Strange Skyrmions: status and observable predictions

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Abstract The chiral soliton approach (CSA) provides predictions of the rich spectrum of baryonic states with different values of strangeness for any baryon number $B$. In the sector with $B = 1$ the well known octet and decuplet of baryons are described within CSA, and some exotic states are predicted. In the $B = 2$ sector there are many predictions, but only few of them - e.g., the virtual $\Lambda N$ state - have been observed. Possible reasons for this are discussed.

1 INTRODUCTION. THE $B = 1$ SECTOR

There is growing evidence now that the chiral soliton approach (CSA) proposed at first by Skyrme allows one to describe the properties of baryons - octet and decuplet - and also the basic properties of lightest nuclei with baryon number $B = 2$, $3$ and $4$. This approach has rich consequences for the spectra of baryons and baryonic systems with nonzero strangeness. However, its status in the sectors with baryon number $B = 1$ and $B \geq 2$ is quite different. In the $B = 1$ sector the octet and decuplet of baryons are known for many years. When the chiral soliton approach was applied for description of the baryon properties it was a problem to describe corresponding mass splittings. Reasonable agreement with data has been reached when the flavor symmetry breaking was taken into account not only in meson masses but also in the meson decay constants, with $F_K/F_\pi \simeq 1.26$.

Within the CSA the mass formula for the quantized baryonic states has the following general structure:

$$M = M_{cl} + E_{rot}(p,q,Y,T,J;\Theta_T,\Theta_S,\Theta_J,...) + E_{Cas}$$

where $M_{cl}$ is the classical mass of the soliton with baryon number $B$ including the symmetry breaking terms, $M_{cl} \sim N_c$, the number of colors in the underlying QCD. $E_{rot}$ is the zero-modes quantum correction depending on the quantum numbers of state and moments of inertia $\Theta$, defined by the profile functions of the solitons. $E_{rot}$ contains the terms $\sim 1/N_c$ and terms $\sim N_0$, as it was shown recently by Walliser. $p,q,Y,T$ and $J$ denote the $SU(3)$ multiplet, hypercharge of the state, its isospin and angular momentum. $E_{Cas} \sim N_0$ is the so called Casimir energy of solitons closely connected with the loop corrections to the mass of solitons. It is a problem to calculate this energy because the model is not renormalizable. Till now $E_{Cas}$ was estimated in few cases only.

In the simplest case of $B = 1$ only two moments of inertia come into the game, $\Theta_T = \Theta_J$ and $\Theta_S$, so called strange, or kaonic inertia. The rotational energy depending on $\Theta_S$ for a state with any $B$-number equals to ($N_c = 3$):

$$E_{rot}(\Theta_S,B) = [3B/2 + m(3B/2 + m + 1 - N)]/(2\Theta_S(B))$$

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Here $m$ is the difference between triality and the $B$-number, $m = (p + 2q)/3 - B$ which can be interpreted as the number of additional quark-antiquark pairs present in the multiplet $(p, q)$, $N = (p + m)/2$ is the “right” isospin. For “minimal” $SU(3)$ multiplets $m = 0$. For $B = 1$ octet and decuplet of baryons are just such minimal multiplets, $(p + 2q)/3 = 1$. The first term in (2), $3B/(4 \Theta S)$, is the same for all minimal multiplets because of cancellation of the second order Casimir operators of the groups $SU(2)$ and $SU(3)$. The antidecuplet and 27-plet of baryons contain exotic states which cannot be constructed from the valence quarks only. The additional energy of these multiplets depending on the inertia of baryon $Θ_S(1)$ is given by second term in (2) proportional to $m$, with $m = 1, B = 1$.

In many variants of the model for baryons $Θ_S(1) ≃ 2.1 Gev^{-1}$, therefore, for $m = 1, N = 1/2$ (antidecuplet) the term $\sim m$ in (2) $ΔE_{rot, i0} = 3/(2Θ_S) ≃ 714 Mev$. Antidecuplet contains the positive strangeness, $S = +1$, isospin $T = 0$ component $Z^+$ which is of special interest as the lowest baryon with positive strangeness. The first numerical calculation of the mass difference of $Z^+$ and nucleon gave $ΔM_{Z^+} = M_{Z^+} - M_N ≃ 740 Mev$ [7]. The Schwesinger-Weigel slow rotator approach fitting the mass splittings of the octet and decuplet of baryons gives $ΔM_{Z^+} = 795 Mev$. Recently the problem of antidecuplet received much attention in [3]. Fitting the mass difference of $N^*(1710)$ resonance and the nucleon in the assumption that $N^*(1710)$ is just the nonstrange component of $i0$ the authors obtained $ΔM_{Z^+} = 590 Mev$ and estimated the width of $Z^+$ to be $\sim 15 Mev$. The searches of $Z^+$ as well as exotic $Ξ^{-σ}$ and $Ξ^{+σ}$ states, the components of the iso-quartet with $S = -2$, are of interest. The latter state should have the mass about $1.2 Gev$ greater than nucleon mass and the width of several tens of $Mev$, at least.

