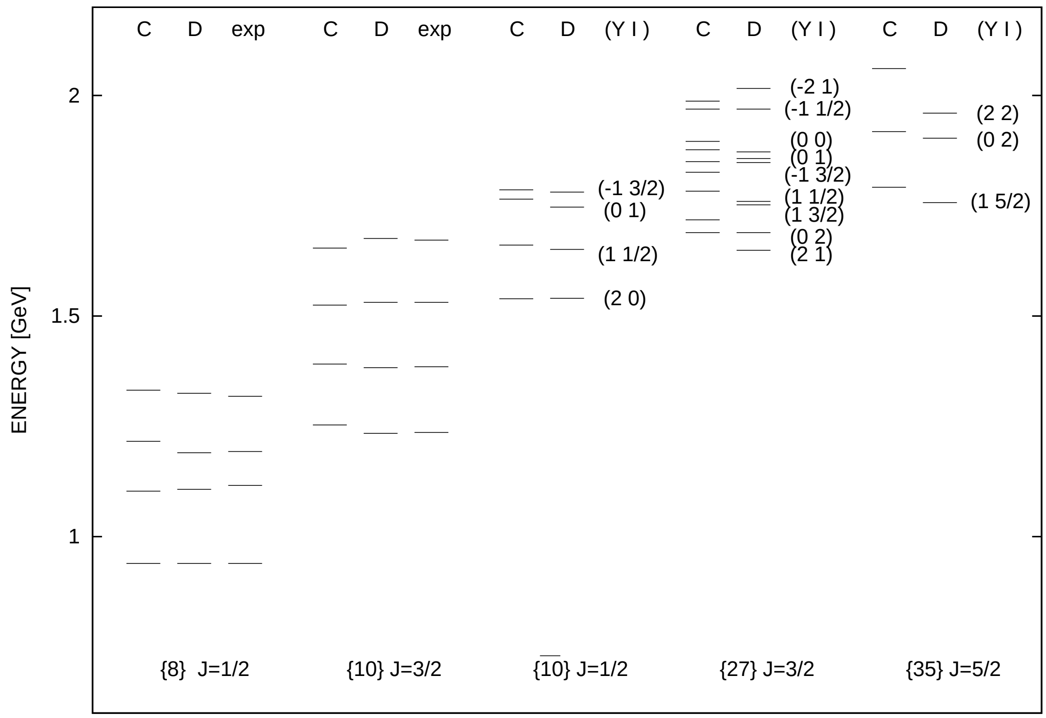


Figure 2: Lowest rotational states in the $SU(3)$ soliton model for fits C and D. The experimental masses of the $\{8\}$ and $\{10\}$ baryons are depicted for comparison. Not all states of the $\{35\}$ are shown. This figure is taken from [33]. The variant D shown here takes into account the term in $H_{SB}$ which appears from the $\rho - \omega$ mixing in effective lagrangian [30, 33].