CONFINING BUT CHIRALLY SYMMETRIC QUARKYONIC MATTER*

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(Received July 27, 2011)

Here, we overview a possible mechanism for confining but chirally symmetric matter at low temperatures and large densities.

DOI:10.5506/APhysPolBSupp.4.709
PACS numbers: 12.38.Aw, 11.30.Rd

1. Introduction

One of the most intriguing questions of the strong interaction physics is a possibility for existence of the chirally symmetric matter with confinement at low temperatures and large densities. It is quite possible that a confining mode persists up to a very dense nuclear matter. Here, by a matter with confinement, we imply a matter with only the color singlet excitation modes of hadronic type, where uncorrelated colored excitation are not possible. In the large N_c limit confinement survives in a matter at low temperatures up to arbitrary large density, because the quark–antiquark loops as well as the quark–quark hole loops are suppressed at large N_c. Nothing can screen a confining gluonic field and a gluodynamics in a medium is the same as in a vacuum. In this case it is possible to define a quarkyonic matter as a very dense nuclear matter where some bulk properties, *e.g.*, pressure, are determined by the quark Fermi surface (like for a Fermi gas), while uncorrelated single quark excitations are not allowed [1]. We do not know how to rigorously define a confining mode in a matter at $N_c = 3$, because there is no strict order parameter for confinement. So we will imply under

* Presented at the Workshop "Excited QCD 2011", Les Houches, France, February 20–25, 2011.

confining matter a matter with the color singlet excitation modes. We will also assume that such a confining matter exists in the real $N_c = 3$ world up to very large densities[1].

What happens with chiral symmetry breaking in a very dense cold matter with confinement? Is it possible to have a chiral symmetry restoration phase transition in a mode with confinement both below and above the phase transition?

If the chiral restoration phase transition exists in a system with confinement, then the origin of mass of the confining strongly interacting matter above the phase transition is not related at all with the chiral symmetry breaking. Such a possibility was not considered in the past on the *a priori* grounds: It was believed that a hadron mass generation is necessarily connected with the chiral symmetry breaking in a vacuum and that a hadron mass in the light quark sector is at least mostly directly related to the quark condensate of a vacuum. Indeed, the 't Hooft anomaly matching conditions [3] require that at zero density and temperature in a confining mode there must appear a Goldstone mode related to breaking of chiral symmetry. However, the anomaly matching conditions can be trivially satisfied in a two flavor nuclear matter built with chirally symmetric baryons (*i.e.*, without any Goldstone mode associated with spontaneous breaking of chiral symmetry). The Casher's argument, claiming that in a confining mode the quark Green function must necessarily contain a chiral symmetry breaking part [4] is not general enough and can be easily bypassed [5]. At last, the effective restoration of chiral symmetry in highly excited hadrons [6], if finally established, will imply that the mass generation mechanism of these hadrons is not related to the chiral symmetry breaking in a vacuum. Summarizing, today there are no *a priori* arguments that would rule out a possibility for a confining but chirally symmetric dense and cold strongly interacting matter.

2. Confining but chirally symmetric liquid phase

In the large N_c limit nucleons are infinitely heavy, a nuclear matter is in a crystal phase where translational and rotational invariances are spontaneously broken. In this situation all possible chiral order parameters cannot simultaneously average to zero and if chiral symmetry is broken locally, it is also broken in average [7]. However, we do know that in the real $N_c = 3$ world a nuclear matter is a liquid with manifest translational and rotational invariances. Then, it is not unreasonable to assume that a dense (and a superdense) $N_c = 3$ baryonic matter with confinement (*i.e.*, by definition

[1] It is shown on the lattice for the $N_c = 2$ QCD that at low temperatures confinement persists up to densities of the order of 100 times nuclear matter density [2]. It is quite natural then to assume that for the $N_c = 3$ QCD confinement will survive even for essentially larger densities.

a quarkyonic matter) is also in a liquid phase. Given this assumption, one can ask a question whether a chiral restoration phase transition is possible or not in such a matter. If possible, then by what mechanism?