2 THE $B = 2$ SECTOR: $SO(3)$ HEDGEHOG AND $SU(2)$ TORUS

Situation is different in the sector with baryon number $B = 2$. The chiral soliton approach is of special interest for $B \geq 2$ because it provides unconventional point of view at the baryonic systems and nuclear fragments. The baryons individuality is absent in the bound states of skyrmions and can be restored when non-zero modes quantum effects are taken into account [2], [4].

Till now three different types of dibaryons are established within the chiral soliton approach. There is long-standing prediction of the $H$-dibaryon in the framework of MIT quark-bag model [1], confirmed also in the $SU(3)$ extension of the Skyrme model [2] and in the quark-cluster model [3]. The $SO(3)$ hedgehog with the lowest possible for this subgroup baryon (winding) number, $B = 2$, is interpreted usually as $H$-dibaryon. Big efforts of different groups during several years did not lead to the experimental confirmation of this prediction till present time.

The state with the azimuthal winding $n = 2$ has $B = 4$ and the torus-like form of the mass and $B$-number distributions. It is bound relative to the decay into two $B = 2$ hedgehogs [4]. This tendency of binding of two $H$-particles has been confirmed also within some variant of the quark model [5].

As it was shown in [3] the $H$-particle can be unbound when Casimir energies (CE) of solitons are taken into account. It should be noted that, within the CSA, $H$-particle is an object considerably smaller than the deuteron, $<R_H>^2 ≃ (0.2 - 0.3)Fm^2$, [4]. Therefore, theoretical estimates of the $H$ production cross sections based on the similarity between $H$ and the deuteron can be overestimated at least by one order of magnitude.

The second type of dibaryons is obtained by means of the quantization of bound $SU(2)$-solitons in $SU(3)$ collective coordinates space. The bound state of skyrmions with
$B = 2$ possesses generalized axial symmetry and torus-like distributions of the mass and $B$–number densities $[16]$. Now it is checked in several variants of chiral soliton models and also in the chiral quark-meson model. Therefore, the existence of $B = 2$ torus-like bound skyrmion seems to be firmly established.

After zero-modes quantization procedure the $SU(3)$ multiplets of dibaryons appear, with the ratio of strangeness to baryon number $S/B$ down to $-3$. The possible $SU(3)$ multiplets which could consist of minimal number of valence quarks are antidecuplet, $27-$, $35-$ and $28-$plets. The contribution to the energy from rotations into "strange" direction is the same for minimal irreps satisfying the relation $\frac{\ell_1 + 2q}{3} = B = 2$, as it was noted above, see Eq. (2). The deuteron binding energy within this approach is about $30\text{MeV}$ instead of $2.2\text{MeV}$, so, $\sim 30\text{MeV}$ is uncertainty of the model predictions. All strange states are bound when contributions linear in $N_c$, the classical mass, and also $E_{rot}$ are taken into account. However, after renormalization of masses which is necessary to take into account also the CE of the torus (of the order $N_C^0$) and to produce the nucleon-nucleon $^1S_0$-scattering state on the right place all states with strangeness different from zero are above thresholds for the strong decays $[17]$. Therefore, it will be difficult to observe such states experimentally. The virtual $\Lambda N$ level seen many years ago in reaction $pp \rightarrow p\Lambda K^+$ $[18]$ and confirmed in recent measurements can be one of the states with $S = -1$ obtained in $[17]$.

