Abstract The Bose-Einstein condensation of α particles in the multicomponent environment of dilute, warm nuclear matter is studied. We consider the cases of matter composed of light clusters with mass numbers $A \leq 4$ and matter that in addition these clusters contains $^{56}\text{Fe}$ nuclei. We apply the quasiparticle gas model which treats clusters as bound states with infinite life-time and binding energies independent of temperature and density. We show that the α particles can form a condensate at low temperature $T \leq 2$ MeV in such matter in the first case. When the $^{56}\text{Fe}$ nucleus is added to the composition the cluster abundances are strongly modified at low temperatures, with an important implication that the α condensation at these temperatures is suppressed.

Keywords Nuclear Matter · Bose Einstein condensation · α particles

1 Introduction

The physics of Bose-Einstein condensation of α particles and their superfluidity is one of the exciting “condensed matter” aspects of nuclear physics.
clustering and condensation in dilute nuclear matter is of interest in nuclear structure calculations, heavy ion collisions in laboratory experiments as well as in astrophysics of supernovas and neutron stars. For example, the processes of neutrino emission and absorption, which are an important part of the mechanism of core-collapse supernovas and nucleosynthesis, strongly depend on the composition of warm low-density nuclear matter [1,2,3,4,5].

The purpose of this work is to investigate the properties of light-nuclei in nuclear matter in thermodynamic equilibrium in the density regime \( n \leq 0.3 \, n_{\text{sat}} \), where \( n_{\text{sat}} \approx 0.16 \, \text{fm}^{-3} \) is the saturation density, and the temperature regime in the range \( 2 \leq T \leq 10 \, \text{MeV} \). We consider matter composed of a mixture of clusters and free nucleons. As we are interested in physical processes which occur on time-scales shorter than the relaxation time needed to establish \( \beta \)-equilibrium, we will specify the isospin asymmetry in terms of proton fraction \( Y_p = N_p / (N_p + N_n) \), where \( N_p \) and \( N_n \) are the net number densities of protons and neutrons.

The determination of the composition and properties of dilute nuclear matter is a long-standing problem which has gained renewed interest in recent years in various contexts, for a recent review see [6]. The topics of current interest are, for example, the improvements on the supernova and warm neutron star equations of state and thermodynamics [7,8] which include the multi-cluster composition of matter [9,10,11,12,13,14,15,16,17,18,19,20,21]. Another aspect of the problem is the effects of light clusters in intermediate energy heavy ion collisions [22,23,24,25,26,27] which were extensively studied using various methods, see for example [28,29,30]. Furthermore, the general many-body problem of bound state formation in nuclear medium is an outstanding problem on its own right [31,32,33,34,35,36,37,38,39,40,41,42].

In this work we adopt the quasiparticle gas model [10] to explore the composition and thermodynamics of isospin symmetrical and asymmetrical nuclear matter. We update and improve on the results of Ref. [10] and provide additional information which facilitates a comparison with the results obtained within alternative models. The quasiparticle gas model includes mean-field effects on the nucleon masses (including those nucleons that are bound in clusters), but neglects the interactions among clusters with \( A > 1 \). Thus, the clusters are treated as quasiparticles with infinite life-time with binding energies that are independent of the temperature and density.

The main focus of this work is the Bose-Einstein condensation (hereafter BEC) of \( \alpha \) particles in the clustered environment. The BEC in \( \alpha \) matter has attracted much (and renewed) attention in relation to the problem of \( \alpha \) cluster structure of a number of nuclei, notably \( ^{12}\text{C} \) [43,44], as well as \( \alpha \) condensation in infinite nuclear systems [45,46,47,48,49,50,51,52,53,54,55]. It is our aim to study this phenomenon in infinite nuclear system under the condition of chemical equilibrium between \( \alpha \) particles and other light clusters. We further explore the effect of a heavy nucleus on the system of light cluster and show that the number density of \( \alpha \) particles reduces in this case and, as a consequence, their condensation is suppressed.
The paper is organized as follows. Section 2 reviews the formalism of quasi-particle gas model adopted in this work and details the approximations used. In Sec. 3 we present the numerical results for the composition and equation of state of matter. The problem of $\alpha$ particle condensation and the effect of a heavy nucleus $^{56}\text{Fe}$ on the cluster abundances is discussed. A summary and outlook is given in Sec. 4.

