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CONCENTRATIONS OF HADRONS AND QUARK-GLUON PLASMA IN MIXED PHASE

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This paper presents the results of the first investigation of a new statistical model of deconfinement at finite baryon densities. The model takes into consideration a mixed phase of nuclear matter. In this state one can find hadrons as well as unbound quarks and gluons. The investigation of such a mixed state allowed us to get a quantitative agreement with the lattice QCD predictions for the zero baryon density. Due to the absense of reliable lattice results beyond the zero baryon density, the predictions for the finite baryon densities in the frame of the statistical model are of great importance.

The investigation has been performed at the Bogoliubov Laboratory of Theoretical Physics, JINR.

Концентрации адронов и кварк-глюонной плазмы в смешанной фазе

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В статье представлены результаты первых исследований новой статистической модели деконфайнмента при ненулевых барионных плотностях. Эта модель учитывает смешанную фазу ядерного вещества, в которой адроны сосуществуют с несвязанными кварками и глюонами. Учет такого смешанного состояния позволил нам получить количественное согласие с предсказаниями КХД на решетках для нулевой барионной плотности. Так как в настоящее время нет надежных решеточных результатов для ненулевых барионных плотностей, предсказания рассматриваемой статистической модели в указанной области термодинамических переменных ядерной материи особенно важны.

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Recently a new statistical model of deconfinement has been advanced [1—3]. The fundamentals of this model consist in taking into account a mixed phase of nuclear matter. The mixed phase is the state where unbound quarks and gluons coexist with hadrons. Probing the model at zero baryon density demonstrates the crucial importance of considering the mixed phase for adequate description of deconfinement. Indeed, near the deconfinement point the hadronic state as well as quark-gluon plasma turned out to be less advantageous than the mixed phase, from the thermodynamic point of view [1—3]. Besides, assuming only two possible states for nuclear matter: the hadronic phase and quark-gluon plasma, the traditionally used statistical models [4—7] predict the first order for deconfinement. On the contrary, lattice simulations testify to the gradual type of this phase transition in nuclear matter at zero baryon density [8—11]. The problem is solved with the new statistical model, for the coexistence of hadrons and quark-gluon plasma provides the gradual character of the deconfinement at zero baryon density.

The effective Hamiltonian of our model has the following form:

$$H = \sum_{s} \int \overset{+}{\psi}_{g} (\mathbf{x}, s) (\sqrt{-\nabla^2} + A\rho^{-\gamma}) \psi_{g} (\mathbf{x}, s)\, d\mathbf{x} + \\ + \sum_{a} \sum_{s} \int \overset{+}{\psi}_{a}(\mathbf{x}, s) (\sqrt{-\nabla^2 + m_a^2} + A\rho^{-\gamma}) \psi_{a}(\mathbf{x}, s)\, d\mathbf{x} + \\ + \sum_{nj} \sum_{s} \int \overset{+}{\psi}_{nj} (\mathbf{x}, s) (\sqrt{-\nabla^2 + M_{nj}^2} + U_{nj}) \psi_{nj} (\mathbf{x}, s)\, d\mathbf{x} - CV. \tag{1}$$

In expression (1) we have

$$U_{nj} \equiv n \left\{ A\, \rho^{-\gamma} \left(1 - (1 - w_{pl})^{-\gamma} \right) + \frac{\Phi}{9} \rho\, (1 - w_{pl}) \right\}, \tag{2}$$

$$C \equiv \frac{\gamma A}{1 - \gamma}\, \rho^{1-\gamma} \left((1 - w_{pl})^{1-\gamma} - 1 \right) + \frac{\Phi}{18} \rho^2 (1 - w_{pl})^2, \tag{3}$$

where

$$\rho \equiv \rho_g + \sum_{a} \rho_a + \sum_{nj} n\rho_{nj}, \\ w_{pl} \equiv \frac{1}{\rho} (\rho_g + \sum_{a} \rho_a). \tag{4}$$

In the above equations, ψ_i (**x**, s) stands for the field operator of the particles of the i-sort: $i = g$ corresponds to unbound gluons; $i = a$, to unbound quarks of the a-kind ($a = u, \bar{u}, d, \bar{d}$); $i = nj$, to the j-sort of hadrons made of n constituents. The density of the particles of the i-kind is denoted as ρ_i ; m_a stands for the bare mass of the quarks of the a-sort; M_{nj} is the mass of the nj-clusters. Constants γ, A, Φ have the values: $\gamma = 0.62$, $A = 225^{3\gamma+1}$ MeV$^{3\gamma+1}$, $\Phi = 4.1 \cdot 10^{-5}$ MeV^{-2}. Details of deriving this Hamiltonian can be found in papers [1—3].

