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DIBARYONS IN NUCLEI

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Some results of high energy nuclear collision experiments and more recently the so-called EMC effect have led many authors, see, e.g., /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 dibaryon mass is found.

The nuclear matter with multibaryon admixtures at zero temperature has been earlier 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. Namely, we introduce, in an explicit form, the two-particle interaction using delta-like pseudopotential, see, e.g., Ref./4/. On the other hand in contrast to Ref.3 numerical methods are not used.

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 the chemical potentials of dibaryons and nucleons, respectively. At zero temperature one finds (in a nonrelativistic approximation) the following equation for μ

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

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 dibaryon; 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 from the dibaryons. It is seen that there are two kinds of solutions of Eq. (1)

$$\mu = \begin{cases} M/2 & \text{for} \quad M < 2(m + E_F), \\ E_F + m & \text{for} \quad M > 2(m + E_F). \end{cases} \qquad (2)$$

where E_F is the Fermi energy of pure nucleon gas $E_F = \frac{p_F^2}{2m}$, $p_F = (\frac{3}{2}\pi^2 \frac{B}{V})^{1/3}$. From Eqs. (1) and (2) it follows that the number of dibaryons, D, in the gas is

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

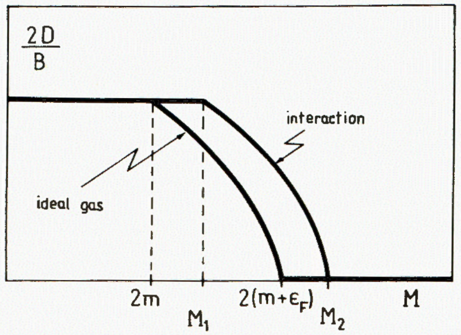
At a fixed dibaryon mass the above relationship describes the dibaryon concentration as a function of density expressed through the Fermi energy. The ratio $2D/B$ as a function of M is illustrated in the Figure.

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, make higher the Fermi level, and consequently they can lead to an increase of dibaryon admixture. The short-range forces for densities close to normal nuclear one can be represented by the delta-like pseudopotential.

In such a case the Hamiltonian of the system looks as follows

$$H = \sum_{i=1}^{B-2D} (\frac{\vec{p}_i^{\,2}}{2m} + m) + \sum_{k=1}^{D} (\frac{\vec{p}_k^{\,2}}{2M} + M) + \sum_{i=1}^{B-2D} \sum_{\substack{j=1 \\ i<j}}^{B-2D} \frac{4\pi a}{m} \delta^{(3)} (\vec{r}_i - \vec{r}_j) +$$
$$+ \sum_{i=1}^{B-2D} \sum_{k=1}^{D} \frac{2\pi \tilde{a}}{m_R} \delta^{(3)} (\vec{r}_i - \vec{r}_k) + \sum_{k=1}^{D} \sum_{\substack{\ell=1 \\ k<\ell}}^{D} \frac{4\pi a_D}{M} \delta^{(3)} (\vec{r}_k - \vec{r}_\ell),$$

where $a, \tilde{a}, a_D$ are scattering lengths (diameters of a hard core potential) in nucleon-nucleon, nucleon-dibaryon and dibaryon-dibaryon interactions.



The concentration of dibaryons versus dibaryon mass.

$m_R = \frac{m \cdot M}{m+M}$ is the reduced mass of a nucleon-dibaryon system. Assuming that the numbers of nucleons with opposite spin are equal, one finds the energy of the system

$$E = \sum_{\vec{p}} (\frac{\vec{p}^{\,2}}{2m} + m) N_{\vec{p}} + \sum_{\vec{p}} (\frac{\vec{p}^{\,2}}{2M} + M) D_{\vec{p}} +$$
$$+ \frac{3}{2} \frac{\pi a (B-2D)^2}{mV} + \frac{2\pi \tilde{a} (B-2D) D}{m_R V} + \frac{4\pi a_D}{MV} (D^2 - \sum_{\vec{p}} D_{\vec{p}}^2), \tag{3}$$

where $N_{\vec{p}}$ and $D_{\vec{p}}$ are the numbers of nucleons and dibaryons, respectively, with momentum $\vec{p}$. Using Eq.(3), one gets the following analogue of the equation (1)

$$B = \frac{2}{3} \frac{V}{\pi^2} [2m(\mu - m)]^{3/2} [1 - \frac{\pi}{(\mu - m)V} (\frac{3a}{m} (B - 2D) + \frac{2\tilde{a}}{m_R} D)]^{3/2} +$$
$$+ 2g \lim_{\beta \to \infty} \{[\exp \beta (M + \frac{2\pi \tilde{a}}{m_R} \frac{B-2D}{V} + \frac{2\pi a_D}{M} \frac{D}{V} - 2\mu) - 1]^{-1}\}. \tag{4}$$