3 SKYRMION MOLECULES

The third type of states is obtained by means of quantization of strange skyrmion molecules (SSM) found recently $[19]$. To obtain the strange skyrmion molecule we used the ansatz of the type

$$U = U_L(u,s)U(u,d)U_R(d,s)$$

where $U_L(u,s)$ and $U_R(d,s)$ describe solitons located in $(u,s)$ and $(d,s)$ $SU(2)$ subgroups of $SU(3)$, one of $SU(2)$-matrices, e.g. $U(u,d)$ depends on two parameters:

$$U(u,d) = \exp(ia\ell_2)\exp(ib\ell_3)$$

and thus describes the relative local orientation of these solitons in usual isospace. The configuration considered depends totally on 8 functions of 3 variables. It should be noted that the baryon number density as well as chirally invariant contributions to the energy of solitons can be presented in the form symmetric in different $SU(2)$ subgroups of $SU(3)$:

$$B = -\frac{1}{2\pi^2}\int\left[(\tilde{L}_1\tilde{L}_2\tilde{L}_3) + (\tilde{L}_4\tilde{L}_5\tilde{L}_3) + (\tilde{L}_6\tilde{L}_7\tilde{L}_3) + \frac{1}{2}[(\tilde{L}_1,\tilde{L}_4\tilde{L}_7 - \tilde{L}_5\tilde{L}_6) + (\tilde{L}_2,\tilde{L}_4\tilde{L}_6 + \tilde{L}_5\tilde{L}_7)]\right]d^3r$$

Here $\tilde{L}_3 = (L_3 + \sqrt{3}L_8)/2$, $\tilde{L}_3 = (-L_3 + \sqrt{3}L_8)/2$ are the 3-d components of chiral derivatives in the $(u,s)$ and $(d,s)$ $SU(2)$ subgroups of $SU(3)$, $i\lambda_k\tilde{L}_k = U^\dagger\partial U$, $\lambda_k$ are 8 Gell-Mann matrices.

To get the $B = 2$ molecule we started from two $B = 1$ skyrmions in the optimal attractive orientation at relative distance between topological centers close to the optimal one, a bit smaller. Special algorithm for minimization of the energy functionals depending on 8 functions was developed and used $[19]$. The energy functional of arbitrary $SU(3)$ solitons can be written also in the form which respects the democracy of different $SU(2)$ subgroups of $SU(3)$ $[20]$:

$$M_{cl} = \int(M_2 + M_4 + M_{SB})d^3r$$

(6)
With
\[ M_2 = \frac{F_s^2}{8} \left[ \vec{L}_1^2 + \vec{L}_2^2 + \vec{L}_3^2 + \vec{L}_4^2 + \vec{L}_5^2 + \vec{L}_6^2 + \frac{2}{3}(\vec{L}_3^2 + \vec{L}_3^2 + \vec{L}_3^2) \right] \] (7)
\[ M_4 = \frac{1}{4e^2} \left\{ (\tilde{s}_{12} + \tilde{s}_{45})^2 + (\tilde{s}_{45} + \tilde{s}_{67})^2 + (\tilde{s}_{67} - \tilde{s}_{12})^2 + \frac{1}{2} \left[ (2\tilde{s}_{13} - \tilde{s}_{46} - \tilde{s}_{57})^2 + (2\tilde{s}_{23} + \tilde{s}_{47} - \tilde{s}_{56})^2 + \\
+ (2\tilde{s}_{34} + \tilde{s}_{16} - \tilde{s}_{27})^2 + (2\tilde{s}_{35} + \tilde{s}_{17} + \tilde{s}_{26})^2 + (2\tilde{s}_{36} + \tilde{s}_{14} + \tilde{s}_{25})^2 + (2\tilde{s}_{37} + \tilde{s}_{15} - \tilde{s}_{24})^2 \right] \right\} \] (8)
\[ \tilde{s}_{ik} = [\vec{L}_i \vec{L}_k], \tilde{s}_{45} = [\vec{L}_3 \vec{L}_4], \text{ and } \tilde{s}_{36} = [\vec{L}_5 \vec{L}_6], \text{ similar for } \tilde{s}_{37}. \text{ Note that } \vec{L}_8 \text{ or } \tilde{L}_8 \text{ do not enter } \tilde{\sigma}_5 \text{.} \]

The mass term \( M_{SB} \) violates the chiral symmetry and contains the flavor symmetric as well as flavor symmetry breaking parts:
\[ M_{SB} = F_s^2 m_\pi^2 (3 - v_1 - v_2 - v_3)/8 + (F_s^2 m_K^2 - F_s^2 m_\pi^2)(1 - v_3)/4, \] (9)
\( v_1, v_2, v_3 \) are the real parts of the diagonal elements of \( SU(3) \) matrix \( U \). Expressions (5)–(9) and (10) below provide the framework for studies of any \( SU(3) \) Skyrmions located originally in arbitrary \( SU(2) \) subgroups of \( SU(3) \).