This short communication presents the results of the first investigation of the model at nonzero baryon densities. Due to the absence of reliable lattice evaluations for thermodynamic quantities of nuclear matter beyond zero baryon density [12], predictions for the finite baryon densities in the frame of the new statistical model are of great interest. The results concern the concentrations of particles-constituents of nuclear matter at temperatures $0 < \theta < 700$ MeV and baryon densitites $0 < n_B/n_{0B} < 20$ ($n_{0B} \approx 1.33 \cdot 10^6$ MeV^3 , the baryon density of the normal nuclear matter). The quantity

$$w_{nj} \equiv \frac{n\rho_{nj}}{\rho}$$

is the concentration of the hadrons of the nj-type. The concentration of the quark-gluon plasma w_{pl} is defined in (4). Besides, it is convenient to use the concentration of the n — particle clusters

$$w_n \equiv \sum_j w_{nj} .$$

Why are we interested in the concentrations? Knowing the behaviour of the concentrations we can figure out the scenario of deconfinement. There are three basic possibilities for the deconfinement scenario:

(i) First, deconfinement can be the result of the hadronic fusion. Indeed, it is well known that the density of hadrons rises when increasing baryon density or/and temperature of the hadronic phase. So, the hadron interaction becomes harder. This implies that hadrons can cluster into bigger hadrons with the increase of θ or/and n_B [13]. The end of the process of the hadronic fusion is the formation of a giant quark-gluon cluster when the system reaches close packing of hadronic spheres. The giant cluster occupies all the system in which quarks and gluons, hence, can move freely.

(ii) Second, deconfinement may also be the effect of the hadron disintegration into their constituents. Really, increasing the temperature or/and baryon density, the energy of hadronic collisions rises, too. Hard collisions can result in hadron disintegration to smaller hadrons and, may be, into their unbound constituents. Note, that the absence of colour particles among the products of the collisions of the isolated hadrons, does not prove that unbound quarks and gluons cannot appear in the hadronic collisions inside nuclear matter where the conditions of particle existence differ from those in vacuum.

(iii) Third, unbound quarks and gluons are able to appear in the hadronic collisions inside nuclear matter due to the generation from vacuum, which can be realized without any fusion or disintegration of particles. The increase of the collision energies, that occurs with the rise of temperature or/and baryon density, can intensify the generation of unbound quarks and gluons from vacuum and lead to their predominance in nuclear matter.

Perhaps, some of the mentioned possible scenarios of the deconfinement can coexist. Thus, the aim of investigating the concentrations is to realize the true scenario of deconfinement.

In the hadronic sector of the model we took into account the mesons with the masses less than 800 MeV, nucleons and anti-nucleons. These particles play the major role among hadrons in nuclear matter with low baryon densities $n_B < n_{0B}$. Besides, multibaryons (six-quark clusters, nine quark configurations, etc.) and their anti-partners have been also taken into consideration. These exotic hadrons can make a significant contribution to the thermodynamic quantities of nuclear matter at high baryon densities $n_B > n_{0B}$ [14—17]. The specifications of multibaryons were chosen as in the papers concerning the simplified variant of the model [18,19]. Our investigation provided the following results. The large n-quark clusters with $n > 6$ do not survive in nuclear matter. For their concentrations we have found the estimate

$$\sum_{n>6} w_n < 10^{-3}.$$

The concentrations of other hadrons and quark-gluon plasma as functions of temperature and baryon density, are given in Figs.1—5. Here some notations are changed to present the results more clearly. In particular, w_π denotes the concentration of pions, $w_{\eta\,\rho\omega} = w_2 - w_\pi$ stands for the total concentration of η-, ρ- and ω-mesons. The numerical data are presented

