Color chiral solitons

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Abstract

We discuss specific features of color chiral solitons in low energy QCD at an example of isolated SU(2) color skyrmions, i.e. skyrmions in a background field which is the vacuum field forming the gluon condensate.

Introduction

In low energy QCD the idea of flavor Skyrmions [1, 2, 4, 5] was quite fruitful. Color chiral solitons and skyrmions were studied less, although to find stable color configurations could be an important step towards understanding of diquarks and exotic hadrons. A possibility of color chiral solitons with baryon number N_F/N_C was mentioned in the first paper on colour bosonization [6] . However, the effective action in bosonization [6] was implicitly gauge dependent, the choice of background colour fields was not discussed, and soliton stability was not investigated. It was found [7] that direct application of an effective bosonized lagrangian [6] does not lead to stable configurations. The idea of color skyrmions from different viewpoints was explored [8, 9, 10, 11] in attempt to construct a constituent quark for $N_F = 1$, but further development in this direction was suspended after the conclusion [12] that stable colour solitons do not exist. Recently it was shown that color solitons become stable due to background vacuum field which should always be present with isolated soliton [13, 14]

In this talk we describe some specific feature of color solitons compared with flavor solitons.

In QCD the flavor soliton action arises as a result of bosonization. The chiral color bosonization in QCD follows , in general, the lines of flavor bosonization [15, 16, 17, 18] . The gluon field is a dynamical gauge field, while the flavor field in the Dirac lagrangian is an external one. In order to get a chiral color action, the background field should be also chirally rotated giving an additional contribution to the standard chiral action. In flavor bosonization no such terms are present [13]. This contribution is not considered here.

For a color soliton, the background field describes soliton environment and produces corresponding interaction terms in the effective chiral lagrangian. In this paper we consider a separate (free) soliton, and, therefore, take color vacuum field as a background

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field. Such color vacuum fields form the gluon condensate. Experimentally, the condensate is positive, so that the vacuum field is chromomagnetic. Its value is a parameter of the theory. Asymptotic behaviour of soliton configuration at large distances from the centre is determined by the condensate: it is exponentially decreasing for positive condensate and periodic otherwise.

In section 2 we start with general expression for a bosonization motivated effective chiral lagrangian and work out an effective chiral action in the case of the gauge group SU(2) and one flavor $N_F = 1$ for the hedghog configuration, study asymptotic behavior and evaluate the mass. In section 3 we define a two-soliton potential at large distances and show that it may lead to confinement. In section 4 we briefly discuss quantization of color $SU(2)$ skyrmion.

Effective lagrangian for SU(2) soliton and choice of background field

We write an effective bosonization lagrangian for the color chiral field U in the form, where we have omitted terms inessential for our discussion

$$L_{eff}(U) = N_F tr_C \{ \frac{f_0^2}{4} D_\mu U D^\mu U^{-1}$$

$$+\frac{1}{192\pi^2}\left[\frac{1}{2}\left[UD_\nu U^{-1}, UD_\mu U^{-1}\right]^2 - (UD_\nu U^{-1}UD^\nu U^{-1})^2\right]\}, \tag{1}$$

As in bosonization, we write the kinetic term with a constant f_0^2 which is an analogue of the pion decay constant f_π^2. The first term in the second line is the Skyrme potential, next term is specific for the bosonization potential . We need it to show that it does not change general properties of classical color soliton. $D_\mu U = \partial_\mu U + [G_\mu, U]$.

Color configurations are always associated with background color field G_μ because of necessity to maintain color gauge invariance. In this respect, color solitons is quite different from flavor solitons, where there is no flavor gauge invariance, and the external flavor gauge field can be eliminated from the chiral action. We consider the color gauge group SU(2) with antihermitian generators $T_a = \frac{\tau_a}{2i}$, where τ_a are the Pauli matrices.