After minimization of the energy functional we obtained the configuration of molecular type with the binding energy about half of that of the torus, i.e. about \( \sim 75 \text{ MeV} \) for parameters of the model \( F_s = 186 \text{ MeV} \) and \( e = 4.12 \) [19]. The attraction between unit Skyrmions which led to the formation of torus-like configuration when they were located in the same \( SU(2) \) subgroup of \( SU(3) \) is not sufficient for this when solitons are located in different subgroups of \( SU(3) \). It is connected with the fact that solitons located in different \( SU(2) \) subgroups interact through one common degree of freedom, instead of 3 degrees, as in the first case.

4 QUANTIZATION OF THE SSM

The quantization of zero modes of strange Skyrmion molecules cannot be done using the standard procedure, its substantial modification is necessary [20]. To proceed we calculated the Wess-Zumino term for arbitrary \( SU(3) \) Skyrmions. It is linear in the angular velocities of rotation in the \( SU(3) \) configuration space defined in the standard way:
\[ A^i A = -\frac{i}{2} \omega_k \lambda_k, \quad k = 1, 2, \ldots, 8, \text{ and } WZ \sim (WZ_k^L + WZ_k^R) \omega_k. \] The 8-th component of the WZ-term is most important and is equal to
\[ WZ_k^L = -\sqrt{3} (\vec{L}_1 \vec{L}_2 \vec{L}_3) + (\vec{L}_8 \vec{L}_4 \vec{L}_5) + (\vec{L}_8 \vec{L}_6 \vec{L}_7) \] (10)

Similar expression holds for \( WZ_R \) in terms of right chiral derivatives \( \vec{R}_k \). As a result, the quantization condition established first in [3] is changed, and for strange Skyrmion molecule we obtained
\[ Y_{R}^{min} = 2\partial L^WZ/\sqrt{3} \partial \omega_k \simeq -(B_L + B_R)/2 = -1 \] (11)
for \( B_L = B_R = 1 \) [20] instead of the right hypercharge \( Y_R = B, [3] \) (we put here the number of colors \( N_c = 3 \), \( B_L \) and \( B_R \) are the \( B \)-numbers located in \( (u, s) \) and \( (d, s) \) \( SU(2) \) subgroups. The interpolating formula proposed in [13] for \( Y_{R}^{min} \) is
\[ Y_{R}^{min} \simeq N_c B(1 - 3C_s)/3 \] (12)
with \( C_s = < 1 - v_3 > / < 3 - v_1 - v_2 - v_3 > - \text{ scalar strangeness content of solitons.} \) (12) is exact for any \( (u, d) \) \( SU(2) \) solitons rotated in \( SU(3) \) collective coordinates space as well as for
SO(3) solitons ($C_S = 1/3$). For strange molecule $C_S \simeq 1/2$ and (12) is valid approximately [20].

The zero-modes energy - quadratic form in 8 angular velocities of rotation in SU(3) configuration space - can be obtained from (8) by means of substitution in $M_4 \bar{L}_i \rightarrow \tilde{\omega}_i/2$, and in $M_4 \tilde{\omega}_k \rightarrow [\tilde{\omega}_k L_k - \tilde{\omega}_k \bar{L}_k]/2$, $\tilde{\omega}_i$ being some linear combination of 8 components of angular velocities $\omega_i$, details can be found in [20]. The moments of inertia of SU(3) skyrmions can be calculated from this expression.

In view of the evident relation $(p + q)/3 \geq Y_R^{\min} \geq -(q + 2p)/3$ the lowest multiplets obtained by means of quantization of strange skyrmion molecule are octet, decuplet and antidecuplet with central values of masses about 4.2, 4.5 and 4.7 GeV. Within the octet the states with strangeness $S = -1, -2$ and $-3$ are predicted. They are coupled correspondingly to $\Lambda N - \Sigma N$, $\Lambda \Sigma - \Xi N$ or $\Lambda \Xi - \Xi \Xi$ channels, see the discussion of the absolute values of masses within CSA below in Section 5.

