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INSTANTONS IN QUARK PLASMA, MULTIBARION HADRONS AND NEUTRON STARS

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Abstract

The energy density of the quark plasma is calculated with the account of instanton induced effects. The first order phase transition to hadronic gas is found. Neutron star mass limit is calculated and, as compared with data, it seems to rule out the existence of multibarion hadrons. However, they can be stabilized by the small admixture of heavy (charmed) quarks.

In our preceeding work [1] it was shown that in matter with high enough barion charge density n_B (also at high temperature or strong field) the nonlinear fluctuations of the gauge field, the instantons [2], are suppressed. The most important consequence of this phenomenon is the derivation of the bag-type structure of hadrons [3] directly from Q C D.

The present work is devoted to more detailed discussion of the equation of state of quark plasma in the intermediate density region $n_B \sim n_0 = 1(\text{fermi})^{-3}$. For smaller n_B the nuclear matter calculations [4] are valid, while for larger ones the perturbative Q C D calculations [5] may be used. The account of the instanton induced effects allows one to say more about the intermediate region where the hadronic gas-quark plasma phase transition takes place.

As we show below, this phase transition is of the first type with the finite density jump. This result is one more argument in favour of the bags with sharp boundaries. However, the discussion of the usual hadrons can only be made at the qualitative level [1], since they are not macroscopic and many corrections like surface energy must be included. Therefore we confine ourselves to the question whether there exist hadronic states with large barion number, the multibarions. In order this to be the case, the plasma and vacuum pressure balance must be possible. In the naive bag model [3] it is possible for any number and combination of quarks. Therefore many states appear, some of them even in conflict with the known stability of normal nuclei. This defect of the bag model is automatically improved in our QCD approach, where the instanton induced effects and the effective bag constant are density dependent. So, depending on so far unknown suppression factor C (see [1] and below) the pressure balance may or may not be reached in the macroscopic limit. We have found, that the existing data on neutron star masses seems to rule out the former case and therefore the large bags with light quarks, if created, would blow out and decay into barions. However, as we show below, the small admixture of the heavy (say charmed) quarks essentially stabilizes the system and therefore the "slightly charmed" multibarions seems to exist.

Let us begin with the qualitative discussion of the instanton induced effect starting from the nuclear matter side. The typical instanton radius in vacuum is known to be close to 1 fermi [6]. So, if the gap between nucleons does not exceed this value there must be also some suppression of instantons inside the gap. As a result, the vacuum pressure [1] on the gap side of the nucleon is smaller and some effective attraction appears. We can not say now what part of the nuclear potential well $U_{eff} \approx -40$ MeV is due to this effect at nuclear density $n_B \approx 0.17\ (\text{fermi})^{-3}$, but we know that at $n_B \sim n_0$ instantons are essentially suppressed and the effective potential well is much deeper: $U_{eff} \sim \mathcal{E}_0 / n_0 = -450$ MeV. Here $\mathcal{E}_0$ is the vacuum energy density [1]:

$$\mathcal{E}_0 \equiv -B \approx -0.0035\ \text{Gev}^4 \approx -450\ \text{Mev}/f^3 \quad (1)$$

So, the instantons make the equation of state to be softer for

The same conclusion (but at much more quantitative level) can be reached starting from the quark plasma end. The energy density $\mathcal{E}$ and the pressure p can be represented as

$$\mathcal{E} = \mathcal{E}^{P.T.} + B - B \cdot C \cdot n_B^{-5/3}$$
$$p = p^{P.T.} - B + \frac{8}{3} B \cdot C \cdot n_B^{-5/3} \quad (2)$$

where $\mathcal{E}^{P.T.}$, $p^{P.T.}$ are those due to perturbative effects. According to [5], one has for massless u, d, s quarks

$$p^{P.T.} = \frac{3\pi^{2/3} n_B^{4/3}}{4}\left[1 + \frac{2\alpha_s}{3\pi} + \frac{\alpha_s^2}{\pi^2}\ln\alpha_s + \dots\right] \approx \frac{1}{3}\mathcal{E}^{P.T.} \quad (3)$$

where $\alpha_s \equiv g^2(gP_F)/4\pi$.

The second terms in (2) are the subtracted vacuum energy density and pressure (1), and the third ones represent the contribution of instantons in plasma according to estimates in [1]. Note that its signs are opposite to the second ones, and that for $n_B \to \infty$ they are very small, showing the instanton suppression. The parameter C is the instanton suppression factor not yet known theoretically (see discussion in [1]) and is treated as a free parameter. Its value must be of the order of 1 $(\text{fermi})^{-5}$.

The dependence $p(n_B)$ is shown at Fig. 1 for various C values. One can see the minimum near n_0 being some trace of the existing of bound states, the hadrons [1]. For $C < 0.095\ f^{-5}$ the pressure curve crosses zero. If this is the case, the multibarions should exist. The calculation of their energy shows that they are metastable since their decay into nucleons is energetically favourable.