2 Formalism

2.1 The quasiparticle gas model

In this work we consider nuclear matter composed of unbound nucleons and light nuclei with mass numbers $A \leq 4$ plus a single heavy nucleus. Such an approach was introduced already by Refs. [7,8] and has been used subsequently in many studies. The matter is in equilibrium at temperature $T$ with total number density of nucleons $n$. The nuclear clusters (bound states) are uniquely characterized by their mass number $A$ and charge $Z$, which we combine in a single index $\alpha = (A, Z)$ (no confusion with the $\alpha$ particle should arise). In the quasiparticle gas model, which assumes that clusters are particles with infinite life-time, the grand canonical potential of the ensemble is expanded into partial contributions from individual constituents (nucleons and clusters) according to

$$\Omega(\mu_n, \mu_p, T) = \sum_\alpha \Omega_\alpha(\mu_\alpha, T),$$  \hspace{1cm} (1)

where $\mu_n$ and $\mu_p$ are the chemical potentials of neutrons and protons and $\mu_\alpha$ is the chemical potential of the cluster $\alpha$. Baryon number and charge conservation implies that in chemical equilibrium

$$\mu_\alpha = (A - Z)\mu_n + Z\mu_p.$$  \hspace{1cm} (2)

The thermodynamic potential for cluster $\alpha$ appearing in Eq. (1) is written as

$$\Omega_\alpha(\mu_\alpha, T) = -\int_{-\infty}^{\mu_\alpha} d\mu_\alpha' n_\alpha(\mu_\alpha', T),$$  \hspace{1cm} (3)

where $n_\alpha(\mu_\alpha', T)$ is the number density of clusters with a given value of $\alpha$. Here we assume that the quasiparticle self-energies (which in the quasi-particle picture are approximated by an effective mass) weakly depend on the density, therefore the corresponding derivatives can be neglected to leading order. The densities of the species are in turn given by

$$n_\alpha = g_\alpha \int \frac{d^3p}{(2\pi)^3} f_\alpha(p),$$  \hspace{1cm} (4)

where $g_\alpha = 2s_\alpha + 1$ is the degeneracy factor for the spin degree of freedom and $f_\alpha(p)$ are the Fermi/Bose distribution functions

$$f_\alpha(p) = \left[ \exp \left( \frac{E_\alpha - \mu_\alpha}{T} \right) - (-1)^A \right]^{-1},$$  \hspace{1cm} (5)
where the quasiparticle energies are given by

\[ E_\alpha = \begin{cases} \frac{p^2}{2m^*}, & \text{unbound nucleons} \\ \frac{p^2}{2m^*A} - B_\alpha, & \text{clusters} \end{cases} \]  

(6)

where \( p \) is the momentum of a cluster in its center-of-mass frame, \( m^* \) is the nucleon effective mass and \( B_\alpha \) is the binding energy. Here and in the following we neglect the small mass difference between proton and neutron.

The key feature of the quasiparticle gas model is that the density is a sum of contributions from infinite life-time quasiparticles - clusters - characterized by the value of index \( \alpha \). The thermodynamic quantities of interest now can be computed from the thermodynamic potential Eq. (1). The pressure and the entropy are obtained as

\[ P = -\frac{\Omega}{V}, \quad S = -\frac{\partial \Omega}{\partial T}. \]  

(7)

It is clear that the pressure of the system is the sum over pressures of each type of clusters present in the mixture: \( P = \sum \alpha P_\alpha \), where

\[ P_\alpha = \frac{\Omega_\alpha}{V} = \pm \frac{g_\alpha T}{2\pi^2} \int_0^\infty \ln \left[ 1 \pm \exp \left( \frac{\mu_\alpha - E_\alpha}{T} \right) \right] k^2 \, dk. \]  

(8)

Similarly, the net entropy of the system is given by \( S = V^{-1} \sum \alpha S_\alpha \), where

\[ S_\alpha = \pm \frac{g_\alpha V}{2\pi^2} \int_0^\infty \left[ f_\alpha \ln f_\alpha + (1 \mp f_\alpha) \ln(1 \mp f_\alpha) \right] k^2 \, dk. \]  

(9)

Finally, we establish the relations between the number densities of clusters given by Eq. (4) and the total proton number density \( N_p \), the total neutron number density \( N_n \) at temperature \( T \)

\[ N_n(T, \mu_p, \mu_n) = \sum_{\alpha} (A - Z)n_\alpha(T, \mu_p, \mu_n), \]  

(10)

\[ N_p(T, \mu_p, \mu_n) = \sum_{\alpha} Zn_\alpha(T, \mu_p, \mu_n). \]  

(11)

We will use below as independent variables the total nucleon number density and isospin asymmetry parameter defined as

\[ n = N_n + N_p, \quad Y_p = N_p/n. \]  

(12)

