Multibaryons with strangeness and charm

V. Kopeliovich
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Problem of element. particle and nuclear physics: can the fragments of nucl. matter exist with flavor s, c or b, stable relative to strong interactions?
Or even absolutely stable (for strangeness)?

Astrophysical and/or cosmological applications: neutron stars (pulsars) can be Strange Matter stars. (Alcock, Farhi, Olinto, '86; Madsen '88)

In our Earth conditions the only way is to produce fragments of flavored matter using accelerators of protons or heavy ions. The energy of several tens of GeV is sufficient.

1. $M_{FF} > \Sigma (m_{NF} + m_{\Lambda_F (\Sigma_F)})$ unstable, strong decay +

2. $M_{FF} < \Sigma (m_{NF} + m_{\Lambda_F (\Sigma_F)})$ metastable, weak decay +

3 $M_{FF} < \Sigma (m_{NF} + m_e)$ stable −

Essentially many-body problem; there are known difficulties in convent. approaches

Chiral soliton approach (Skyrme '61, Witten '83...) based on effective field theories, allows to „circumwent" many of difficulties.

Effective field theories – eff. chiral lagr-ns, which have justification in QCD provide description of low-energy phenomena in meson-baryon sectors.

$$\mathcal{L}^{eff} = \mathcal{L}^{(2)} + \mathcal{L}^{(4)} + \mathcal{L}^{(6)} + \dots + \mathcal{L}_M$$

$$\mathcal{L}^{(2)} = -\frac{F_\pi^2}{16} \mathrm{Tr}\, L_\mu L^\mu, \qquad L_\mu = \partial_\mu U U^+,$$

unitary matrix $U \in SU_2$ or SU_3

$$\mathcal{L}_A^{(4)} = \frac{1}{32e^2} \mathrm{Tr}\,(\partial_\mu L_\nu - \partial_\nu L_\mu)^2$$ – Skyrme term.

....

$$\mathcal{L}_M = \frac{F_\pi^2 m_\pi^2}{16} \mathrm{Tr}\,(U + U^+ - 2) + (\text{FSB-term})$$

Trunkated eff. lagr-n including 2-d, 4-th and 6-th order terms has solitonic solutions which can be identified with baryons or baryon. systems. (Skyrme '61, Witten '83, Balachandran...) according to known fact in topology that

$$\left| \begin{array}{l} \pi_3(SU_2) = Z \to B \text{ - integer}, \\ \pi_3(SU_N) = Z \end{array} \right.$$

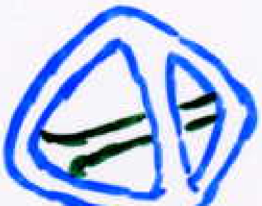
$$B = \frac{1}{24\pi^2} \int \varepsilon_{ijk} \mathrm{Tr}(L_i L_j L_k)\, d^3r$$ – in SU_N

SK4 (Skyrme) and SK6 variants are studied

$M = 1.232$ $\quad \frac{M}{B} = 1.171$ $\quad \frac{M}{B} = 1.143$ $\quad$ in $3\pi^2 \frac{F_\pi}{e}$

$B=1$ '61
Skyrme

$B=2$ '87
YBK, B. Stern



$B=3$. '90

$\frac{M}{B} = 1.116$

$B=4$ '90
Braaten, Townsend, Carson

$\frac{M}{B} = 1.099$

dodecahedron, 12 pentagons

$B=7$ '97
Battye, Sutcliffe

Configurations of lowest energy - examples.
Mass and B-number density distributions - along the edges of polyhedrons.

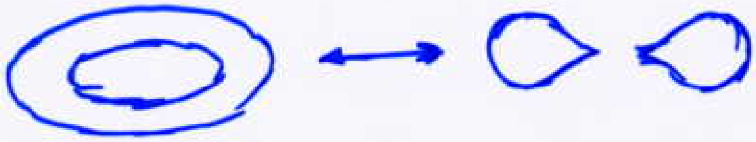
Symmetries and masses of MS are determined for $B \leq 22$ (Battye, Sutcliffe, 2000):
higher polyhedrons, $2B-2$ faces, mostly trivalent vertices - similar to fullerenes (carbon chem.)

