LETTERS TO THE EDITOR

PARTIAL DECONFINEMENT AND STRANGE-QUARK PRODUCTION IN NUCLEAR MATTER

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Using the thermodynamic model at zero temperature and density-dependent quark mass approach to confinement, the possibilities of light quark liberation and strange quark formation near ground state nuclear matter have been investigated.

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Nuclear matter undergoes a color deconfinement transition to quark matter at high temperatures ($T_c \sim 200$ MeV) and/or high densities ($n \geqslant n_0$, $n_0 \sim 0.16\ \mathrm{fm}^{-3}$), in which, the local SU(3) color symmetry is broken and the quarks become de-localized. There are essentially two different approaches to study the phase transition, both qualitatively as well as quantitatively; they are the lattice calculations and perturbative methods.

The existence of a finite temperature confinement phase transition in a gauge theory is a long standing conjecture. For pure lattice gauge theory, its existence has been proved analytically [1, 2] and finite temperature QCD lattice Monte-Carlo calculations show that for a pure Yang-Mills field, the transition is first order and the critical temperature for this transition is about 200 MeV [3, 4]. However, rigorous results from full QCD calculations are not available at present, and lattice calculation give only a crude description of the Quark-Gluon system.

In the second approach there is no unique way to incorporate the confinement mechanism for quarks. Unlike lattice calculations, where both the hadronic and quark matter phases are treated on the same footings, in this method there is no unique equation of state for quark phase, it depends on the confinement mechanism.

The most popular phenomenological description of confinement is the bag model [5, 6], which apriori assumes that within the boundary of the bag, quarks are asymptotically free. But the recent results from lattice calculations [7] show, that the quark matter does not become asymptotically free immediately after the phase transition from hadronic matter, even if it is a first order phase transition; it approaches the free gas equation of state rather slowly. In this context the bag model is thus an inadequate description of confinement. There exists in the literature however, other phenomenological description of confinement. Indeed, a density-dependent quark mass approach to confinement was proposed several years ago [8–10], which, although arbitrary and without any real support from an underlying field theory was successful in fitting experimentally extracted values of some thermodynamic variables — namely the velocity of sound, over a large range of temperatures [11–13]. A first step into this direction was originally taken by Pati and Salam [14], who pictured confinement as the quark having a small mass inside a hadron and a very large mass outside. Confinement is mimicked through the requirement that the mass of an isolated quark becomes infinitely large, so that the vacuum is unable to support it.

Now what is the method to study partial deconfinement in nuclear matter near normal nuclear density? According to color dielectric model, the QCD vacuum is characterized by zero color dielectric constant, i.e. it behaves like a perfect dielectric for color electric field. For an isolated hadron, therefore, the color dielectric field leads to absolute quark confinement, outside the hadron, the effective quark mass becomes infinite. But in nuclear matter, due to the medium effect, the color dielectric constant of QCD vacuum is non-zero, which allows the quark to leak out of their nucleon bags. This partial deconfinement inside nuclear matter can be treated by introducing dynamical density-dependent quark mass. At the same time it also removes the arbitrariness in the constituent quark mass.

In this letter, we shall reinvestigate the possibility of light quark liberation in nuclear matter near normal nuclear density, which was investigated by Mrówczyński [15] and extend it, to investigate the formation of strange quarks, using dynamical density-dependent mass for both the non-strange and strange quarks.

The effective masses for non-strange and strange quarks are changing with the density in the following manner [13, 16]

$$m_i = B/n_q, \tag{1}$$

$$m_s = m_s^0 + m_i, \tag{2}$$

where B is the constant energy density in the zero density limit, n_q the total quark number density $= 3n_b$, n_b is the baryon number density, i = u and d. We assume the effective masses of light flavours become negligible in accordance with our expectation from asymptotic freedom and restoration of chiral symmetry at very high density, on the other hand the strange quarks have a non-negligible current mass $m_s^0 = 150$ MeV [16].

Then following Mrówczyński [15], we have the total baryon number density

$$n_b = \frac{2}{3\pi^2}(\mu^2 - M^2)^{3/2}\theta(\mu - M) + \frac{2}{3\pi^2}\left(\frac{\mu^2}{9} - \frac{B^2}{9n_b^2}\right)^{3/2}\theta\left(\mu - \frac{B}{n_b}\right)$$
$$+ \frac{1}{3\pi^2}\left(\frac{\mu^2}{9} - \left(m_s^0 + \frac{B}{3n_b}\right)^2\right)^{3/2}\theta\left(\frac{\mu}{3} - \left(m_s^0 + \frac{B}{3n_b}\right)\right), \tag{3}$$

where M is the nucleon mass and here we assume, the chemical potential for all the three flavours are equal and each equal to 1/3 of nucleon chemical potential (μ).