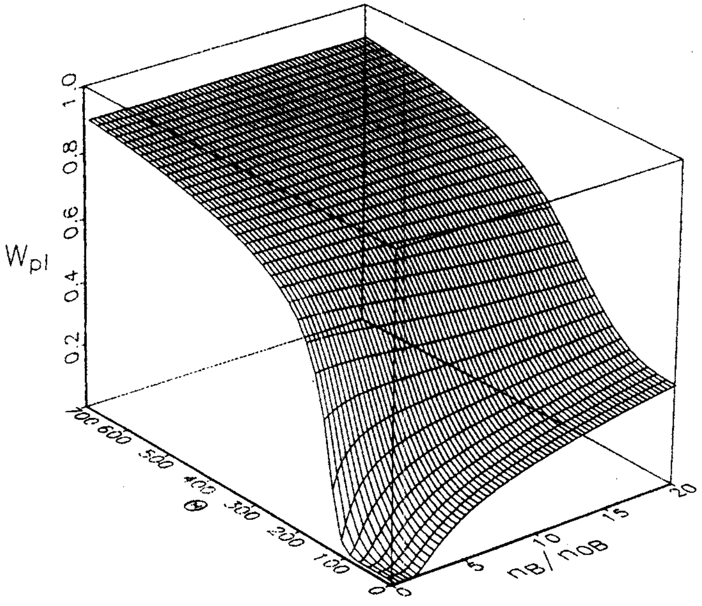

Fig.1. The concentration of the quark-gluon plasma versus temperature and relative baryon density

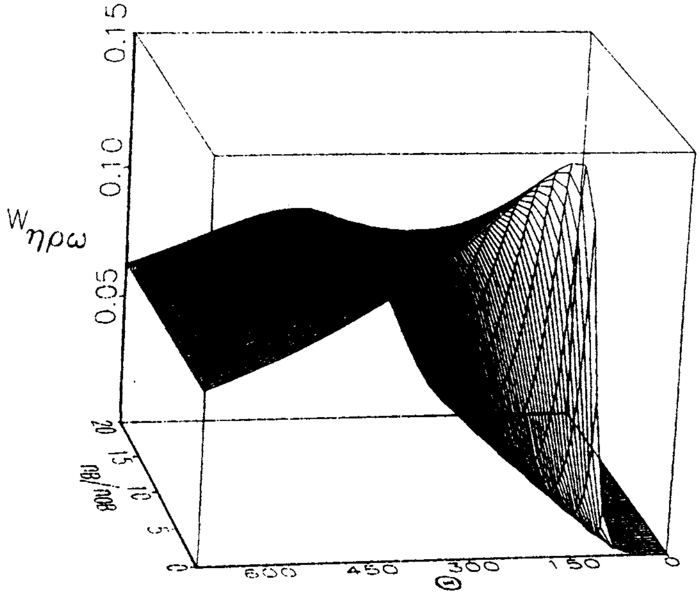

Fig.2. The behaviour of the pion concentration for various temperatures and baryon densities