2.2 Bose-Einstein condensation of \( \alpha \) particles

The formalism described above fully accounts for the quantum statistics of the clusters, therefore any putative BEC in clustered matter is automatically included. The expression for the densities of clusters Eq. (4) is not valid in the case of BEC, because in this case macroscopic number of particles occupy the
ground state with zero momentum. If the number of particles occupying the zero-momentum mode is \( n_0 \) then cluster density is given by

\[
n_{\alpha} = n_0 + \frac{g_{\alpha}}{2\pi^2} \int_{0^+}^{\infty} f_{\alpha} k^2 dk,
\]

(13)

where \( 0^+ \) indicates exclusion of the zero-momentum mode from the integral and the index \( \alpha \) may refer to the \( \alpha \) particle as well as to the deuteron \( d \).

The chemical potential of bosonic clusters lies in the interval \(-\infty \leq \mu_{\alpha} \leq -B_{\alpha} \). The condition of the Bose condensation is achieved at the upper limit, where the chemical potential approaches the binding energy of the cluster. The temperature corresponding to the limit \( \mu_{\alpha} = -B_{\alpha} \) for fixed density is identified as the critical temperature \( T_c \) of BEC. This temperature can be determined from the transcendental equation

\[
n_{\alpha} = \frac{g_{\alpha}}{2\pi^2} \int_0^{\infty} \frac{k^2 dk}{\exp \left( \frac{k^2}{2Am^*T} \right) - 1},
\]

(14)

which leads to the critical temperature

\[
T_{c\alpha} = \frac{2\pi}{Am^*} \left( \frac{n_{\alpha}}{g_{\alpha}\zeta(3/2)} \right)^{2/3},
\]

(15)

where the Riemann zeta-function has the value \( \zeta(3/2) = 2.612 \), \( A = 4 \) and \( g_{\alpha} = 1 \) for the \( \alpha \) particle.

With the onset of the BEC the number density of the condensed clusters does not depend on the chemical potential, as it is exactly canceled by the contribution from the binding energy. On the other hand the conversion from one type of a cluster to another is controlled through the chemical equilibrium condition (2). Thus, after clusters of type \( \alpha \) condense the equation determining their number density is decoupled from the rest of the system and inter-cluster transformations from and to the condensate will not occur. This reflects the fact that after the onset of BEC the condensate particles in the ground state do not interact with the environment. Therefore, at a given temperature, an increase in the density of the system will result only in an increase of the density of the condensate, whereas the densities of the remaining clusters will be frozen.

2.3 Further approximations

The effective mass of nucleons is determined from the Skyrme functional and is given by

\[
\frac{m^*}{m} = \left\{ 1 + \frac{mn}{2} (t_1 + t_2) + \frac{mn}{8} (t_2 - t_1)[l \pm (1 - 2Y_p)] \right\}^{-1},
\]

(16)

where the parameters \( t_0, t_1 \) and \( t_2 \) have the following values \( t_0 = -1128.75 \) MeV fm\(^3\), \( t_1 = 395 \) MeV fm\(^3\), and \( t_2 = -95 \) MeV fm\(^3\). Note that the effective mass of a nucleon is used uniformly both for unbound nucleons and
clusters, but its actual value is very close to unity at low densities of interest. We neglect the weak density dependence of the effective mass in evaluating the thermodynamical potential of the system. In the following we will also neglect the medium modifications of the binding energies of clusters, i.e., their dependence on the temperature and density of the ambient matter, which is justified at densities below $n_{\text{sat}}/3$. These modifications are discussed elsewhere \[13, 14, 24, 33, 40\]. The numerical values of the binding energies of light clusters used in our computations are $B_d = 2.225$ (deuteron), $B_t = 8.482$ (triton), $B_h = 7.718$ (helion) and $B_\alpha = 28.3$ MeV ($\alpha$ particle). The degeneracy factors are $g_n = g_p = g_t = g_h = 2$, $g_d = 3$ and $g_\alpha = 1$.

3 Results

3.1 Light clusters only

The system of coupled non-linear equations (4) (one equation per cluster) was solved simultaneously for unknown chemical potentials $\mu_n$ and $\mu_p$ at fixed temperature $T$, number density $n$ and asymmetry parameter $Y_p$. Consider first symmetric nuclear matter with $Y_p = 0.5$ composed of neutrons ($n$), protons...
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The size of the temperature step is 2 MeV.

$p$, deuterons ($d$), tritons ($t$), helions ($h$) and $\alpha$ particles ($\alpha$) and denote their abundance as $Y_\alpha = n_\alpha / n$.