At large B, MS can be studied analytically, in Rational Map approximation with good accur. better 1% (YBK, '01)

This picture contradicts to conventional one of nuclear or baryonic matter, made of separate nucleons: principally new concept of matter.

Conventional picture of nuclei appears when nonzero modes (breathing, vibration...) are taken into account.

For $B=2$ transition torus $\leftrightarrow$ two hedgehogs was reproduced



B. Stern, '89

The binding energy $\varepsilon_d \to 6$ MeV (instead of ~30 MeV)

Leese, Manton, Schroers '95

For $B=3,4,7$ only part of such work has been made. N. Walet, '95; C. Barnes, Baskerville, Turok '97

Main uncertainty in the absolute values of masses is due to Casimir energy (loop corrections) $\sim N_c^0$. But it cancels in the differences of binding energies of the quantized states with different F-flavor n.

The spectra of baryonic systems (BS) with different values of s, c or b can be calculated in this way.

This approach provides the picture of BS from outside.

Rigid oscillator version of the bound state model (Kaplan, Klebanov, Westerberg, '90–'96).

SU_2 bound skyrmion is background, collective coordinates are:

$$\mathcal{A}(t) = \begin{vmatrix} A(t) & 0 \\ 0 & 1 \end{vmatrix} e^{i\mathcal{D}(t)}, \quad U(r,t) = \mathcal{A}\, U_0(r)\, \mathcal{A}^+$$

$\mathcal{D}(t)$ describes the motion into „charmed" (bottom, strange) direction,

$A(t) \in SU_2$ describes internal SU_2 rotations.

$$\mathcal{D}(t) = \begin{vmatrix} 0 & \sqrt{2}D \\ \sqrt{2}D^+ & 0 \end{vmatrix}, \quad D = \begin{vmatrix} D_1 \\ D_2 \end{vmatrix} \text{ – 2-component field}$$

$\mathcal{D} \in SU_3$ (Callan, Klebanov, '87)

In the lowest order in D Lagrangian is of oscillator type:

$$L \simeq -M_{cl} + 4\Theta_F \dot{D}^+\dot{D} - \Gamma(m_D^2 - m_\pi^2)D^+D + i\frac{N_cB}{2}(D^+\dot{D} - \dot{D}^+D)$$

N_c - number of colors, B - baryon number, WZW - term

$\Gamma = \frac{F_\pi^2}{2}\int(1-c_f)\,d^3r$ - defines the mass term

$\Theta_F = \frac{1}{8}\int(1-c_F)\left[F_\pi^2 + \frac{1}{e^2}\left((\vec\nabla f)^2 + s_f^2(\vec\nabla\alpha)^2 + s_f^2 s_\alpha^2(\vec\nabla\beta)^2\right)\right]d^3r$ - „flavor" inertia.

$$\Theta_F = \frac{\Gamma}{4} + \Theta_F^{Sk}.$$

f, α, β – 3 functions describing arbitrary SU_2 skyrmion: $U = c_f + s_f\vec{n}\vec{\tau}$, $n_z = c_\alpha$, $n_x = s_\alpha c_\beta$

Hamiltonian:

$$H = M_{cl} + \frac{\Pi^+\Pi}{4\Theta_F} + \left(\Gamma m_D'^2 + \frac{N_c^2 B^2}{16\Theta_F}\right) D^+ D +$$

$$+ i\frac{N_c B}{8\Theta_F}(D^+\Pi - \Pi^+ D)$$

$m_D^{2\prime} = m_D^2 - m_\pi^2$

Π is the momentum canonically conjugate to D.

