J. Phys. G: Nucl. Phys. 11 (1985) L235–L238. Printed in Great Britain

LETTER TO THE EDITOR

Liberated quarks in nuclear matter

St Mrøwczyński[†]
Laboratory of High Energies, JINR, Dubna, USSR

Received 25 July 1985

Abstract. The possibility of the existence of liberated quarks in zero-temperature nuclear matter is briefly considered. It is argued that at densities close to the normal one the quark admixture is allowed. However, constituent quarks can carry only a small fraction of the baryon number of the system.

It is widely believed that at high temperature and/or density of nuclear matter the deconfinement of quarks from hadron interiors occurs. Two deconfinement pictures can be put forward. In the first, hadrons form a giant hadron and one observes a homogeneous phase of quarks and gluons separated from the hadron phase. In the second picture hadrons dissociate into quarks, and a mixture of quarks and hadrons exists. The two possibilities are presented schematically in figure 1. Great attention has been given (see, e.g., [1]) to the first picture of deconfinement while in this Letter we briefly speculate on the dissociative one.

Let us first explain that this picture does not contradict the common understanding of quark confinement which seems to be absolute for a single hadron. The QCD vacuum is sometimes presented (see, e.g., [2]) as a perfect dielectric medium of zero dielectric constant for colour field. It is then argued that the energy of an isolated colour charge is infinite because of the antiscreening effect. In this way the non-existence of coloured objects is justified. What are the properties of the QCD vacuum for a dense hadron gas? In spite of the hadron colourlessness the vacuum structure is probably strongly influenced as a result of the presence of hadrons since interhadron forces are undoubtedly of QCD origin. In analogy to a QED dielectric one can expect that the colour forces are screened in the dense hadron gas with a screening length of the order of the interhadron distance. Thus it can be expected that the dielectric constant of the hadron gas medium is, at least, non-zero, which makes the energy of isolated colour charge finite [2]. If one finally compares the confinement radius of quarks in a nucleon of about 1 fm with an average internucleon distance of 1.8 fm (at the normal nuclear density $\rho_0 = 0.17\ \mathrm{fm}^{-3}$) it seems reasonable to suppose that quarks can be liberated from the nucleon interior by a tunnelling transition. When the density of nuclear matter increases, quark deconfinement is, of course, more probable. A model where the colour dielectric nuclear medium allows quarks to leak outside the nucleon bag has been considered in reference [3].

We can analyse the quark–hadron mixture by means of methods of chemically reacting gases or partly ionised electromagnetic plasma. We consider nuclear matter at

---

[†] Permanent address: High Energy Department, Institute for Nuclear Studies, 00-681 Warsaw, Hoza 69, Poland.

0305-4616/85/120235 + 04$02.25

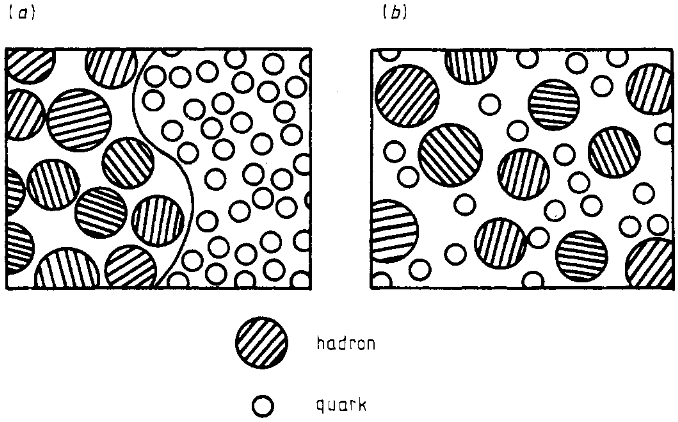

Figure 1. Two pictures of deconfinement (see text).

zero temperature since in this case the description of the hadron gas is greatly simplified because only the most energetically favourable configurations are involved, and we are not forced to take into account a rich spectrum of hadrons.

Let us start from an ideal gas of nucleons and quarks. Baryon number conservation and the assumption of chemical equilibrium provide the relation $\mu_q = \mu/3$, where μ_q and μ are the chemical potentials of quarks and nucleons, respectively. At zero temperature one finds the following equation for μ:

$$B = \frac{2}{3\pi^2} V(\mu^2 - m^2)^{3/2}\Theta(\mu - m) + \frac{g}{18\pi^2} V(\mu^2/9 - m_q^2)^{3/2}\Theta(\mu/3 - m_q) \qquad (1)$$

where B is the total baryon number of the system, V the volume of the system, m and m_q are the masses of nucleon and quark, respectively, g the quark degeneration factor ($g = 12$) and Θ is the step function. This equation expresses baryon number conservation. The first term comes from the nucleons, the second one from the quarks. As the system is considered at zero temperature the contributions of antiquarks and strange quarks are omitted. There are also no gluons. The quarks are not localised in a definite space region (bag), so there is no point in including in equation (1) the vacuum pressure as in the MIT bag model [4].

The question arises as to what quark mass should be put in equation (1): the almost zero mass of the QCD current quark or the constituent quark mass which is greater than $m/3$. According to the bag model [4], the hadron interior is homogeneously filled with current quarks and gluons. On the other hand, there are numerous arguments, see reference [5], in favour of the two-stage model of hadron structure according to which baryons (mesons) consist of three- (two-) constituent dressed quarks built of QCD current quarks and gluons. If the value of current quark mass is substituted in equation (1), the nucleon contribution is found to be negligibly small for a density of the order of the normal nuclear one. Thus at a density which is sufficient for colour force screening and quark liberation, there should be a sharp transition to quark matter. However, our speculations are only reasonable for the two-stage model because in this approach a non-trivial structure of the QCD vacuum and a role of gluons are effectively taken into account as a consequence of the concept of constituent quarks. Thus later on we assume that $m_q > m/3$.