Fig. 1 shows the abundances of clusters at two temperatures as a function of the net density. We recall that in our model the nuclear interaction renormalizes the nucleon masses and no further inter-cluster interactions are taken into account. This should be a good approximation valid at low densities of interest. Therefore, the system minimizes the energy of a collection of clusters with various masses, which determine the magnitude of their kinetic energy. Consequently, the competition is between binding the nucleons in a cluster and moving it with relatively low velocity (because of the larger mass of the cluster) or keeping nucleons unbound but moving them with larger velocities. It is seen that at high temperatures and low densities the ensemble chooses to have larger number of nucleons and deuterons, i.e., many constituents with large velocities. At lower temperatures $\alpha$ particles dominate, i.e., smaller number of more massive constituents with lower velocities is preferable.

In Fig. 2 we show the entropy and pressure of our thermodynamic ensemble for various constant temperatures and varying density. The dependence of these quantities is clearly consistent with the earlier findings on the thermodynamics of the quasiparticle gas model [10].

We turn now to the cluster abundances at fixed density and varying temperature, as shown in Fig. 3. For the lower of the chosen values of density
Fig. 3 Dependence of components of symmetrical nuclear matter on temperature at fixed total density $n = 0.001$ fm$^{-3}$ (upper panel) and $n = 0.008$ fm$^{-3}$ (lower panel).

the nucleons and deuterons dominate the matter composition. Among heavier clusters $\alpha$ particles dominate at low temperatures, whereas $t$ and $h$ are more abundant at high temperatures. For the higher value of the density and low temperatures $\alpha$ particles completely dominate the matter, which opens up the possibility of their condensation at a critical temperature. As the temperature is increased the general trends seen at low density remain, however $\alpha$ particles start to dominate matter already at higher temperature and the three-body clusters overtake the $\alpha$ particle only at the upper edge of the temperature range considered.

The current set-up allows us to explore the dependence of the composition on the isospin asymmetry, see Fig. 4. The parameter $Y_p$ is varied in the range $0 \leq Y_p \leq 1$, the lower limit corresponding to pure neutron matter, $Y_p = 0.5$ - to symmetrical nuclear matter and $Y_p = 1$ - to pure proton matter. The deuteron and $\alpha$ particle have largest abundances in symmetrical nuclear matter, i.e., $Y_p = 0.5$. The triton and helion show symmetrical (mirror) behaviour with respect to the $Y_p = 0.5$ value (the slight numerical difference arises from the difference in their binding energies). The decrease in $\alpha$ and $d$ abundances away from the symmetrical limit is the consequence of the asymmetry in nucleon number which suppresses binding in isospin symmetrical bound states. In other words, for a given temperature and density the number of neutrons for $Y_p > 0.5$ and the number of protons for $Y_p < 0.5$ is insufficient to built $\alpha$ particles or $d$ in
Fig. 4 Dependence of composition of asymmetrical nuclear matter on parameter $Y_p \in (0, 1)$ at fixed total density $n = 0.04 \text{ fm}^{-3}$ and temperature $T = 6 \text{ MeV}$.

Fig. 5 Dependence of abundances of components ($A \leq 4$) on total matter density for temperature at $T = 2 \text{ MeV}$. The onset of BEC occurs at the maximal density shown in this figure.
the same amount as in the symmetrical case. The maxima in the abundances of \( t \) and \( h \) lie away from the symmetric limit and reflect the fact that on the neutron rich side it is easier to build a \( t \) (with two neutrons and a proton) and conversely on the proton rich side it is easier to create an \( h \).

Having established that at low enough temperatures \( \alpha \) particles form the dominant component of matter we now turn to their BEC. In Fig. 5 we show the abundances of clusters up to the point of the onset of BEC, which is marked by the condition \( \mu_\alpha = -B_\alpha \). Once condensed \( \alpha \) particles decouple from the other components and any increase in the number of nucleons can be accommodated in the condensate (in the isospin symmetrical matter). The variation of the critical temperature of BEC of \( \alpha \) particles with density is shown in Fig. 6. Clearly, because \( \alpha \) particles are not interacting we are dealing essentially with the condensation in an ideal quantum Bose gas; as a consequence the condensate fraction in \( \alpha \) matter is controlled by the temperature and all particles condense in the ground state at \( T = 0 \). The condensate fraction may reduce substantially if the \( \alpha-\alpha \) interactions are taken into account [45,46].