We cannot answer this question from first principles. What can be done, however, is to construct a model. If demonstrated within such a model, this scenario could also be realized in QCD and further theoretical efforts to clarify this interesting questions would be called for. A minimal set of requirements for such a model is that it must be manifestly confining, chirally symmetric and provide dynamical breaking of chiral symmetry in a vacuum. This model must admit solutions for hadrons with nonzero mass as bound states of quarks both in the Wigner–Weyl and Nambu–Goldstone modes of chiral symmetry. Such program has been performed in Refs. [5, 8, 9], where it was explicitly demonstrated that a confining chirally symmetric liquid phase at low temperature can indeed be obtained at least within a model that meets all requirements above.

3. The model

It is assumed within the model that the only interquark interaction is a linear instantaneous potential of Coulomb type. Then the $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R} \times \mathrm{U}(1)_\mathrm{A} \times \mathrm{U}(1)_\mathrm{V}$ symmetric Hamiltonian is

$$\begin{aligned} \hat{H} &= \int d^3x \bar{\psi}\left(\vec{x},t\right)\left(-i\vec{\gamma}\cdot\vec{\bigtriangledown}\right)\psi\left(\vec{x},t\right) \\ &\quad + \frac{1}{2}\int d^3x d^3y\, J^a_\mu\left(\vec{x},t\right) K^{ab}_{\mu\nu}\left(\vec{x}-\vec{y}\right) J^b_\nu\left(\vec{y},t\right)\,, \end{aligned} \tag{1}$$

where $J^a_\mu(\vec{x},t) = \bar{\psi}(\vec{x},t)\gamma_\mu \frac{\lambda^a}{2}\psi(\vec{x},t)$ and the interaction is assumed to be

$$K^{ab}_{\mu\nu}\left(\vec{x}-\vec{y}\right) = g_{\mu 0} g_{\nu 0}\delta^{ab} V\left(\left|\vec{x}-\vec{y}\right|\right)\,; \qquad \frac{\lambda^a\lambda^a}{4}V(r) = \sigma r\,, \tag{2}$$

with a, b being color indices. This model was intensively used in the past to study chiral symmetry breaking, chiral properties of hadrons, *etc.*, [10]. The model can be considered as a straightforward $3+1$ dim generalization of the $1+1$ dim 't Hooft model [11]. An important aspect of this $3+1$ dim model is that it manifestly exhibits effective restoration of chiral symmetry in hadrons with large spin J [12].

The self-energy of quarks in a vacuum

$$\Sigma\left(\vec{p}\right) = A_p + \left(\vec{\gamma}\hat{\vec{p}}\right)\left(B_p - p\right) \tag{3}$$

consists of the Lorentz-scalar chiral symmetry breaking part A_p and the chirally symmetric part $(\vec{\gamma}\hat{\vec{p}})(B_p - p)$. The unknown functions A_p and B_p

can be obtained from the gap equation. All color singlet quantities, like quark condensate, hadron masses are finite and well defined. In contrast, all color non-singlet quantities, like a single quark energy, are infinite. It is a manifestation of confinement.

We want to address chiral symmetry and confining properties of a dense matter at $T = 0$. We treat the system in a mean field approximation and assume a simple valence quark distribution function, see Fig. 1. In reality valence quarks near the Fermi surface interact and cluster into the color singlet baryons. Then a rigid quark Fermi surface in Fig. 1 is diffused. Here, we ignore these effects[2].

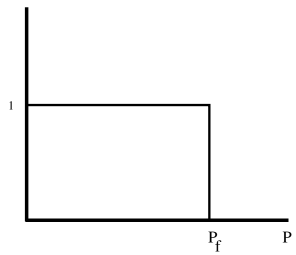

Fig. 1. Valence quark distribution.