The formulae (2) are valid as far as the third terms are small compared to the second ones, otherwise the instanton interaction must be taken into account. It remains unknown how to do this, but it is clear that some transition into the

1) We remind that for usual hadrons the pressure is balanced, which is possible because they are made of different color quarks and the kinetic energy is smaller than in (3).

nucleon gas phase takes place here. This transition is of the second type (see [8] for the discussion of its nature for the high temperature case) and is connected with the lack of confinement in the plasma phase. The presumable behaviour of the curves is shown by the dashed lines.

It is essential that the minima of the curves are reliable, at least for small C, and so the first order transition is demonstrated. Therefore the unknown part of the curve lies in the unstable (and so unobservable) region[2]. According to the well known Maxwell construction, only the integral $\int p dV$ is needed in order to fix the transition parameters. Therefore they (and in particular the density jump) are rather insensitive to the details of the curve.

The physical quantity very sensitive to the equation of state in the region in question is the maximal mass of the cold stars. Solving numerically the Tolman-Oppenheimer-Volkoff equation we have obtained the results shown at Fig.2. The curves correspond to different C values and represent the connection between the star mass M and its central density n_c. Note, that the region above maximum is unstable according to gravitational collapse. The lower part of Fig.2 summarizes the experimental restrictions [6]. The dashed line corresponds to the largest lower bound, so the curves at the plot which do not cross it contradict to data. This consideration makes it possible to conclude that the parameter C is larger than 0.15 (fermi)$^{-5}$, therefore no multibarions made of light quarks exist.

Let us add, that according to these calculations the fraction of the star matter in the quark phase is rather small, but the energy yield and the density jump at the transition still may have some observable consequences.

The very interesting situation takes place if we add some number N_h of heavy (say charmed) quarks into the light quark

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2) Note that the usual confinement criterium, the infinite energy growth with quark separation, is unobservable in the same sense, since the quark pairs destroy the string already at finite separation.

plasma. The correlation energy is easily found to be $E_{corr} = -\frac{4}{3} g^2 \varkappa$ where $\varkappa^{-1}$ is the Debye length, so that the correction to pressure (2) is

$$\delta p / p = - \sqrt{\frac{2\pi}{3}} \cdot \frac{64}{9} \alpha_s^{3/2} (N_h / N_{tot}) \qquad (4)$$

The numerical factor is rather large, so the pressure balance may be reached even for rather small N_h / N_{tot}. It is therefore interesting to look for the charm 1, barion number 2 (and more) resonances. In the limit of only heavy quarks such objects are similar to electron-hole liquid drops observed in semiconductors, and probably are even stable (only weak interaction decays), but it is practically impossible to create such an object experimentally.

Let us also add, that some phenomena discussed above can be seen in the heavy ion collisions at energies $E \gtrsim 1$ GeV/nucleon. For example, the first order transition must show itself in the way discussed (in other framework) in [9].

Note added. When this work has been completed we knew about the work [10], the main idea of which: the instanton suppression inside hadrons as the origin of their bag-type structure, is the same as in our work [1]. Also the very important studies of the instanton interaction were made in [10] and the first order phase transition in external field was found, which resembles the transition discussed above. Also the estimate of the vacuum pressure B is given in [10] which for their choice of the normalization (μ = 73 MeV) gives B = 0.0027 GeV^4, which is very close to our value (1) (and 6 times larger than the phenomenological value [3], see discussion in [1]). Such an agreement between quite different and independent approaches is rather encouraging, especially because B is one of the most fundamental parameters of the strong interaction physics.

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Figure Captions

Fig. 1. Pressure P (MeV·(fermi)$^{-3}$) versus barion charge density n_B ((fermi)$^{-3}$). The solid lines correspond to (2), the numbers near curves are the C value in (fermi)$^{-5}$. The dashed area corresponds to nuclear matter calculations [4] , the dashed curves represent their presumable behaviour. The dots at the lowest curve shows the limits of the unstable region. The curve labeled "π" corresponds to pion condensation, it is shown for comparison.

Fig. 2. Dependence of the central density n_c (fermi^{-3}) on the star mass M (in units of Solar mass $M_\odot$). The arrows in the lower part represent the experimental restrictions on the masses of double pulsars [6]. The dashed line corresponds to the largest lower bound, the solid one and the arrow correspond to the maximal mass according to all our calculations. The dashed region is the most probable one for real value of pulsar masses [6].

