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Strange skyrmions: status and observable predictions

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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 spectrum of well known octet and decuplet of baryons can be described within the CSA, and some exotic states are predicted. In the $B = 2$ sector, there are many predictions of strange dibaryons, but only few - e.g., the virtual ΛN 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), first proposed by Skyrme, allows one to describe the properties of baryons - octet and decuplet [1] - and also the basic properties of lightest nuclei with baryon number $B = 2$, 3 and 4 [2]. 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 have been known for many years. When the chiral soliton approach was applied for a description of the baryon properties, it was a problem to describe the corresponding mass splittings [3]. Reasonable agreement with data has been reached when flavor symmetry breaking is taken into account, not only in meson masses but also in the meson decay constants, with $F_K/F_\pi \simeq 1.26$ [1].

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

$$M = M_{cl} + E_{rot}(p, q, Y, T, J; \Theta_T, \Theta_S, \Theta_J, ...) + E_{Cas} \ , \tag{1}$$

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 Θ_i defined by the profile functions of the solitons. E_{rot} contains terms $\sim 1/N_c$ and terms $\sim N_c^0$, as shown recently by Walliser [4]. p, q, Y, T and J denote the SU(3) multiplet, hypercharge of the state, its isospin and angular momentum. $E_{Cas} \sim N_c^0$ 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} has been estimated in only a few cases [5,6,4].

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

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

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), and $N = (p + m)/2$ is the "right" isospin. For "minimal" SU(3) multiplets, $m = 0$. For $B = 1$, the octet and decuplet of baryons are just such minimal multiplets, with $(p + 2q)/3 = 1$. The first term in Eq. (2), $3B/(4\Theta_S)$, is the same for all minimal multiplets because of a cancellation of the second-order Casimir operators of the groups SU(2) and SU(3) [7]. 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 $\Theta_S(1)$ is given by second term in (2) proportional to m, with $m = 1, B = 1$ [7].

In many variants of the model for baryons $\Theta_S(1) \simeq 2.1$ GeV^{-1} [1,8]. Therefore, for $m = 1, N = 1/2$ (antidecuplet) the term $\sim m$ in Eq. (2) $\Delta E_{rot,\overline{10}} = 3/(2\Theta_S) \simeq 714$ MeV. The antidecuplet contains the positive strangeness $S = +1$, $T = 0$ component Z^+, which is of special interest as the lowest baryon with positive strangeness. The first numerical calculation of the mass difference between the Z^+ and the nucleon gave $\Delta M_{Z^+} = M_{Z^+} - M_N \simeq 740$ MeV [8]. The Schwesinger-Weigel slow rotator approach, fitting the mass splittings of the octet and decuplet of baryons, gives $\Delta M_{Z^+} = 795$ MeV. Recently the problem of the antidecuplet received much attention in [9]. Fitting the mass difference of the $N^*(1710)$ resonance and the nucleon under the assumption that the $N^*(1710)$ is just the nonstrange component of the $\overline{10}$, the authors obtained $\Delta M_{Z^+} = 590$ MeV and estimated the width of the Z^+ to be ~ 15 MeV. Searches for the Z^+ as well as the exotic Ξ^{*--} and Ξ^{*+} states, the components of the iso-quartet with $S = -2$, are of interest. The last state should have a mass about 1.2 GeV greater than the nucleon mass and a width of several tens of MeV, at least.

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

The 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 an unconventional point of view of baryonic systems and nuclear fragments. The individuality of the baryons is absent in the bound states of skyrmions and can be restored when non-zero mode quantum effects are taken into account [2], [10].

Till now three different types of dibaryons are established within the chiral soliton approach. There is longstanding prediction of the H-dibaryon in the framework of MIT quark-bag model [11], confirmed also in the SU(3) extension of the Skyrme model [12] and in the quark-cluster model [13]. The SO(3) hedgehog with the lowest possible baryon (winding) number, $B = 2$, for this subgroup is interpreted usually as H-dibaryon. Big efforts by different groups over several years have not yet lead to experimental confirmation of this prediction.

The state with azimuthal winding $n = 2$ has $B = 4$ and a torus-like form of the mass and B-number distributions. It is bound relative to the decay into two $B = 2$ hedgehogs

[14]. This tendency for the binding of two H-particles has also been confirmed within a variant of the quark model [15].

As was shown in [6], the H-particle may be unbound when the Casimir energies (CE) of the solitons are taken into account. It should be noted that, within the CSA, the H-particle is an object considerably smaller than the deuteron, $< R_H >^2 \simeq (0.2 - 0.3)$ fm^2 [6]. Therefore, theoretical estimates of H production cross sections based on a similarity between the H and the deuteron can be overestimates by at least one order of magnitude.