In a dense matter at $T = 0$ the most important physics that leads to restoration of chiral symmetry is the Pauli blocking by valence quarks of the positive energy levels required for the very existence of the quark condensate. This is similar to the chiral restoration in the Nambu and Jona-Lasinio model [14]. At sufficiently large Fermi momentum the gap equation does not admit a nontrivial solution with broken chiral symmetry. Consequently, the chiral symmetry breaking Lorentz scalar part A_p of the quark self-energy vanishes and the chiral symmetry gets restored, see Fig. 2. However, the

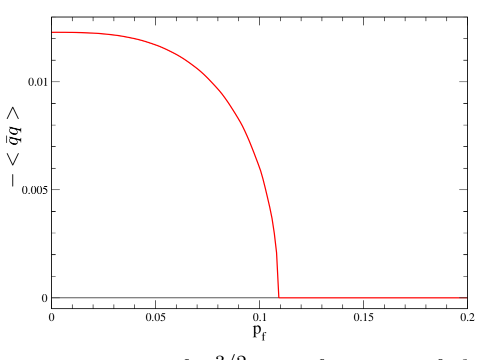

Fig. 2. Quark condensate in units of $\sigma^{3/2}$ as a function of the Fermi momentum, which is units of $\sqrt{\sigma}$.

[2] A reasonable diffusion of the quark Fermi surface does not lead to qualitative modifications of results [13].

chirally symmetric part of the quark self-energy does not vanish and is still infrared divergent, like in vacuum. This means that even with restored chiral symmetry a single quark energy is infinite and such a quark is confined. This infrared divergence cancels exactly in all color singlet hadronic modes that remain finite and well defined.

In this respect, the model is radically different from the non-confining NJL model. In the latter a dense matter is a Fermi gas of free quarks. In the Nambu–Goldstone mode these quarks are massive. In the Wigner–Weyl mode they are massless. In our case physical degrees of freedom, that can be excited, are color singlet hadrons. In the Wigner–Weyl mode these are the chirally symmetric hadrons.

Given a quark Green function from the gap equation, one can solve the Bethe–Salpeter equation to obtain the color singlet mesons. A spectrum of all possible quark–antiquark mesons below and above the chiral restoration phase transition is shown in Fig. 3 and 4. Obviously, the chiral symmetry is manifestly broken in Fig. 3, while in Fig. 4 the hadrons fall into all possible chiral multiplets. Technically, it is more difficult to solve the model for baryons, but in principle it can be done.

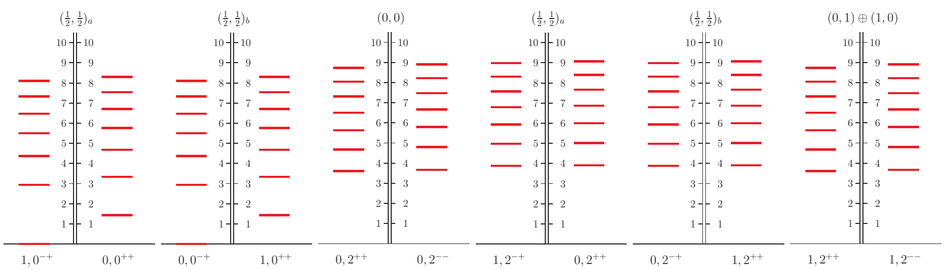

Fig. 3. Spectra for $p_f = 0.05\sqrt{\sigma}$. For $J = 0$ only the two $(\frac{1}{2}, \frac{1}{2})$ multiplets are present (left two panels). For $J > 0$ there are also the $(0, 0)$ and $(0, 1) \oplus (1, 0)$ multiplets. In the remaining four panels we show all multiplets for $J = 2$. Masses are in units of $\sqrt{\sigma}$. Meson quantum numbers are I, J^{PC}.