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 particle mass. Thus, $a_D = a(\frac{M}{m})^{1/3}$, $\tilde{a} = \frac{a}{2}[1 + (\frac{M}{m})^{1/3}]$. Now we will determine critical values of dibaryon mass denoted in the Figure as M_1 and M_2. For M less than 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 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 values of μ has to be compatible with the existence of the dibaryon condensation. Both conditions provide equations for M_1 and M_2:

$$\mu = \frac{M_1}{2} + \pi \frac{a_D D}{M_1 V} = m + 2\pi \frac{\tilde{a} D}{m_R V},$$

$$\mu = \frac{M_2}{2} + \pi \frac{\tilde{a} B}{m_R V} = m + E_F + 3\pi \frac{aB}{mV}.$$

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

$$M_1 \cong 2m + \frac{3.7}{\pi} E_F p_F a, \quad M_2 \cong 2m + 2E_F\left(1 + \frac{1.7}{\pi} p_F a\right).$$

The values of critical masses M_1 and M_2 can be also 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 the mass and interaction with surrounding nucleons) of two nucleons at the Fermi level is equal to the total energy of 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 ideal gas the value of chemical potential for non-zero dibaryon admixture does not depend on the concentration of dibaryons. It is not the case for nonideal gas. In two limits $D = 0$ and $D = B/2$, one finds respectively

$$\mu \cong \frac{M}{2} + \frac{2.3}{\pi} E_F p_F a, \quad \mu \cong \frac{M}{2} + \frac{0.4}{\pi} E_F p_F a.$$

Our final results are the formulae for dibaryon concentration as a function of dibaryon mass for two limiting cases
1) $D \to 0$

$$D \cong \begin{cases} 0 & \text{for} \quad M > M_2 \\ \frac{B}{2}\left[1 - \left(\frac{M-2m}{2E_F} - \frac{1.7}{\pi} p_F a\right)^{3/2}\right] & \text{for} \quad M < M_2 \end{cases}$$

and
2) $D \to \frac{B}{2}$

$$D \cong \begin{cases} \frac{B}{2}\left[1 - \left(\frac{M-2m}{2E_F} - \frac{1.8}{\pi} p_F a\right)^{3/2}\right] & \text{for} \quad M > M_1 \\ \frac{B}{2} & \text{for} \quad M < M_1. \end{cases}$$

It is seen that in both limits the values of 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 dibaryon concentration on 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, $M_2 \cong 2m + 110$ MeV. There are two experimental candidates for dibaryon states with mass less than M_2, namely $M = 1936$ MeV and 1962 MeV[7]. The decay widths of both states reported in Ref.[7] are 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 nucleon for these estimations. If the mass defect of nucleon was taken into account and consequently the dibaryon mass was decreased by a value of two times greater than the nucleon one, the above estimations would remain unchanged. Such big admixtures seem to be unreasonable. Thus, our considerations do not favour the existence of such light dibaryons like those reported in Ref.7. There are heavier dibaryon candidates with masses of 2020 MeV[8], 2024 MeV[9], 2025 MeV[10], 2035 MeV[11] and decay widths between 3 and 15 MeV. The value of critical mass M_2 is about 2060 MeV for twice normal density. Thus, if one assumes the fluctuations of nuclear density, the above states can contribute to the dibaryon admixture in nuclei.

In spite of the uncertainties of the dibaryon 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 hundreds of MeV.

At the end let us stress the importance of the problem being considered for neutron star physics. The point is that the admixture of dibaryons in nuclear matter or finally the transition to pure dibaryon matter make 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 constraint on the density of the nucleus of neutron star or the mass of dibaryon. The problem, however, needs further investigations*.

**The importance of boson multi-quark admixtures in neutron stars has been earlier observed in: B.A.Shahbazian. Proc. of 2nd Workshop "Gravitation and Unification of Fundamental Fields" October 1982, Kiev, in: "Cosmic Research in Ukraine" Vol. 17,, p. 101, ed. by G.S.Pisarenko, Naukova Dumka, Kiev, 1983. B.A.Shahbazian, Proc. of Conf. on Theory of Systems of Few Particle Systems with Strong Interactions", p. 90, ed. by L.D.Fadeev, Leningrad University Press, Leningrad, 1983.*

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Дибарионы в ядрах

Рассматривается ядерная материя с примесью дибарионных состояний в термодинамическом и химическом равновесии при нулевой температуре. Обсуждается приближение идеального газа, а затем роль ядерных сил. С помощью метода псевдопотенциала включено взаимодействие. Получена зависимость концентрации дибарионов от их массы. Обсуждается возможность существования примеси дибарионов в ядрах и оценивается величина таких примесей. Обращается внимание на связь рассмотренной проблемы с физикой нейтронных звезд.

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Сообщение Объединенного института ядерных исследований. Дубна 1984

Mrówczyński St. E2-84-732

Dibaryons in Nuclei

The nuclear matter with an admixture of dibaryons in thermodynamical and chemical equilibrium at zero temperature is studied. The ideal gas approximation is considered. Then the role of nuclear forces is discussed. With the help of the pseudopotential method the interaction is included and the dibaryon concentration versus its mass is obtained. The possibility of dibaryon admixtures in nuclei is discussed. The values of such admixtures are estimated.The connection of the problem being considered with the neutron star physics is pointed out.

The investigation has been performed at the Laboratory of High Energies, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna 1984