DIBARYONS IN NUCLEI

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Nuclear matter with an admixture of dibaryons at zero temperature is studied. The short-range nuclear forces are represented by a delta-like pseudopotential. The concentration of dibaryons as a function of the dibaryon mass is found.

Some results of high energy nuclear collision experiments and more recently the so-called EMC effect has led many authors, see e.g. refs. [1,2], to the conclusion of a significant admixture of multiquark, mainly six-quark, states in nuclei. The aim of this paper is to study such admixtures in the frame of a simple statistical model of the nucleus. The gas of baryons and dibaryons in chemical and thermodynamical equilibrium at zero temperature is considered. The concentration of dibaryons in ideal and nonideal gas approximations as a function of the dibaryon mass is found.

The nuclear matter with multibaryon admixtures at zero temperature has earlier been studied in ref. [3], where the interaction has been taken into account through the Van der Waals correction to the volume. In this paper we try to make a step towards a more realistic description of the problem introducing the interaction into the system with the help of a delta-like pseudopotential, see e.g. ref. [4].

Let us consider an ideal gas of nucleons (fermions) and dibaryons (bosons) at zero temperature. Dibaryons occur in the system as a Bose–Einstein condensate. Baryon number conservation and the assumption of chemical equilibrium lead to the following relation

$$\mu_D = 2\mu ,$$

where μ_D and μ are chemical potentials of dibaryons and nucleons, respectively. At zero temperature one finds (in non-relativistic approximation) the following equation for μ [4]

$$B = \tfrac{2}{3}(V/\pi^2)[2m(\mu - m)]^{3/2} + 2g \lim_{\beta \to \infty} [\{\exp[\beta(M - 2\mu)] - 1\}^{-1}] , \tag{1}$$

where B is the total baryon number of the system, V the volume of the system, m the nucleon mass, M the dibaryon mass, g the number of internal degrees of freedom of the dibaryon, and β the inverse temperature. We use the units where $c = k = \hbar = 1$. The above equation expresses the baryon number conservation. The first term comes from the nucleons while the second one comes from the dibaryons. It is seen that there are two kinds of solution of (1)

$$\mu = M/2 \qquad \text{for } M < 2(m + E_F) ,$$

$$\quad = E_F + m \qquad \text{for } M > 2(m + E_F) , \tag{2}$$

where E_F is the Fermi energy of a pure nucleon gas, and

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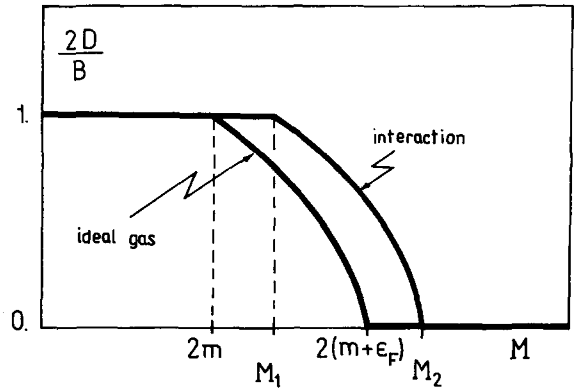

Fig. 1. The concentration of dibaryons versus the dibaryon mass.

$$E_F = p_F^2/2m\ , \quad p_F = (\tfrac{3}{2}\pi^2 B/V)^{1/3}\ .$$

From (1) and (2) it follows that the number of dibaryons, D, in the gas is

$$\begin{aligned} D &= 0 && \text{for } M > 2(m+E_F)\ , \\ &= \tfrac{1}{2}B\{1 - [(M-2m)/2E_F]^{3/2}\} && \text{for } 2(m+E_F) > M > 2m\ , \\ &= \tfrac{1}{2}B && \text{for } 2m > M\ . \end{aligned}$$

At a fixed dibaryon mass the above expression describes the dibaryon concentration as a function of density expressed through the Fermi energy. The ratio $2D/B$ as a function of M is illustrated in fig. 1.