After diagonalization

$$H = M_{cl} + \omega_F a^+ a + \bar\omega_F b^+ b + \ldots$$

a^+ and b^+ are creation operators of corresponding flavor (antiflavor), s, c or b.

$$|D|^2 \sim \left(4\Theta_F \Gamma\, m_D'^2 + N_c^2 B^2/4\right)^{-1/2}$$

$$\omega_F, \bar\omega_F = \frac{N_c B}{8\Theta_F}\left[\left(1 + 16\, m_D^{2\prime}\Gamma\Theta_F / N_c^2 B^2\right)^{1/2} \mp 1\right]$$

If $m_D^2 \gg \frac{N_c^2 B^2}{16\Gamma\Theta_F}$ then $\omega_F, \bar\omega_F \simeq \frac{m_D'}{2}\left(\frac{\Gamma}{\Theta_F}\right)^{1/2} \mp \frac{N_c B}{8\Theta_F}$

$\bar\omega_F - \omega_F = \frac{N_c B}{4\Theta_F}$ - in agreement with coll. coord. approach

This splitting comes from WZW-term.

$$\omega_F(B=1) - \omega_F(B) \simeq \frac{m_D'}{2}\left[\left(\frac{\Gamma_1}{\Theta_{F,1}}\right)^{1/2} - \left(\frac{\Gamma_B}{\Theta_{F,B}}\right)^{1/2}\right] > 0$$

for $B = 2, 3 \ldots$

It gives additional contribution to the binding energies.

Excitation energies for strangeness, charm and bottom

B	ω_s	ω_c	ω_b (Gev)
1	.309	1.542	4.82
2	.293	1.511	4.76
3	.289	1.504	4.75
4	$\underline{.283}$	$\underline{1.493}$	$\underline{4.74}$
5	.287	1.505	4.75
6	.287	1.504	4.75
7	$\underline{.282}$	1.497	4.75
8	.288	1.510	4.77
RM 17	.300	1.542	4.81
RM 22	.308	1.560	4.84

$m_K = 0.495$, $m_D = 1.86$ $m_B = 5.28$ Gev

$\omega_F < m_F$.

It can be proved rigorously since

$$\Theta_F = \frac{\Gamma}{4} + \Theta_F^{(Sk)}, \text{ or}$$

$$\Theta_F = \frac{F_D^2}{F_\pi^2}\frac{\Gamma}{4} + \Theta_F^{(Sk)}, \text{ and } F_D > F_\pi$$

Binding energies for different „flavors"

B	$\Delta\varepsilon_{S=-1}$	$\Delta\varepsilon_{c=1}$	$\Delta\varepsilon_{b=-1}$ (GeV)
2	-0.047	-0.027	$\underline{0.02}$
3	-0.042	-0.010	$\underline{0.04}$
4	$\underline{-0.020}$	$\underline{0.019}$	$\underline{0.06}$
5	-0.027	$\underline{0.006}$	$\underline{0.05}$
6	$\underline{-0.019}$	$\underline{0.016}$	$\underline{0.05}$
7	$\underline{-0.016}$	$\underline{0.021}$	$\underline{0.06}$
8	$\underline{-0.017}$	$\underline{0.014}$	$\underline{0.02}$
17	$\underline{-0.027}$	$\underline{-0.01}$	$\underline{0.0}$

$|F| = 1$

$\Delta\varepsilon_F$ – the difference of b.e. of flavoured and flavourless state (nucleus)

$\varepsilon(^3He) \simeq 7.7$ MeV $= .0077$ GeV

$\varepsilon(^4He) = 0.028$ GeV

$\varepsilon(^7Li) = 0.039$ GeV

$\varepsilon(^8Li) \simeq 0.041$ GeV

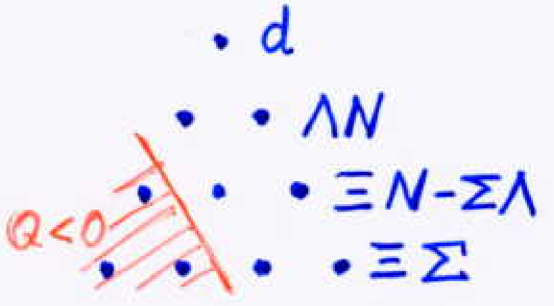
$\underline{\qquad}$ can be bound!