The background color field should be chosen according to the problem under consideration. Our first step is to study a single colour soliton, i.e. a soliton in the vacuum of gluonic field. The gluonic vacuum Ψ_0 is characterized by the condensate

$$C_g = \left(\Psi_0, \frac{g^2}{4\pi^2} O^a_{\mu\nu} O^{\mu\nu a} \Psi_0\right) \cong \frac{g^2}{4\pi^2} G^a_{\mu\nu} G^{\mu\nu a} \neq 0 \tag{2}$$

that is by the non-zero vacuum expectation value of the Yang-Mills lagrangian for the full quantum field O_μ represented by the background vacuum field G_μ in our approximation. According to phenomenological descpription $C_g \succ 0$, so that G_μ is a chromomagnetic field in the real case of SU(3) gauge group. The vacuum field strength G_{kl} in the temporal gauge $G_0 = 0$ is constant up to a time independent gauge transformation. The effective Lagrangian L_{eff} is invariant under gauge transformations of background fields and the chiral field.

We shall consider the simplest case of a chromomagnetic vacuum background field , when it is an Abelian-type field which is a product a coordinate vector field V_k and a SU(2) color vector n^a

$$G_k^a = V_k n^a, V_k = -\frac{1}{2} V_{kl} x_l = -\frac{1}{2} \varepsilon_{klm} x_l \nu_m B, G_k = g G_k^a \frac{\tau_a}{2i} \tag{3}$$

where n^a is a constant unit vector in the colour space, ν_m is a constant unit vector in coordinate space, $\nu_m B = \frac{1}{2} \varepsilon_{mlk} V_{lk}$ is the vacuum chromomagnetism and B is related to the condensate $C_g = \frac{g^2}{2\pi^2} B^2$. In the vacuum all directions n^a and ν_l are equivalent, so that it is necessary to average over them at the end. Such a choice of vacuum field does not lead to stability troubles in QCD; although imaginary terms were detected at one-loop level [20], they disappear in all-loop treatment [21].

Let us write the chiral field in the usual way

$$U = \exp i \left(\frac{x_a \tau_a}{R} \right) F\left(R\right) = \cos F + i \mathbf{r} \sin F, r_a r_a = r^2 = 1, r_a \tau_a = \mathbf{r}, r_a = \frac{x_a}{R} \tag{4}$$

Under a gauge transformation $S(\overrightarrow{x})$ the chiral field U transforms together with the vacuum unit colour vector $\mathbf{n} = n_a \tau_a$ as

$$U' = SUS^+, \mathbf{n}' = S\mathbf{n}S^+ + S\partial_k S^+$$

and it is natural to restrict $S(\overrightarrow{x})$ by a condition $[S, U] = 0$.

Main structures in the Effective Chiral Lagrangian $L_{eff}\left(U\right)$ take on the following form

$$D_k U = \partial_k U + g \frac{V_k}{2i} \left[\mathbf{n}, i\mathbf{r}\right] \sin F$$

$$S_{kl} = \left[U D_k U^+, U D_l U^+ \right] =$$

$$= 4g \left(\left[\overrightarrow{\mathbf{n}}, \overrightarrow{\mathbf{r}}\right]_l V_k - \left[\overrightarrow{\mathbf{n}}, \overrightarrow{\mathbf{r}}\right]_k V_l \right) \frac{\sin^2 F}{R} + \partial_l U \partial_k U^+ - \partial_k U \partial_l U^+ \tag{5}$$

where $R^2 = x_k x_k$. The kinetic structure K and related non -Skyrme term N are given by

$$K = tr \left(D_l U^+ D_l U \right) = 2[(\partial_R F)^2 + \frac{2\sin^2 F}{R^2}] + g^2 V^2 \left[\overrightarrow{n}, \overrightarrow{r}\right]^2 \sin^2 F \tag{6}$$