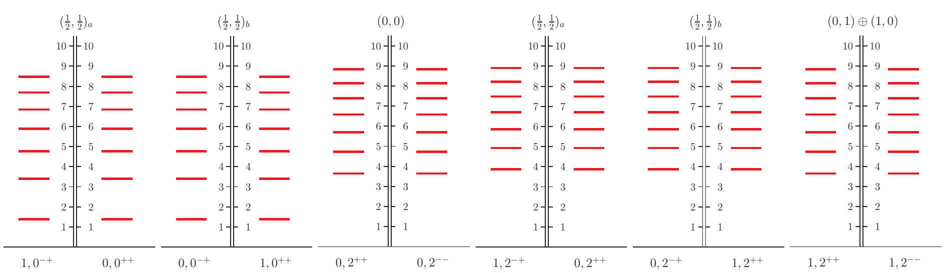

Fig. 4. As Fig. 3 but for Fermi momentum $p_f = 0.2\sqrt{\sigma}$.

Support of the Austrian Science Fund through the grant P21970-N16 is acknowledged.

REFERENCES

[1] L. McLerran, R.D. Pisarski, *Nucl. Phys.* **A796**, 83 (2007).

[2] S. Hands, S. Kim, J.I. Skullerud, *Phys. Rev.* **D81**, 091502 (2010).

[3] G. 't Hooft, in *Recent Developments in Gauge Theories*, ed. by G. 't Hooft *et al.*, Plenum, NY 1980.

[4] A. Casher, *Phys. Lett.* **B83**, 395 (1979).

[5] L.Y. Glozman, *Phys. Rev.* **D80**, 037701 (2009).

[6] L.Y. Glozman, *Phys. Rep.* **444**, 1 (2007); L.Y. Glozman, *Phys. Rev. Lett.* **99**, 191602 (2007).

[7] P. Adhikari, T.D. Cohen, R.R.M. Ayyagari, M.C. Strother, *Phys. Rev.* **C83**, 065201 (2011) [`arXiv:1104.2236 [nucl-th]`].

[8] L.Y. Glozman, R.F. Wagenbrunn, *Phys. Rev.* **D77**, 054027 (2008).

[9] L.Y. Glozman, *Phys. Rev.* **D79**, 037504 (2009).

[10] A. Le Yaouanc *et al.*, *Phys. Rev.* **D29**, 1233 (1984); A. Le Yaouanc *et al.*, *Phys. Rev.* **D31**, 137 (1985); S.L. Adler, A.C. Davis, *Nucl. Phys.* **B244**, 469 (1984); A. Kocic, *Phys. Rev.* **D33**, 1785 (1986); R. Alkofer, P.A. Amundsen, *Nucl. Phys.* **B306**, 305 (1988); P.J. Bicudo, J.E.F. Ribeiro, *Phys. Rev.* **D42**, 1635 (1990); P.J. Bicudo, J.E.F. Ribeiro, *Phys. Rev.* **D42**, 1625 (1990); F.J. Llanes-Estrada, S.R. Cotanch, *Phys. Rev. Lett.* **84**, 1102 (2000).

[11] G. 't Hooft, *Nucl. Phys.* **B75**, 461 (1974).

[12] R.F. Wagenbrunn, L.Y. Glozman, *Phys. Lett.* **B643**, 98 (2006); R.F. Wagenbrunn, L.Y. Glozman, *Phys. Rev.* **D75**, 036007 (2007); A.V. Nefediev, J.E. F. Ribeiro, A.P. Szczepaniak, *JETP Lett.* **87**, 271 (2008); P. Bicudo, M. Cardoso, T. Van Cauteren, F.J. Llanes-Estrada, *Phys. Rev. Lett.* **103**, 092003 (2009).

[13] L.Y. Glozman, V.K. Sazonov, R.F. Wagenbrunn, in preparation.

[14] U. Vogl, W. Weise, *Prog. Part. Nucl. Phys.* **27**, 195 (1991); S.P. Klevansky, *Rev. Mod. Phys.* **64**, 649 (1992); T. Hatsuda, T. Kunihiro, *Phys. Rep.* **247**, 221 (1994).