In ΛN-system the near-threshold virtual level is known since 1968: J.T. Reed et al, Phys. Rev. 168, 1495, 1968

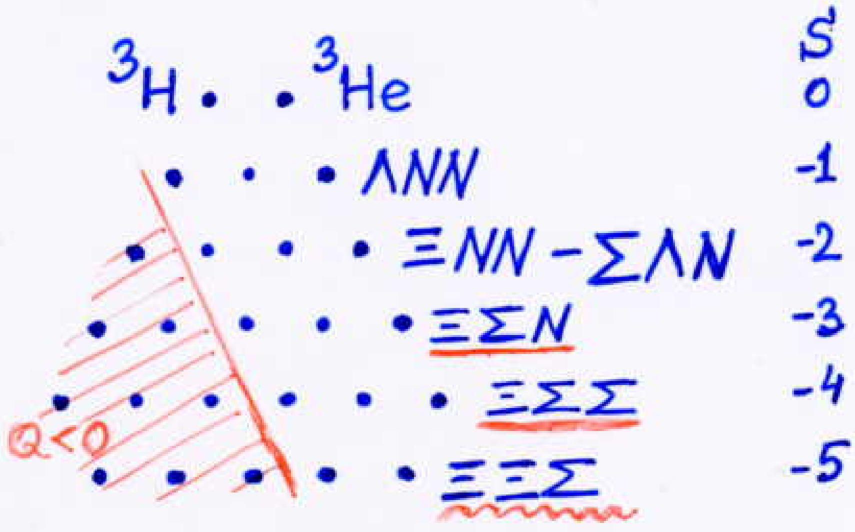
$pp \to K\Lambda N$

Cosy News, 4, 1, 1999

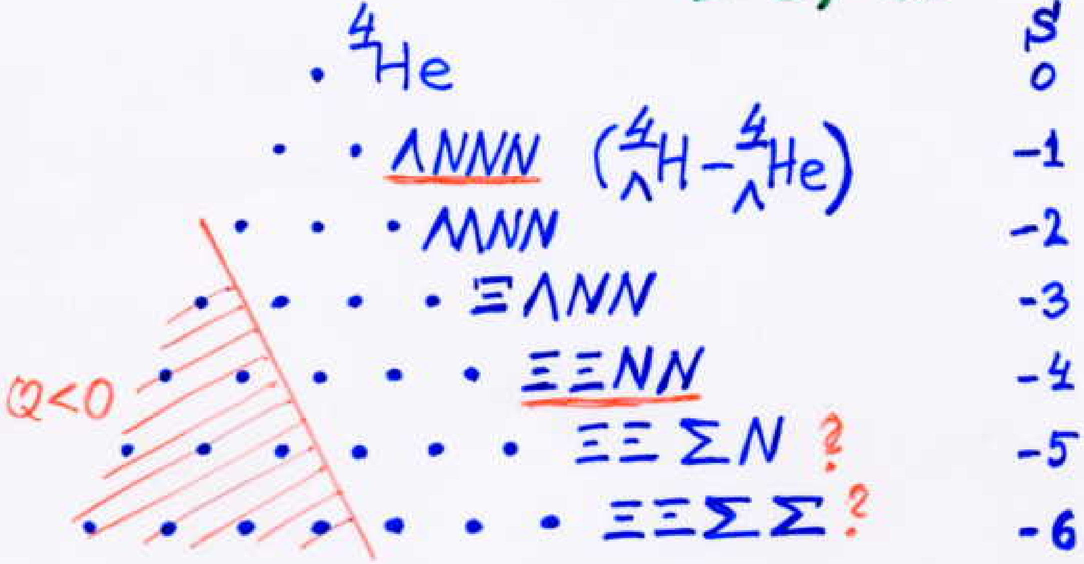
$1/N_c$ quantum correct-ns are included here



$B=2,\ \overline{10}$



$B=3,\ \overline{35}$



$B=4,\ \overline{28}$

For $|S| \geq 4$ the model is not reliable

$|F|=2$, isospin 1 or 3/2.