$$N = tr \left(D_l U^+ D_l U \right)^2 =$$

$$= 2 \left((\partial_R F)^2 + \frac{2\sin^2 F}{R^2} \right)^2 + \frac{16}{15} g^4 V^4 \sin^4 F + \frac{8}{3} g^2 ((\partial_R F)^2 + 3\frac{\sin^2 F}{R^2}) V^2 \sin^2 F \tag{7}$$

where $A^2 = V_k V_k$ and we have averaged over directions $\mathbf{n}$ in the SU(2) colour space putting $\overline{n_k} = 0, \overline{n_k^2} = \frac{1}{3}, \overline{n_k^4} = \frac{1}{5}, \overline{n_k^2 n_l^2} = \frac{1}{15}$.

Similarly, we average over directions $\overrightarrow{\nu}$ of field V_k in space of coordinates x_k and get

$$\overrightarrow{V} = \frac{1}{2} \left[\overrightarrow{\upsilon}, \overrightarrow{r}\right] RB, \overline{V^2} = \frac{1}{6} B^2 R^2, \overline{V^4} = \frac{1}{4} \left(1 - (\overrightarrow{r}, \overrightarrow{\nu})^2 \right)^2_{av} B^4 R^4 = \frac{2}{15} B^4 R^4 \tag{8}$$

It follows that the gauge field dependent part of the Skyrmion structure is given by

$$trS_{kl}S_{kl} - tr(S_{kl}S_{kl})_{B=0} = \frac{32}{9}g^2B^2\sin^4 F \tag{9}$$

while a mixed part of chirally transformed Lagrangian of the background vacuum field acquires $\sin^2 F$

$$trG_{lk}UG_{lk}U^+ = -\frac{4}{3}g^2B^2\sin^2 F, G_{lk} = \frac{g}{2i}B\varepsilon_{lkt}\nu_t n, trG_{lk}G_{lk} = -g^2B^2 \tag{10}$$

We are now able to write down the Effective Color Static Lagrangian

$$\begin{aligned}
L_{eff}(U,G_k) = &-N_F\frac{f_0^2}{16\pi^2}[2((\partial_R F)^2 + 2\frac{\sin^2 F}{R^2}) + \frac{2}{9}g^2B^2R^2\sin^2 F] \\
&-\frac{N_F}{96\pi^2}[\left((\partial_R F)^2 + 2\frac{\sin^2 F}{R^2}\right)^2 + \frac{16}{225}g^4B^4R^4\sin^4 F + \\
&+\frac{2}{9}g^2B^2R^2\left((\partial_R F)^2 + 3\frac{\sin^2 F}{R^2}\right)\sin^2 F] - \frac{N_F}{48\pi^2}\frac{2}{3}g^2B^2\sin^2 F \\
&-\frac{N_F}{12\pi^2}\left[\frac{2\sin^2 F}{R^2}(\partial_R F)^2 + \frac{\sin^4 F}{R^4} + \frac{2}{9}g^2B^2\sin^4 F\right]
\end{aligned} \tag{11}$$

where terms with gB arise from vacuum background field G_μ .

The Euler-Lagrange equation for (11) for the soliton function $F(R)$ has the form

$$\begin{aligned}
&N_F f_0^2\left[\left(1 + \frac{g^2B^2}{6}R^4\right)\sin 2F - 2R\partial_R F - R^2\partial^2 F\right] + \\
&+\frac{N_F}{12\pi^2}\left[\frac{\sin^2 F\sin 2F}{R^2} - \sin 2F(\partial_R F)^2 - 2\sin^2 F\partial^2 F + \frac{2}{3}g^2B^2R^2\sin^2 F\sin 2F\right] + \\
&+\frac{N_F}{24\pi^2}\left[\frac{2\sin^2 F\sin 2F}{R^2} - 2R(\partial_R F)^3 - 3R^2(\partial_R F)^2\partial_R^2 F - 2\partial_R^2 F\sin^2 F - (\partial_R F)^2\sin 2F\right] + \\
&+\frac{N_F}{675}g^4B^4R^6\sin^2 F\sin 2F \\
&+\frac{N_F}{216\pi^2}g^2B^2R^4\left[\frac{3\sin^2 F\sin 2F}{R^2} - 4\partial_R F\frac{\sin^2 F}{R} - \partial_R^2 F\sin^2 F\right] \\
&-\frac{N_F}{432\pi^2}g^2B^2R^4(\partial_R F)^2\sin 2F + \frac{1}{3}\frac{N_F}{24\pi^2}g^2B^2R^2\sin 2F = 0
\end{aligned} \tag{12}$$