The second type of dibaryon is obtained by means of the quantization of bound SU(2)-solitons in SU(3) collective coordinate 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]. This has now been 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 the zero-modes quantization procedure, SU(3) multiplets of dibaryons appear, with a ratio of strangeness to baryon number S/B down to -3. The possible SU(3) multiplets which could consist of the minimal number of valence quarks are the antidecuplet, 27-, 35- and 28-plets. The contribution to the energy from rotations into the "strange" direction is the same for minimal irreps satisfying the relation $(p+2q)/3 = B = 2$, as was noted above (see Eq. (2)). The deuteron binding energy within this approach is about 30 MeV instead of 2.2 MeV, so $\sim$ 30 MeV is the uncertainty in the model predictions. All strange states are bound when contributions linear in N_c, the classical mass, and of the order N_c^{-1} and N_c^0 in 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 in the right place, all states with strangeness different from zero are above thresholds for strong decays [17]. Therefore, it will be difficult to observe such states experimentally. The virtual ΛN level seen many years ago in the reaction $pp \to p\Lambda K^+$ [18], and confirmed in recent measurements, may be one of the states with $S = -1$ obtained in [17].

3. SKYRMION MOLECULES

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

$$U = U_L(u,s)U(u,d)U_R(d,s) \ , \tag{3}$$

where $U_L(u,s)$ and $U_R(d,s)$ describe solitons located in the (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

$$U(u,d) = \exp(ia\lambda_2)\exp(ib\lambda_3) \tag{4}$$

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 a form symmetric in different SU(2) subgroups of SU(3),

$$B \quad = -\frac{1}{2\pi^2}\int[(\vec{L}_1\vec{L}_2\vec{L}_3) + (\vec{L}_4\vec{L}_5\tilde{\vec{L}}_3) + (\vec{L}_6\vec{L}_7\tilde{\tilde{\vec{L}}}_3)$$

$$+\frac{1}{2}[(\vec{L}_1,\vec{L}_4\vec{L}_7-\vec{L}_5\vec{L}_6)+(\vec{L}_2,\vec{L}_4\vec{L}_6+\vec{L}_5\vec{L}_7)]]d^3r\;. \tag{5}$$

Here, $\tilde{L}_3 = (L_3+\sqrt{3}L_8)/2$, $\tilde{\tilde{L}}_3 = (-L_3+\sqrt{3}L_8)/2$ are the 3-d components of chiral derivatives in the (u,s) and (d,s) SU(2) subgroups of SU(3), $i\lambda_k\vec{L}_k = U^\dagger\vec{\partial}U$, and λ_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 - actually a bit smaller. A 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 also be written in a form which respects the democracy of different SU(2) subgroups of SU(3) [20]

$$M_{cl} = \int (M_2+M_4+M_{SB})d^3r\;, \tag{6}$$

with

$$M_2 = \frac{F_\pi^2}{8}[\vec{L}_1^2+\vec{L}_2^2+\vec{L}_4^2+\vec{L}_5^2+\vec{L}_6^2+\vec{L}_7^2+\frac{2}{3}(\vec{L}_3^2+\tilde{\vec{L}}_3^2+\tilde{\tilde{\vec{L}}}_3^2)] \tag{7}$$

$$\begin{aligned}M_4 &= \frac{1}{4e^2}\Big\{(\vec{s}_{12}+\vec{s}_{45})^2+(\vec{s}_{45}+\vec{s}_{67})^2+(\vec{s}_{67}-\vec{s}_{12})^2+\frac{1}{2}[(2\vec{s}_{13}-\vec{s}_{46}-\vec{s}_{57})^2\\ &+ (2\vec{s}_{23}+\vec{s}_{47}-\vec{s}_{56})^2+(2\tilde{\vec{s}}_{34}+\vec{s}_{16}-\vec{s}_{27})^2+(2\tilde{\vec{s}}_{35}+\vec{s}_{17}+\vec{s}_{26})^2\\ &+ (2\tilde{\vec{s}}_{36}+\vec{s}_{14}+\vec{s}_{25})^2+(2\tilde{\vec{s}}_{37}+\vec{s}_{15}-\vec{s}_{24})^2]\Big\}\;,\end{aligned} \tag{8}$$

where $\vec{s}_{ik} = [\vec{L}_i\vec{L}_k]$, $\tilde{\vec{s}}_{34} = [\tilde{\vec{L}}_3\vec{L}_4]$, $\tilde{\vec{s}}_{36} = [\tilde{\tilde{\vec{L}}}_3\vec{L}_6]$, and similarly for $\tilde{\vec{s}}_{37}$. Note that $\vec{L}_8$ or $\tilde{\vec{L}}_8$ do not enter (5) – (8).

The mass term M_{SB} violates the chiral symmetry and contains flavor symmetric as well as flavor symmetry breaking parts

$$M_{SB} = F_\pi^2 m_\pi^2(3-v_1-v_2-v_3)/8+(F_K^2m_K^2-F_\pi^2m_\pi^2)(1-v_3)/4\;, \tag{9}$$

where v_1, v_2, v_3 are the real parts of the diagonal elements of the SU(3) matrix U. Expressions (5) – (9) and (10) below provide the framework for studies of any SU(3) skyrmions originally located in arbitrary SU(2) subgroups of SU(3).