$(p,q)=(0,\frac{3B}{2})$ or $(1,\frac{3B-1}{2})$

B	$\Delta\mathcal{E}_{s=-2}$	$\Delta\mathcal{E}_{c=2}$	$\Delta\mathcal{E}_{b=-2}$	
2	−0.115	−0.088	0.02	$\overline{10}$
3	−0.098	−0.040	0.06	$\overline{35}$
4	−0.051	0.022	0.10	$\overline{28}$
5	−0.063	0.001	0.08	$\overline{80}$
6	−0.045	0.023	0.10	$\overline{55}$
7	−0.041	0.033	0.11	
8	−0.040	0.021	0.03	
17	−0.11	−0.03	0.0	

Binding energies differences of $|F|=2$ states and ordinary nuclei, $I=\frac{|F|}{2}+I_+$

ΛΛ virtual level was reported in J.K. Ahn et al, KEK PS E224, AIP Conf. Proc. 412, 923 (1997)

$|F|=2$, $I=0$ (even B)

B	$\Delta\mathcal{E}_{s=-2}$	$\Delta\mathcal{E}_{c=2}$	$\Delta\mathcal{E}_{b=-2}$	
2	−0.075	−0.029	0.02	27-plet
4	−0.047	0.030	0.09	$\overline{81}$
6	−0.044	0.025	0.09	$\overline{162}$
8	−0.039	0.023	0.03	
12	−0.046	0.00	0.03	
22	−0.073	−0.06	−0.06	

B	$\Delta\varepsilon_{S=-3}$	$\Delta\varepsilon_{S=-4}$
2	-0.013	$-$
3	0.023	0.07
4	-0.03	-0.02
5	-0.046	-0.04
6	-0.078	-0.05
7	-0.070	-0.04
8	-0.068	-0.10

$I = I_r + |F|/2$

$I = 0$

2	$-$
3	-0.08
4	$-$
5	-0.06
6	$-$
7	-0.04
8	$-$
17	-0.08

Comment:

* Starting point of this consideration is $SU(2)$ (u,d) multiskyrmions quantized (rotated) in $SU(3)$ config. space.

Besides, there are $SO(3)$ solitons which can be $SU(3)$-singlets.
$B=2$ H-particle is most famous example.

It is not clear, can it be made from 2 $B=1$ config-ns. (?!)
Its production can be suppressed in coalescence reactions, only $H\bar{H}$ possible.

Configurations of „molecular type" exist for $B=2$ (for greater B also).

In both cases - no normalization to ordinary nuclei.

Parity of these states is not defined.
Further study is necessary.

** Systems with mixed flavors $(cs, c\bar{s} \ldots)$ can be obtained as well.
Technically it is more complicated.

* Negatively charged nuclear fragment

NA52 CERN Pb + Pb 158 A·GeV

$Q = -1$, $\tau > 0.85\ \mu sec$
$M = 7.4$ GeV

S. Kabana et al, J. Phys. G 23 (97) 2135

$B = 7$, $S = -3$ or -4

$\Delta \mathcal{E}\ (B=7, S=-4) \simeq -40$ MeV

** Enhancement of strangeness production observed in heavy ion collisions can be, at least partly, due to production and subsequent decay of strange multibaryons

Multiskyrmions as baryonic bags

In Rational Map approximation skyrmion mass:

$$M = \frac{1}{3\pi}\int\left[A_N r^2 f'^2 + 2B s_f^2(1+f'^2) + \underline{I}\frac{s_f^4}{r^2}\right]dr$$