This expression for the effective action contains terms $R^4\sin^4 F$ and $R^2\sin^2 F$ defining the asymptotic behaviour of $\sin F$ necessary to obtain finite static energy or mass

$$M = -4\pi\int dRR^2L_{eff}(U,G_k) \tag{13}$$

The contribution to the mass functional M from the bosonized action sums from the kinetic term, $d = 4$ terms and the contribution of the background vacuum field. It is easely to see that this part is positive definite and bounded from below and provides with the soliton configuration.

We introduce dimensionless variable $\rho = Ef_0R$, then the asymptotic behavior at large R of the decreasing function $F(\rho)$ is represented by the following equation

$$\partial_\rho\left[\rho^2\partial_\rho F\right] - 2(1 + C\rho^4)F = 0, \tag{14}$$

where the dimensionless parameter $C = \pi^2Cg/9(Ef_0)^4$ is related to the gluon condensate $Cg = g^2B^2/2\pi^2$. The solution of the Eq.(36) is modified Bessel functions of the second kind $K\left(\frac{3}{4}, \sqrt{\frac{C}{2}}\rho^2\right)/\sqrt{\rho}$ and asymptotic behavior

$$F \to \rho^{-\frac{3}{2}}\exp\left(-\sqrt{\frac{C}{2}}\rho^2\right), \rho \to \infty \tag{15}$$

which guarantees that the mass M is finite.

At small ρ, as it can be expected, the soliton function $F(\rho)$ behaves near the origin $\rho = 0$ in the same manner as in the Skyrme model $F(\rho) \approx \pi - b\rho$.

Thus, the function F of the color soliton is quite different from that of the flavor skyrmion.

We consider a family of trial functions

$$F(\rho) = \pi\sqrt{\frac{1 - b\rho + a\rho^2}{1 + A\rho^5}}\exp(-\frac{A}{2}\rho^2) \tag{16}$$

where coefficients a and b are variational parameters and parameter $A = \sqrt{2\pi^2Cg/9(Ef_0)^4}$. We also minimize the mass functional with respect to the scale transformation $\rho \longrightarrow E\rho$. The functions (16) reflects the behaviour at the origin and large distances (15). We look for soliton configuration with $N_F = 1$. We use the value for the gluon condensate $C_g = (350MeV)^4$. We find stable soliton solutions for the wide range of the unknown phenomenological parameter $f_0 = (10...60)MeV$. When f_0 corresponds to the mass scale $\Lambda_C = 100MeV$ of the colour bosonization, we get $M = 460MeV$.

Two-soliton potential and possibility of confinement

Let us consider briefly main point leading to confining potential between colour solitons in the case of $N_C = 2, N_F = 1$ discussed in section 3. For such solitons, the vacuum background field plays the role of a bag. We take two solitons $U(x_1)$ and $U(x_2)$ described by Eq. (4) and ask what is an intersoliton potential $V(x_{12})$ at large distances x_{12} and large R_1, R_2 , that results from lagrangian (1) for two-soliton state $U(x_1, x_2; \mathbf{n}, \nu) = U(x_1, \mathbf{n}, \nu)\, U(x_2, \mathbf{n}, \nu)$ after averaging over common colour and coordinate unit vectors $\mathbf{n}, \nu$ of vacuum background field (3)