After minimization of the energy functional, we obtained a configuration of the molecular type with a binding energy about half of that of the torus, i.e. about ~ 75 MeV for the parameters of the model with $F_\pi = 186$ MeV and $e = 4.12$ [19]. The attraction between unit skyrmions, which led to the formation of a 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). This 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 the zero modes of strange skyrmion molecules cannot be done using the standard procedure, and a 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, namely $A^\dagger\dot{A} = -\frac{i}{2}\omega_k\lambda_k$, $k = 1,...8$ 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

$$WZ_8^L = -\sqrt{3}(\vec{L}_1\vec{L}_2\vec{L}_3) + (\vec{L}_8\vec{L}_4\vec{L}_5) + (\vec{L}_8\vec{L}_6\vec{L}_7)\ . \tag{10}$$

A similar expression holds for WZ^R in terms of the right chiral derivatives $\vec{R}_k$. As a result, the quantization condition first established in [3] is changed, and for the strange skyrmion molecule we obtained

$$Y_R^{min} = 2\partial L^{WZ}/(\sqrt{3}\partial\omega_8) \simeq -(B_L + B_R)/2 = -1 \tag{11}$$

for $B_L = B_R = 1$ [20], instead of the known relation for the right hypercharge $Y_R = B$ [3] (we put here the number of colors $N_c = 3$), where B_L and B_R are the B-numbers located in the (u,s) and (d,s) SU(2) subgroups. The interpolating formula proposed in [20] for Y_R^{min} is

$$Y_R^{min} \simeq N_cB(1 - 3C_S)/3\ , \tag{12}$$

with $C_S =< 1 - v_3 > / < 3 - v_1 - v_2 - v_3 >$ the scalar strangeness content of solitons. Eq. (12) is exact for any (u,d) SU(2) solitons rotated in SU(3) collective coordinate space, as well as for SO(3) solitons ($C_S = 1/3$). For the strange molecule, $C_S \simeq 1/2$ and (12) is valid approximately [20].

The zero-modes energy - a quadratic form in 8 angular velocities of rotation in SU(3) configuration space - can be obtained from (8) by means of the substitution $\vec{L}_i \to \tilde{\omega}_i/2$ in M_2, and $\vec{s}_{ik} \to [\tilde{\omega}_i\vec{L}_k - \tilde{\omega}_k\vec{L}_i]/2$ in M_4, $\tilde{\omega}_i$ being some linear combination of the 8 components of the angular velocities ω_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 $(p + 2q)/3 \geq Y_R \geq -(q + 2p)/3$, the lowest multiplets obtained by means of quantization of the strange skyrmion molecule are the octet, decuplet and antidecuplet with central values for the masses of about 4.2, 4.5 and 4.7 GeV. Within the octet, states with strangeness $S = -1$, -2 and -3 are predicted. They are coupled correspondingly to the ΛN-ΣN, ΛΛ-ΞN or ΛΣ, and ΛΞ-ΣΞ channels. The absolute values of masses within the CSA are discussed below in Section 5.

The mass splittings within the multiplets considered are defined, as usual, by a 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 is

$$\delta M = -\frac{1}{4}(F_K^2m_K^2 - F_\pi^2m_\pi^2)(v_1 + v_2 - 2v_3) < sin^2\nu/2 >\ . \tag{13}$$

The function ν parametrizes, as usual, the λ_4 rotation in the collective coordinate 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, $v_1+v_2-2v_3 \to 2(1 - cosF)$, where F is the profile function of the $B = 1$ hedgehog. Note that the sign in (13) is opposite to the sign of the analogous term when a (u,d) SU(2) soliton is quantized with SU(3) collective coordinates.

The result of a 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 the soliton calculated with the kaon mass included in the Lagrangian (FSB-case). The static energies 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 ~ 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 the decuplet and is large for the antidecuplet. For this reason, a method of calculation should be found where results do not depend on the starting configuration. It could be, probably, some kind of "slow rotator" approximation [1].

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

The inclusion of configuration mixing [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 predictions for strange dibaryons within the chiral soliton approach. The first one is the SO(3) hedgehog, usually identified 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 poorly known Casimir energies of the states - the loop corrections of the order of N_c^0 to the classical masses of solitons. The CE was estimated for the $B = 1$ hedgehog [5,4], and also for $B = 2$ SO(3) hedgehog [6]. For the $B = 1$ case, it has right sign and order of magnitude, about -1.0 to -1.5 GeV. For the torus-like $B = 2$ skyrmion [16], the CE has not been 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 the unit skyrmions are only slightly deformed in comparison with the unperturbed starting 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 molecules are in qualitative agreement with those of [22], where 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 an equal footing. Further theoretical studies, and comparison with predictions of other models (see, e.g. [23]-[25]), would be important, as well as further experimental searches for such states. The enhancement of strangeness production observed in heavy-ion collisions could 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 the SO(3) hedgehog and the strange $B = 2$ molecule do not possess definite parity [12,20] - it may be that some of the predictions of the Skyrme model are artefacts of the model. If this is really so, one should understand the reason for this, and how to separate true predictions from the wrong ones.

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