$A_N = 2(N-1)/N$, N-number of flavors, $A_2 = 1$

I-characterizes the map $S^{(2)} \to S^{(2)}$ (in SU_2)

f - profile function, $s_f = \sin f$

1-st step: quantity $\underline{I}$ is found, $\underline{I \geq B^2}$

2-d step: profile f is found at fixed I,

$$\cos f = \varphi = \frac{(r/r_0)^b - 1}{(r/r_0)^b + 1}\;,\quad r_0, b \text{ should be found}$$

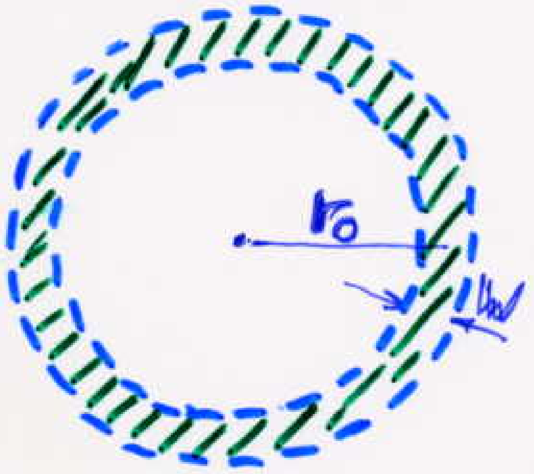
This allows to describe masses with accuracy better than 0.5% for large B, and to make conclusions concerning the properties of MS independently on precise value of $\underline{I}$.

$$b \simeq 2(I/A_N)^{1/4} \sim B^{1/2}, \quad \text{since } I \simeq 1.3B^2$$

$$r_0 \simeq \left[\frac{2}{3}\left(\sqrt{\frac{I}{A_N}} - \frac{1}{4}\right)\right]^{1/2} \sim B^{1/2} \text{ at large } B \text{ (in } 2/F_\pi e)$$

Similar to the domain wall (spherical)

Flavor s, c, b is bound in the shell



At large B multisk-ns look like spherical bubbles, or domain walls with mass and B-number densities concentr. mainly in the shell of thickness W.

$$r_0 \sim \sqrt{B}, \quad W = Const \simeq \frac{3.6}{F_\pi e}$$

W does not depend on B and N.

Large B multisk-ns are made from universal material (web) with constant thickness and constant dimensions of each cell.

All properties of MS (r_B, r_M, tensors of inertia) can be calculated analytically, in terms of Euler-type integrals | VBK, JETP Lett. 73, 587, '01 hep-ph/0105102

$$\frac{1}{3}\left(2+\sqrt{\frac{IA_N}{B^2}}\right) < \frac{M}{B} < \frac{1}{3}\left(2+\sqrt{\frac{IA_N}{B^2}}\right)\frac{4}{b\sin\frac{\pi}{b}}\left[\frac{2}{3}\left(1-\frac{1}{b^2}\right)\right]^{1/2}, \text{ in } 3\pi^2\frac{F_\pi}{e}$$

$$\left.\frac{M^{max}}{M^{min}}\right|_{B\to\infty} \longrightarrow \frac{4}{\pi}\left(\frac{2}{3}\right)^{1/2} \simeq 1.0396$$

gap is less than 4%

Similar results are obtained for SK6 model (6-th order term in L-n).

At large B ($\sim 10^2$?) transition to conf-ns like skyrmion crystals should take place. Not investigated yet.

Prospects

At the energy of 50 GeV BS the production will be possible of Baryonic systems with

* several units of strangeness ($S=-3,-4 \ldots$)

** 1–2 units of charm ($c=1,2$)

*** $b=-1$ BS can be produced in subthreshold way due to 2-step processes and Fermi-motion of nucleons inside the target nucleus

Effective for $\bar{p}$ production (at ~3 GeV), lowers the threshold almost twice.
Similar mechanism can work for charm also.