$$V(x_{12})\, F_1F_2 = \langle H\left[U(x_1, x_2; \mathbf{n}, \nu)\right]\rangle - \langle H\left[U(x_1, \mathbf{n}, \nu)\right]\rangle - \langle H\left[U(x_2, \mathbf{n}, \nu)\right]\rangle$$

where $\langle H \rangle$ denotes averaging over $\mathbf{n}, \nu$ and H is the static energy density following from (1). Second and third terms in V are given by $-L_{eff}$ in (11). The QCD part of the effective lagrangian does not contribute. A gauge invariant potential is

$$\begin{aligned} V\left(x_{12}\right) F_1 F_2 &= \frac{f_0^2}{4} \left\langle tr \left[DU_2 DU_1^+ + DU_1 DU_2^+ \right] \right\rangle \cong tr\{\left[G_k\left(x_1\right), U_1\right] \left[G_k\left(x_2\right), U_2^+\right]\} \\ V\left(x_{12}\right) &= \frac{f_0^2}{36} g^2 B^2 \left(\overleftarrow{x_1} - \overleftarrow{x_2}\right)^2 \end{aligned}$$

Such potential describes confined solitons. However, this does not explain whether an isolated colour soliton can exist and propagate.

Quantization of a color soliton

Quasiclassical quantization of solitons starts with introduction of collective coordinates related to symmetries to be quantized. Method of collective (group) coordinates was first developed by N.N.Bogolyubov for quantization of polaron. We follow approach considered by Balachandran and al. [3] for flavor skyrmions. Quantization of color $SU(2)$ skyrmion within color $SU(3)$ was exposed by Kaplan [8]. Time development of static solution is associated with time dependent unitary matrix $A(t)$ reflecting the symmetry of total (non-static) lagrangian. In the color case [8]A also a function of x_k and describes time development of color field as well.

For the soliton U in the background field of quasiabelian type $G_k^a(x) = v_k(x) N^a$ in the temporal gauge, color gauge symmetry is reduced to the global one. Therefore, matrix $A(t)$ can not depend on coordinated x_k , and we introduce time dependent soliton

$$U(x,t) = A(t) W(x) A^+(t) \tag{17}$$

Here $W(x)$ denotes the static chiral field configuration which enters L_{stat} as $\mathrm{U}(x)$.

Suppose now that the vacuum background field becomes time dependent too

$$\hat{G}_k(x,t) = v_k(x) A(t) N A^+(t), \hat{G}_0 = 0, \tag{18}$$

remaining at the same time in the temporal gauge for $\hat{G}_\mu$, while G_μ gets $G_0 = A^+\dot{A}$. The time development of $\hat{G}_k(x,t)$

$$i\partial_0 \hat{G}_k = v_k A \left[\left(A^+ \dot{A} \right), N \right] A^+ \tag{19}$$

depends on orientation of $\left(A^+\dot{A}\right)$ in the color space with respect to the vacuum unit vector N . The lagrangian of the gluonic field L_G will get a G_0 -dependent chromoelectric contribution containing solitonic variables $A^+\dot{A}$ to be quantized

$$\delta L_G = \frac{1}{2g^2} tr\left[G_0, G_k\right]^2 = -\frac{v_k^2}{2g^2} tr\left[\left(iA^+\dot{A} \right), N \right]^2 \tag{20}$$

and leading to a change of the gluon condensate. Thus, the assumtion that background vacuum field becomes time dependent leads to inconsistency. Therefore we require that within a domain vacuum direction N is not influenced by the unitary transformation $A(t)$

$$A(t)\,NA^{+}(t) = N, A = \exp iNa(t)\,,$$

$$\left(iA^{+}\dot{A}\right) = N\dot{a}(t) \tag{21}$$

so that $\left(iA^{+}\dot{A}\right)$ is also oriented in direction N. We note that the one-loop Gauss law for the background field

$$\frac{\delta L_G}{\delta G_0} = 0, \left[N, \left[N, \left(iA^{+}\dot{A}\right)\right]\right] = 0 \tag{22}$$

is satisfied for time-independent N.