It is not possible to solve equation (1) analytically, but one easily finds that there are no (free) quarks in the system for a baryon number density lower than the critical one

$$\rho_c = \frac{2}{3\pi^2}(9m_q^2 - m^2)^{3/2}.$$

According to the current estimations [6], the masses of u and d constituent quarks are in the interval of 320–360 MeV. Therefore $0.4\rho_0 < \rho_c < 7\rho_0$. On the other hand, it follows from equation (1) that the number of quarks, Q, in the system is limited by the inequality $Q/3N \leqslant 1/27$, where N is the number of nucleons. The equality is reached for an infinite density and/or for $m_q \rightarrow m/3$.

Let us now discuss how the results are modified by the interaction. Short-range repulsive forces are crucial for the properties of nuclear matter [7]. In particular, these forces, in contrast to long-range attractive ones, make the Fermi level higher and consequently they can lead to an increase of the quark admixture. The short-range forces can be represented by a delta-like pseudopotential [8]. The attractive quark–quark interaction which leads to hadron formation is, in fact, taken into account in equation (1) since we simultaneously consider quarks and hadrons. We omit other quark interactions observing that additional attractive quark–nucleon or quark–quark interactions would increase the quark admixture while the repulsive interaction would decrease it.

Taking into account the nucleon interaction described by the pseudopotential [8], the nucleon contribution in equation (1) has to be modified as follows:

$$\frac{2}{3\pi^2} V \left[\left(\mu - 3\pi\frac{aN}{mV}\right)^2 - m^2\right]^{3/2} \Theta\left(\mu - 3\pi\frac{aN}{mV} - m\right)$$

where a is the nucleon–nucleon scattering length, $a = 0.4$ fm [7]. In the above formula it has been assumed that the numbers of protons and neutrons with opposite spin are equal. If one treats the nucleon interaction as a perturbation, the critical density above which the quarks occur in the system is

$$\rho_c \simeq \frac{2}{3\pi^2}\left[\left(3m_q - 2\frac{a}{\pi m}(9m_q^2 - m^2)^{3/2}\right)^2 - m^2\right]^{3/2}.$$

With the help of the above formula we have estimated the lower limit of critical density related to the lower limit of quark mass, $\rho_c > 0.1\rho_0$. The upper limit cannot be found in this way since at densities much exceeding the normal one the nucleon interaction cannot be treated as a perturbation. Hence, the upper limit has been found numerically, $\rho_c < 3\rho_0$.

For the densities close to the critical one the number of quarks in the system can be easily found:

$$Q \simeq \frac{2}{\pi^2} V \left[\frac{1}{9}\left(\mu_F + 3\pi\frac{a}{m}\rho\right)^2 - m_q^2\right]^{3/2}$$

where

$$\mu_F = [(\tfrac{3}{2}\pi^2\rho)^{2/3} + m^2]^{1/2}.$$

An interesting situation occurs if the constituent quarks form diquarks, i.e. boson states of baryon charge equal to $\frac{2}{3}$. Because the diquarks occur in the system as a Bose–Einstein condensate, the admixture of diquarks can be much larger than that of quarks and the transition to a pure diquark phase is possible. The problem of diquarks is very similar to that studied in our previous papers [9], where the nuclear matter of nucleons and dibaryons has been considered. See also the recent paper [10], where the existence of diquark plasma has been suggested.

We conclude our speculations on the dissociative picture of deconfinement as follows.

(1) A density close to the normal one seems sufficient to liberate quarks from hadron interiors. Thus one can expect the existence of quark admixture in nuclei.

(2) The constituent quarks, in contrast to diquarks, can carry only a small fraction of the baryon number of the system.

I am grateful to M I Gorenstein for fruitful discussion.

References

[1] Satz H (ed.) 1981 *Statistical Mechanics of Quarks and Hadrons* (Amsterdam: North-Holland)
Jacob M and Satz H 1982 *Quark Matter Formation and Heavy Ion Collisions* (Singapore: World Scientific)
[2] Quigg C 1981 *Models for Hadrons, Fermilab-Conf-81/78-THY, Batavia, USA*
[3] Nachtmann O and Pirner H J 1984 *Z. Phys.* C **21** 277
[4] Chodos A *et al* 1974 *Phys. Rev.* D **9** 3471
[5] Shuryak E V 1983 *CERN report* 83-01
[6] Anisovich V V, Gerasyuta S M and Keltujala I V 1983 *Yad. Fiz.* **38** 200
[7] Fetter A L and Walecka J D 1971 *Quantum Theory of Many-Particle Systems* (New York: McGraw-Hill)
[8] Huang K 1963 *Statistical Mechanics* (New York: Wiley)
[9] Mrøwczyński St 1985 *Phys. Lett.* **152B** 299; *Phys. Lett.* submitted for publication
[10] Ekelin S and Fredriksson S 1985 *Proc. 2nd Int. Conf. on Nucleus–Nucleus Collisions, Visby, 1985*, ed. B Jakobsson and K Aleklett (Lund: Studsvik) vol. 1, p 132