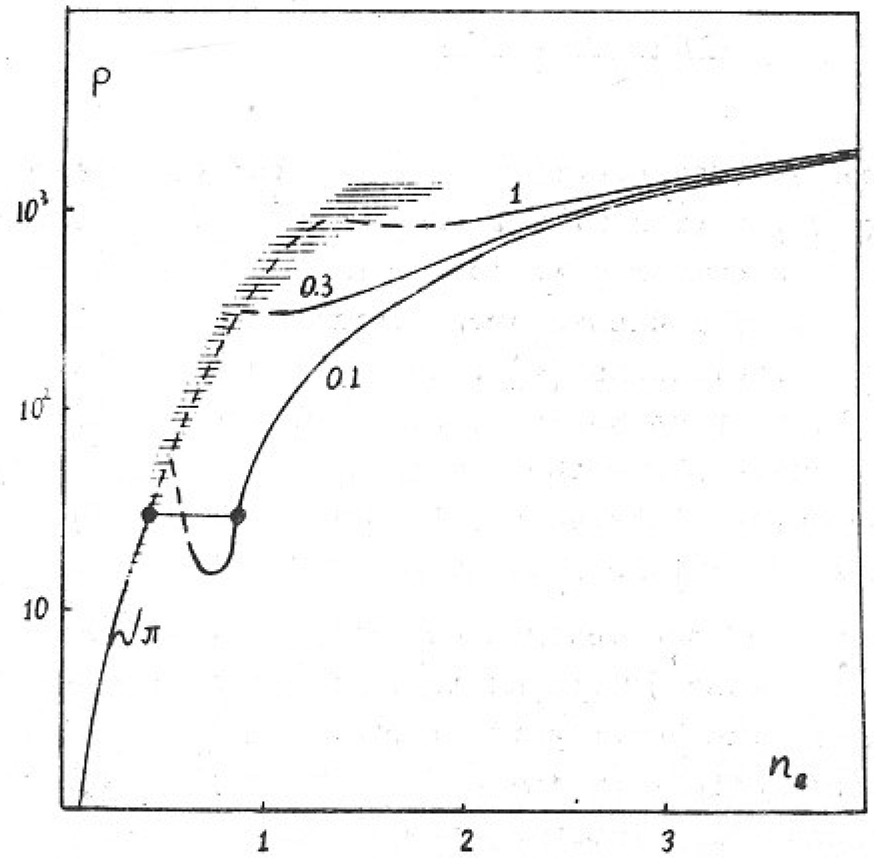

Fig. 1.

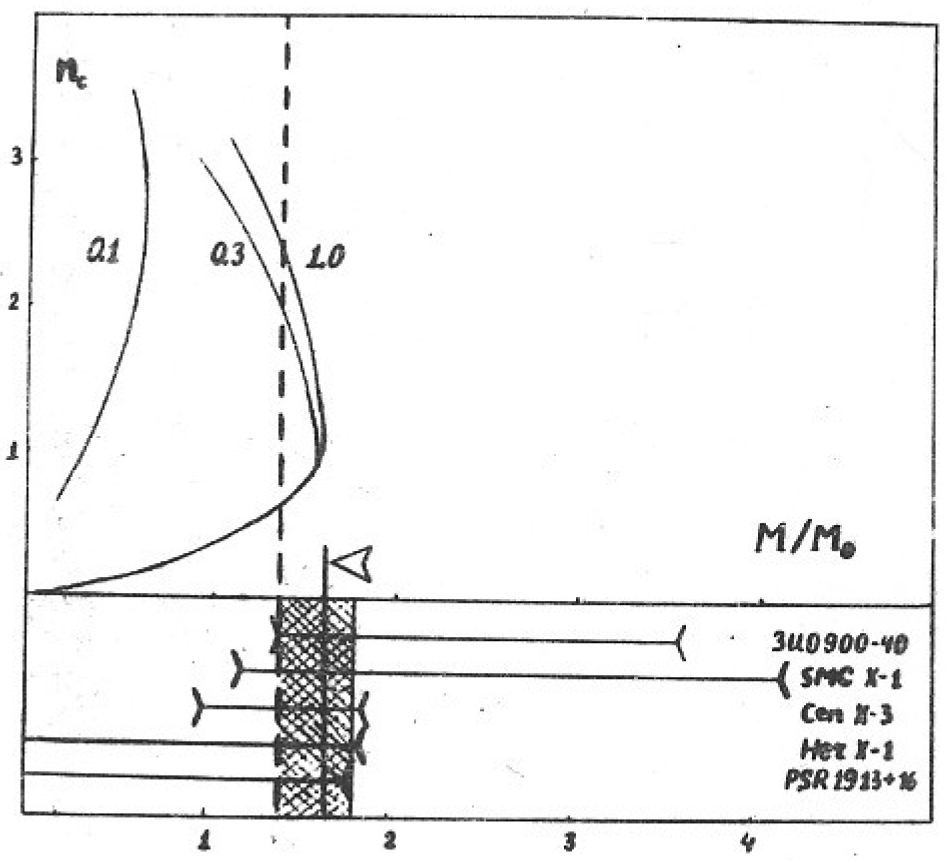

Fig. 2.

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