Let us now discuss how the results are modified due to the interaction present in nuclei. The short-range repulsive forces are crucial for properties of nuclear matter. In particular, these forces, in contrast to long-range attractive ones, increase the Fermi level and consequently can lead to an increase of dibaryon admixture. The short-range forces for not too high densities can be represented by a delta-like pseudopotential [4]. In such a case the hamiltonian of the system looks as follows

$$\begin{aligned} H = &\sum_{i=1}^{B-2D} (p_i^2/2m + m) + \sum_{k=1}^{D} (p_k^2/2M + M) \\ &+ \sum_{\substack{i=1\\ i<j}}^{B-2D} \sum_{j=1}^{B-2D} (4\pi a/m)\delta^{(3)}(r_i - r_j) + \sum_{i=1}^{B-2D} \sum_{k=1}^{D} (2\pi\tilde{a}/m_R)\delta^{(3)}(r_i - r_k) + \sum_{\substack{k=1\\ k<l}}^{D} \sum_{l=1}^{D} (4\pi a_D/M)\delta^{(3)}(r_k - r_l)\ , \end{aligned}$$

where $a, \tilde{a}, a_D$ are scattering lengths (diameters of a hard core potential) in nucleon–nucleon, nucleon–dibaryon and dibaryon–dibaryon interactions. $m_R = mM/(m+M)$ is the reduced mass of a nucleon–dibaryon system. Assuming that the numbers of nucleons with opposite spin are equal, one finds [4] the energy of the system

$$\begin{aligned} E = &\sum_p (p^2/2m + m)N_p + \sum_p (p^2/2M + M)D_p \\ &+ \tfrac{3}{2}\pi a(B-2D)^2/mV + 2\pi\tilde{a}(B-2D)D/m_R V + (4\pi a_D/MV)\left(D^2 - \sum_p D_p^2\right)\ , \end{aligned} \tag{3}$$

where N_p and D_p are the numbers of nucleons and dibaryons, respectively, with momentum p. Using (3) one gets the following analogue of eq. (1)

$$B = \tfrac{2}{3}(V/\pi^2)[2m(\mu - m)]^{3/2}\{1 - [\pi/(\mu - m)V][(3a/m)(B - 2D) + (2\tilde{a}/m_R)D]\}^{3/2}$$

$$+ 2g \lim_{\beta\to\infty} [(\exp\{\beta[M + (2\pi\tilde{a}/m_R)(B - 2D)/V + (2\pi a_D/M)D/V - 2\mu]\} - 1)^{-1}] . \qquad (4)$$

To diminish the number of parameters, we make an assumption, justified in the bag model [5], that the radius of a hard core in the third power is proportional to the particle's mass. Thus,

$$a_D = a(M/m)^{1/3} , \quad \tilde{a} = \tfrac{1}{2}a[1 + (M/m)^{1/3}] .$$

We shall now determine the critical values of the dibaryon mass denoted in fig. 1 as M_1 and M_2. For $M < M_1$ there are no nucleons in the system while for $M > M_2$ there are no dibaryons. For a fixed value of dibaryon mass M_1 and M_2 are related to the critical values of density. The values of M_1 and M_2 can be found as follows. For $M = M_1$ ($M = M_2$) the nucleon (dibaryon) contribution to the total baryon number (4) has to vanish. On the other hand, the value of μ has to be compatible with the existence of the dibaryon condensation. Both conditions provide equations for M_1 and M_2:

$$\mu = \tfrac{1}{2}M_1 + \pi a_D D/M_1 V = m + 2\pi\tilde{a}D/m_R V , \quad \mu = \tfrac{1}{2}M_2 + \pi\tilde{a}B/m_R V = m + E_F + 3\pi aB/mV .$$

The above equations can approximately be solved by putting the values of M_1 and M_2 found in the ideal gas approximation in the terms containing the small parameter a. It proves to be enough to put $M_{1,2} = 2m$. In this way one finds

$$M_1 \cong 2m + (3.7/\pi)E_F p_F a , \quad M_2 \cong 2m + 2E_F[1 + (1.7/\pi)p_F a] .$$

The values for the critical masses M_1 and M_2 can also be found in another way. The state of a system is determined by a minimum of free energy, which coincides with the energy of the system for zero temperature. Thus, the dibaryon admixture occurs when the total energy (including mass and interaction with surrounding nucleons) of two nucleons at the Fermi level is equal to the total energy of the dibaryon at rest. On the other hand, the nucleons disappear when the total energy of two nucleons at rest is equal to the dibaryon energy.