The mass splittings within multiplets considered are defined, as usually, by chiral and flavor symmetry breaking mass term in the effective lagrangian. Its contribution to the masses of the states in the case of strange skyrmion molecules equals to

$$\delta M = -\frac{1}{4}(F_K^2m^2_K - F^2_m^2\pi^2)(v_1 + v_2 - 2v_3) < \sin^2\nu/2 >$$

The function $\nu$ parametrizes as usually the $\lambda_4$ rotation in the collective coordinates quantization procedure, and the average over the wave function of the state should be taken for $\sin^2\nu$. For two interacting undeformed hedgehogs at large relative distances $v_1 + v_2 - 2v_3 \rightarrow 2(1 - \cos F)$ where $F$ is the profile function of the hedgehog. Note, that the sign in (13) is opposite to the sign of analogous term when $(u, d)$ SU(2) soliton is quantized with SU(3) collective coordinates.

The result of calculation depends to some degree on the way of calculation. We can start with the soliton calculated for all meson masses equal to the pion mass (flavor symmetric, FS-case), or with soliton calculated with the kaon mass included into the lagrangian (FSB-case). The static energy of solitons are greater in the FSB case, the moments of inertia are smaller, and the mass splittings within the SU(3) multiplets are squeezed by a factor about $\sim 2.5$ in the latter case in comparison with the FS-case [20]. The results of both ways of calculation are close to each other for the octet of dibaryons, the difference increases for decuplet and is large for antidecuplet. By this reason the method of calculation should be found where results do not depend on the starting configuration. It can be, probably, some kind of “slow rotator” approximation [1].

The relative binding energy of quantized states ranges from $\sim 0.14$ for the octet, to $\sim 0.11$ for decuplet down to $\sim 0.07$ for antidecuplet of dibaryons.

The inclusion of the configuration mixing into consideration [21] usually increases the mass splittings within multiplets, although it does not change the results crucially.

5 SUMMARY AND DISCUSSION

To summarize, there are different branches of the predictions of strange dibaryons within the chiral soliton approach. The first one is the SO(3) hedgehog identified usually with the $H$-particle predicted within the MIT quark-bag model. The second is obtained by means of the quantization of the bound torus-like biskyrmion. The third is the quantized strange skyrmion molecule.

The main uncertainty in the masses of all predicted states comes from the poor known Casimir energies of states - the loop corrections of the order of $N^0_c$ to the classical masses of solitons. The CE was estimated for the $B = 1$ hedgehog [3, 4] and also for
$B = 2 \ SO(3)$ hedgehog $^{[3]}$. For $B = 1$ case it has right sign and order of magnitude, about $(-1 - 1.5) \ Gev$. For the torus-like $B = 2$ skyrmion $^{[16]}$ the CE is not estimated yet.

The skyrmion molecules found in $^{[19]}$ should have the lowest uncertainty in Casimir energies relative to the $B = 1$ states since in the molecule unit skyrmions are only slightly deformed in comparison with starting unperturbed configurations. Therefore, one can hope that the property of binding of dibaryons belonging to the lowest multiplets, octet and decuplet, will not disappear after inclusion of the CE and vibration, breathing, etc. quantum corrections. The results for strange molecule are in qualitative agreement with those of $^{[22]}$ where the attraction between hyperons was found at large relative distances.

The prediction of the existence of multiplets of strange dibaryons some of them being bound relative to strong interaction, remains a challenging property of the chiral soliton approach. Quite similar predictions can be obtained also for baryonic systems with $B = 3, 4$, etc. These predictions are on the same level as the existence of strange hyperons in the $B = 1$ sector of the model because, within the chiral soliton approach, skyrmions with different values of $B$ are considered on equal footing. Further theoretical studies and comparison with predictions of other models (see, e.g. $^{[23]}-^{[25]}$) would be important, as well as the experimental searches for such states. The enhancement of strangeness production observed in heavy ion collisions can be, at least partly, due to copious production and subsequent decays of strange baryonic systems (nuclear fragments).

However, in view of specific internal problems of the CSA - e.g., both $SO(3)$ hedgehog and strange $B = 2$ molecule do not possess definite parity $^{[12, 20]}$ - it can be that some of the predictions of the Skyrme model are the artefact of the model. If it is really so, one should understand the reason for this, and how to separate true prediction from the wrong one.

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