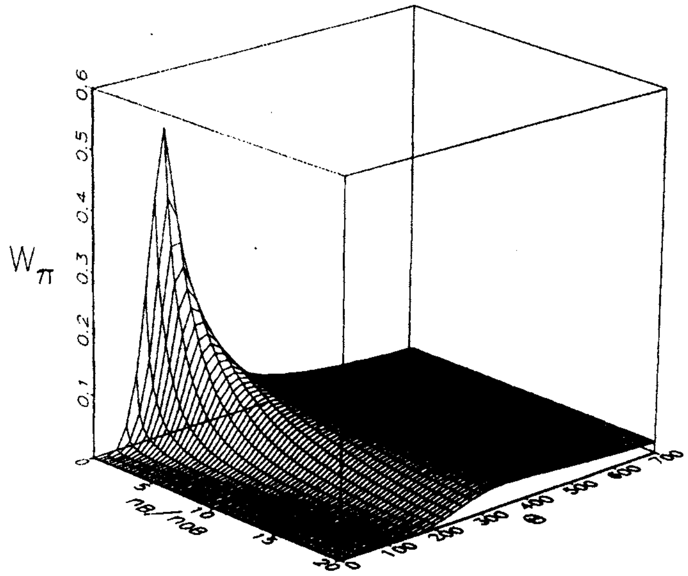

Fig.3. The total concentration of η-, ρ-, ω-mesons

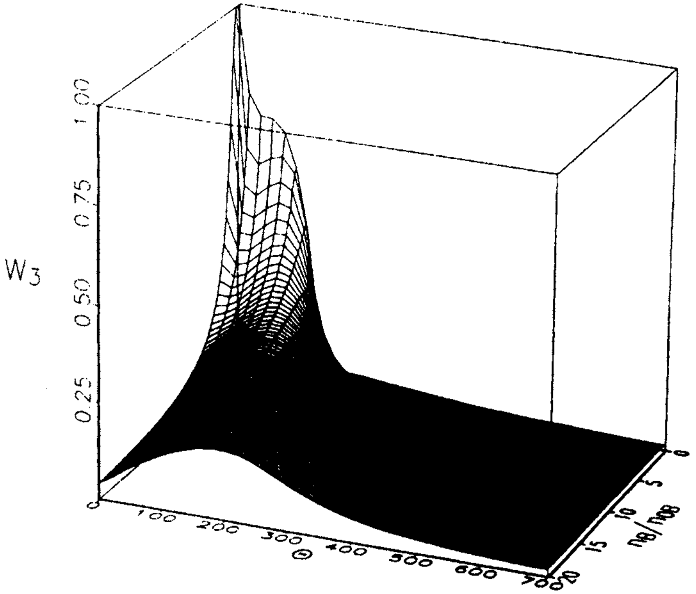

Fig.4. The concentration of three-quark clusters

in the figures with the step $0.3n_{0B}$ in baryon density, from $0.3n_{0B}$ up to $20n_{0B}$, and with the step 20 MeV in temperature, from zero up to 700 MeV. The derived data demonstrate that deconfinement in nuclear matter has nothing in common with the result of the hadron

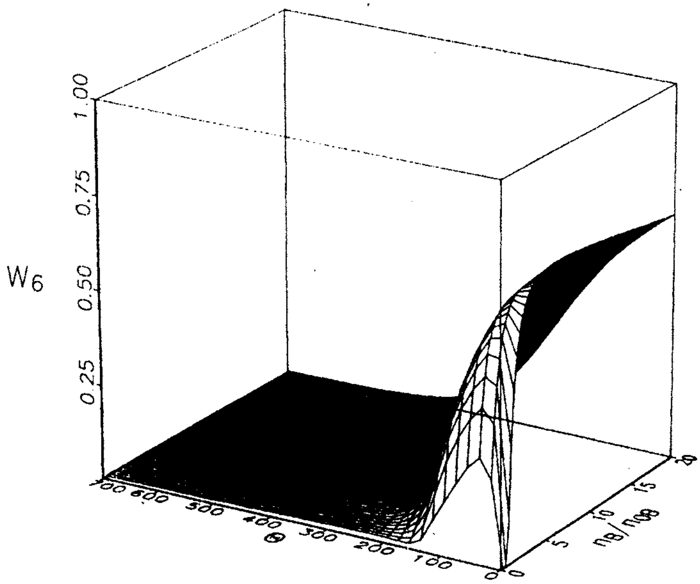

Fig.5. The concentration of six-quarks as function of temperature and relative baryon density

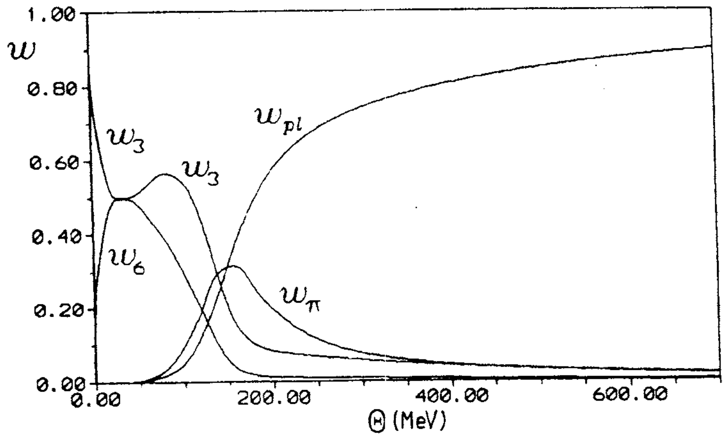

Fig.6. The concentrations of the main particles-constituents of nuclear matter as functions of temperature at $n_B = n_{0B}$

fusion into the giant quark-gluon cluster. Deconfinement is caused by both: disintegration of hadrons into their unbound constituents and generation of unbound gluons and quarks from vacuum. To clarify the details, let us consider which processes take place in nuclear matter with the quasistatic increase of temperature of baryon density. As the starting point we choose the point corresponding to the normal nuclear matter $\theta = 0$, $n_B = n_{0B}$. To simplify the consideration, the concentrations of the main particles-constituents of nuclear matter