For an ideal gas the value of the chemical potential for non-zero dibaryon admixture does not depend on the concentration of dibaryons. This is not the case for a nonideal gas. In two limits, $D = 0$ and $D = B/2$, one finds respectively

$$\mu \cong \tfrac{1}{2}M + (2.3/\pi)E_F p_F a , \quad \mu \cong \tfrac{1}{2}M + (0.4/\pi)E_F p_F a .$$

Our final results are the formulae for dibaryon concentration as a function of the dibaryon mass for two limiting cases:

(1) $D \to 0$.

$$D \cong 0 \qquad \text{for } M > M_2 ,$$

$$\cong \tfrac{1}{2}B\{1 - [(M - 2m)/2E_F - (1.7/\pi)p_F a]^{3/2}\} \qquad \text{for } M < M_2 ,$$

and

(2) $D \to \tfrac{1}{2}B$.

$$D \cong \tfrac{1}{2}B\{1 - [(M - 2m)/2E_F - (1.8/\pi)p_F a]^{3/2}\} \qquad \text{for } M > M_1 ,$$

$$\cong \tfrac{1}{2}B \qquad \text{for } M < M_1 . \qquad (5)$$

It is seen that in both limits the values of the function $D(M)$ for $M_1 < M < M_2$ are very close. For a fixed dibaryon mass the above formulae can be understood as a dependence of the dibaryon concentration on the nuclear density. However, our results cannot be extrapolated to the densities significantly higher than the normal one.

For normal nuclear density $E_F = 42$ MeV while $p_F a = 0.57$ [6]. The critical masses are $M_1 \cong 2m + 30$ MeV, $M_2 \simeq 2m + 110$ MeV. There are two experimental candidates for dibaryon states with mass less than M_2, namely $M = 1936$ MeV and $M = 1962$ MeV [7]. The decay width of both states reported in ref. [7] is 2 MeV. The ratio $2D/B$ is about 0.8 for $M = 1936$ MeV and about 0.4 for $M = 1962$ MeV. We have taken the mass of free nucleons for these estimations. If we would take into account the mass defect of the nucleon – the dibaryon mass, consequently, would be decreased by a value of two times the nucleon mass – the above estimations would remain unchanged. Such a big admixtures seem to be unreasonable, what makes the dibaryon signal observed in the experiment [7], in our opinion, doubtful.

There are heavier dibaryon candiates with masses 2020 MeV [8], 2024 MeV [9], 2025 MeV [10] and 2035 MeV [11], and decay widths between 3 and 15 MeV. The value of the critical mass M_2 is about 2060 MeV for twice the normal density. Thus, if one assumes fluctuations of nuclear density, the above states can contribute to the dibaryon admixture in nuclei.

Besides the rather poor experimental states of dibaryons and the uncertainties of their masses one has to remember that our calculations do not provide a quite realistic basis for dibaryon admixture estimations in nuclei. The reasons are the following:

(1) Our calculations are valid in the lowest order of the $p_F a$ parameter which is not much less than unity.

(2) The nucleus is assumed to be an infinite system.

(3) Dibaryons are treated as stable particles. More precisely, for validity of our calculations the dibaryon decay width has to be much less than the Fermi energy. However, dibaryons in the nucleus can be very short-lived particles with a decay width of some hundred MeV.

In conclusion, let us stress the importance of the problem considered here for neutron-star physics. The point is that the admixture of dibaryons in nuclear matter or finally the transition to pure dibaryon matter makes the equation of state significantly softer. On the other hand, there are arguments [12] that the equation of state cannot be softer than the so-called Moszkowski one [13] where dibaryons are not taken into account. Both facts can give constraints on the density of the nucleus of neutron start or the mass of dibaryons. The problem, however, needs further investigations.

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