The critical density n_c of nuclear matter for light quark liberation is given by

$$n_c = \frac{2}{3\pi^2}\left(\frac{B^2}{n_c^2} - M^2\right)^{3/2} \theta\left(\frac{B}{n_c} - M\right) \tag{4}$$

and in the case of strange quark formation, it is given by

$$n_c = \frac{2}{3\pi^2}\left(9\left(m_s^0 + \frac{B}{3n_c}\right)^2 - M^2\right)^{3/2} \theta\left(3\left(m_s^0 + \frac{B}{3n_c}\right) - M\right)$$
$$+ \frac{2}{3\pi^2}\left(\left(m_s^0 + \frac{B}{3n_c}\right)^2 - \frac{B^2}{9n_c^2}\right)^{3/2}. \tag{5}$$

Equations (4) and (5) can be solved for n_c numerically for different values of B.

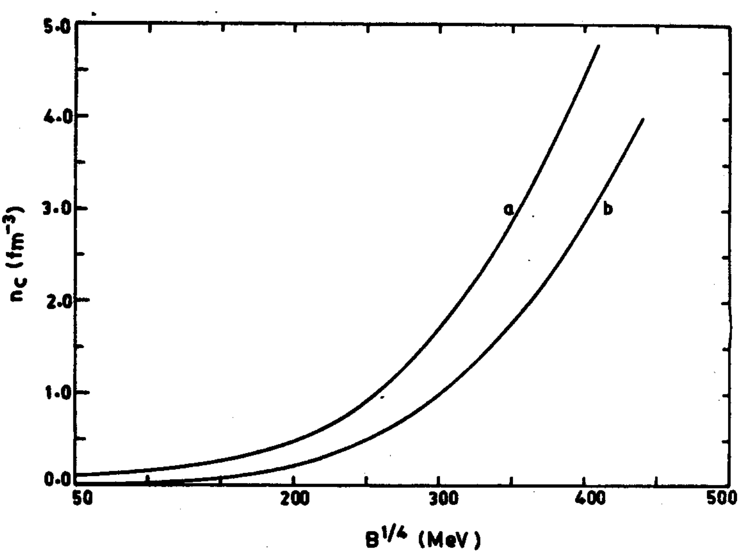

Fig. 1. The variation of critical density n_c with $B^{1/4}$ for non-strange (curve b) and strange (curve a) quarks

In Fig. 1, curve b represents the variation of n_c, the critical density for light flavour liberation, with $B^{1/4}$. This curve shows that for a particular value of B ($B^{1/4} = 180$ MeV [17]), $n_c < n_0$ ($n_c \sim 0.14\ \mathrm{fm}^{-3}$).

The variation of n_c, the critical density for strange quark production is shown in curve a of Fig. 1, which shows, that for the same value of B, and for $m_s^0 = 150$ MeV, the critical density $n_c > n_0$ ($n_c \sim 0.27\ \mathrm{fm}^{-3}$).

Therefore near nuclear density, both u and d quarks can be liberated from the nucleons inside the nuclear matter and strange quarks are produced through the weak reactions

[16, 18, 19], leads to an admixture of quarks and hadrons. In order to decide whether the strange quark matter is energetically more favourable over nuclear matter and also normal quark matter, one has to minimize the free energies and compare the magnitudes of the energy per baryon of the systems [16, 18, 19].

When a short range repulsive interaction is introduced in the hadron sector [15], equation (3) gets modified, and is given by

$$n_b = \frac{2}{3\pi^2}\left(\left(\mu - 3\pi\frac{an_b}{M}\right)^2 - M^2\right)^{3/2}\theta\left(\mu - 3\pi\frac{an_b}{M} - M\right)$$
$$+ \frac{2}{3\pi^2}\left(\frac{\mu^2}{9} - \frac{B^2}{9n_b^2}\right)^{3/2}\theta\left(\mu - \frac{B}{n_b}\right)$$
$$+ \frac{1}{3\pi^2}\left(\frac{\mu^2}{9} - \left(m_s^0 + \frac{B}{3n_b}\right)^2\right)^{3/2}\theta\left(\frac{\mu}{3} - \left(m_s^0 + \frac{B}{3n_b}\right)\right), \tag{6}$$

where a is the scattering length or roughly speaking the effective diameter of the potential and is equal to 0.4 fm.

Performing the same exercise as before, we have seen that the short range repulsive interaction reduces the critical density for the liberation of light flavours. In this case the critical density is given by $n_c \sim 0.5\, n_0$. Where as for strange quark formation n_c almost remains un-affected ($n_c \sim 0.22\,\text{fm}^{-3}$).

We therefore conclude that with this dynamical density-dependent quark mass model of colour confinement, light flavours are allowed to leak out of their nucleon bag near normal nuclear density, and strange quarks are produced through the weak processes. The first observation is in agreement with the results obtained by Mrówczynski [15]. The question, whether the strange quark matter is energetically preferred over nuclear matter and normal quark matter is by no means resolved from the observations. However, a comparison of the threshold densities of nuclear matter for light quark liberation and strange quark production shows that the strange quarks can be produced in nuclear matter near nuclear density [18, 19], which indirectly supports the speculation of Witten [20].

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