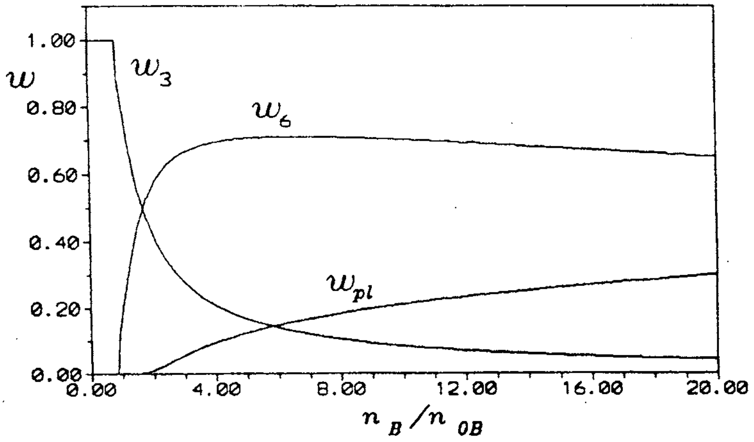

Fig.7. The concentrations of six-quarks clusters, three-quark configurations, and the quark-gluon plasma for various baryon densities at zero temperature

are presented in fig.6 for the fixed baryon density $n_B = n_{0B}$ and in fig.7 for the case of zero temperature. At first, the increase of temperature or baryon density of the normal nuclear matter leads to the rapid rise of the concentration of sixquark configurations. So, in the case of the fixed baryon density $n_B = n_{0B}$, the nucleons which prevail at zero temperature, lose their predominance at $\theta \approx 40$ MeV, where $w_3 \approx w_6 \approx 0.5$. In its turn, for the fixed temperature $\theta = 0$, the sixquark clusters become dominating at $n_B \approx 4n_{0B}$. Remind, that new particles can appear in nuclear matter via transformations of the primordial hadrons which exist in the system at $\theta = 0$, $n_B = n_{0B}$, for example, via fusion of small clusters into bigger configurations. In this case, the full number of quarks in the system does not change. Besides, new particles can arise without any hadronic disintegration or fusion by means of the generation from vacuum when a part of the energy of colliding particles is spent for this. In that case the full number of quarks and gluons before particles collision differs from this number after the reaction. Our calculations have shown that the generation from vacuum in nuclear matter at $n_B > n_{0B}$ can play a significant role only at $\theta > 80$ MeV. Thus, one can conclude that the hadronic fusion causes the changes with temperature increasing from zero to 40 MeV ($n_B = n_{0B}$) or baryon density rising from n_{0B} to $4n_{0B}$ ($\theta = 0$). But the subsequent rise of the temperature or baryon density is accompanied by the gradual decrease of the sizes of the particles predominating in nuclear matter. In particular, with the fixed temperature $\theta = 0$ and for all values of baryon density $n_B > 6n_{0B}$, the hadronic concentrations are decreasing functions of n_B, while w_{pl} is an increasing function of baryon density. As to the situation at $n_B = n_{0B}$, it is more complicated and, correspondingly, interesting. In the temperature range from 40 MeV to 80 MeV the concentration of sixquark clusters diminishes so that at 80 MeV again nucleons become dominating in the system:

$w_3 \approx 0.6$, $w_6 \approx 0.4$. Further, at $\theta = 150$ MeV the coexistence of the three-quark clusters, pions and the quark-gluon plasma mainly determines the thermodynamic properties of nuclear matter: $w_{pl} \approx 0.35$, $w_\pi \approx 0.30$, $w_3 \approx 0.25$. Finally, at $\theta = 200$ MeV the quark-gluon plasma already prevails: $w_{pl} \approx 0.6$, $w_\pi \approx 0.2$, $w_{\eta\,\rho\omega} \approx 0.1$, $w_3 \approx 0.1$. Thus, the deconfinement which occurs at zero temperature with increasing baryon density, is the result of disintegration of sixquark clusters and nucleons into unbound quarks. On the other hand, the deconfinement taking place at the fixed baryon density $n_B = n_{0B}$ with rising temperature, is mainly caused by generation of the inbound quarks and gluons from vacuum. Of course, there is such a process of simultaneous increase of temperature and baryon density at which both, generation from vacuum and disintegration of hadrons, are equivalent partners leading the system to deconfinement.

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