Let us express the effective lagrangian $L_{eff}\left(U, \hat{G}\right)$ in terms of new variables

$$L_{eff}\left(U, \hat{G}\right) = L_{stat}(W, G) + tr\left\{\left[\left(iA^{+}\dot{A}\right), W\right]\left[\left(iA^{+}\dot{A}\right), W^{+}\right]\right\} +$$

$$tr\left[W^{+}[\left(iA^{+}\dot{A}\right), W], W^{+}D_lW\right]^2 \tag{23}$$

In absence of background field and after $flavor \longleftrightarrow color$ exchange, the lagrangian $L_{eff}(U, 0)$ coincides with skyrmion lagrangian in the flavor case. The Wess-Zumino action vanishes for $SU(2)$ soliton. Apart from L_{stat} , the background field is present only through $[G_l, W]$ in D_lW in the last term.

Integrating over coordinates we get the lagrangian for collective solitonic variables in a particular vacuum domain with background vacuum field in direction N

$$\hat{L}\left(A, \dot{A}; N\right) = -\frac{1}{2}\alpha(W, N)\left(A^{+}\dot{A}\right)_i N_i \left(A^{+}\dot{A}\right)_j N_j \tag{24}$$

where α is a numerical coefficient - "momentum of inertia" - represented by space integrals over functionals of W , as a solution of variational equation for $L_{stat}(W, N)$.

Applying the quantization procedure we get the hamiltonian for the soliton in a particular vacuum domain

$$H = \frac{(R_iN_i)(R_iN_i)}{2\alpha}, \tag{25}$$

where R_k are $SU(2)$ generators with commutation relations

$$[R_i, R_k] = -2ie_{ikj}R_j, [R_i, A_{kj}] = -[A\sigma_i]_{kj}, [A_{ik}, A_{jl}] = 0.$$

Averaging over domains, i.e. over directions of domain vacuum fields, gives us the hamiltonian for states of isolated soliton, as they are seen "from outside"

$$\hat{H} = \frac{R_iR_i}{6\alpha} \tag{26}$$

Thus, averaging over vacuum domains reinstates the complete Hilbert space. We refer to papers [22] for its description in terms of spin and isospin.

Conclusions and discussion

We have derived chiral colour action in a background field satisfying standard conditions of one-loop QCD in background gauge. We applied this action to the case of soliton configuration defined as a configuration in a vacuum background field related to the gluon condensate, and considered the static case. Experimentally, the condensate is positive, so that the vacuum field is chromomagnetic. The vacuum field gives rise to terms in the effective chiral lagrangian with $R^2 \sin^2 F$ and $R^4 \sin^4 F$ where R is a distance from the center of the standard hedgehog configuration of the shape F. Vacuum background field ensures exponential decrease in asymptotic region for chromomagnetic condensate, which is essential for stability of soliton and finiteness of mass. The (renorm-invariant) condensate is considered as a phenomenological quantity. Variational estimates with the trial function with proper asymptotics behaviour and the gluon condensate $(350Mev)^4$ shows that for the one flavor case the mass cannot be more then 460 MeV. Color solitons definitely exist in bosonization action and as Skyrmions.

Two-soliton potential displays confinement behavior. An essential element leading to such potential is averaging over directions of vacuum fields in different vacuum domains.

Quantization of collective color coordinates can be performed in the same way as in the flavor case. Inside a particular vacuum domain the hamiltonian of collective coordinates has cylindrical color symmetry determined by the color vacuum field. Averaging this hamiltonian over vacuum domains we recover spherical symmetry and an interpretation of spin- color isospin states analogous to the flavor case.

Other topics of recent developments in color chiral solitons are discussed in Ref [13, 14, 23].

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