In Fig. 7 we show the mass fractions \( X_\alpha = A n_\alpha/n \) of clusters along the trajectory defined by \( T_c(n) \) for \( \alpha \) particles. As can be anticipated from the discussion of the previous figure we find the mass fractions of \( A \neq 4 \) quasiparticles are negligible compared to those of \( \alpha \) particles. Even at the highest density their mass fractions do not exceed 1% of the total mass.
3.2 Including a heavy cluster

As well known, the $^{56}$Fe nucleus is one of the most tightly bound nuclei (8.8 MeV binding energy per nucleon), therefore one can anticipate that at asymptotically low densities matter will consist of iron nuclei. To access their role on the composition of matter with light clusters we have added the contribution from $^{56}$Fe to thermodynamic potential and recomputed the abundance of the ensemble consisting of light clusters plus iron.

Figure 8 shows these abundances for several fixed temperatures as a function of number density. The main modification arises at low temperatures; it is seen that at $T = 2$ the main element in matter is $^{56}$Fe, followed by $\alpha$ particle with about 10% throughout most of the density range. An exception is the extreme low-density asymptote where the roles of these elements are interchanged. Interestingly, because $^{56}$Fe contains 30$n$ and 26$p$ it introduces an isospin asymmetry even in symmetrical matter and, consequently, the degeneracy in abundances of $t$ and $h$ as well as $n$ and $p$ is lifted. It is seen that for a given number of $^{56}$Fe nuclei the $h$ and $p$ abundances are much larger than those of $t$ and $n$, which is in agreement with the fact that there is a proton excess. As the temperature is increased to 5 MeV the abundance of $^{56}$Fe decreases strongly below densities $0.04 \text{ fm}^{-3}$ and it has no influences on the low density asymptotics of the abundances, while still contributing substan-
Fig. 8 Dependence of abundances of light clusters and $^{56}\text{Fe}$ nucleus on density for $T = 2$ MeV (upper panel), 5 MeV (middle panel) and 10 MeV (lower panel).

...ially at densities above 0.06 fm$^{-3}$. Finally, at temperature $T = 10$ MeV there is a negligible amount of $^{56}\text{Fe}$ nuclei and we recover the composition studied initially. The dominance of $^{56}\text{Fe}$ nuclei in the low-temperature limit has an important consequence on the $\alpha$ particle condensation: as we have seen it suppresses the number density of $\alpha$ particles and consequently the conditions for their condensation are not met anymore. We find that $\alpha$ condensation is completely suppressed if $^{56}\text{Fe}$ nuclei are allowed in the composition of matter. Nevertheless, in a number of situations the time-scales of formation of heavy nuclei such as $^{56}\text{Fe}$ may be too long (as, for example, in heavy-ion collisions or at some stages of supernova explosions) so that the matter could be composed predominantly of light $A \leq 4$ nuclei. In that case BEC of $\alpha$ particles can indeed take place in clustered matter as argued above.

4 Summary and outlook

We have calculated the composition of isospin symmetric and asymmetric warm dense nuclear matter within the framework of quasiparticle gas model. The composition of the nuclear matter with light clusters and unbound nucleons is determined by solving nonlinear equations for their densities subject to the condition of chemical equilibrium. Because the quantum-statistic of
clusters is taken into account from the outset we are in a position to monitor possible BEC of bosons in general. Our findings can be summarized as follows:

- At high temperatures $T \simeq 10$ MeV the main component of matter are nucleons and deuterons at low densities. At higher densities we find a mixture of comparable numbers of $A \leq 4$ clusters. At low temperatures $\alpha$ particles dominate the composition of matter above certain density; the lower the temperature the lower is the density at which they start to dominate.

- We find BEC of $\alpha$ particles in a clustered environment for $n \leq 0.3 \ n_{\text{sat}}$ with critical temperature $T_c \leq 2$ MeV. However, in this temperature-density range the abundances of the ambient clusters and their effect on the BEC are found to be negligible. Therefore, we observe essentially BEC in “alpha-matter”. As a consequence the critical temperature of condensation scales as $T_c \simeq n_\alpha^{2/3} \simeq n^{2/3}$. Note that the condition for the occurrence of BEC is given by the requirement of equality of $\alpha$ particle chemical potential to its negative binding energy, as it would be in an non-interacting Bose gas.

- The addition of a heavy nucleus (in our numerical example $^{56}\text{Fe}$) modifies the composition of matter substantially only in the low-temperature limit. This has, however, an important consequence of reducing the density of $\alpha$ particles and suppressing the $\alpha$ condensation phenomenon. Nevertheless, the short time scale dynamics of heavy-ion collisions and supernovas may not allow for formation of heavy nuclei, in which case matter composed of $A \leq 4$ clusters will undergo BEC of $\alpha$ particles. It may be also of interest under inhomogeneous conditions, where heavier nuclei form a separate phase. We anticipate that the $\alpha-\alpha$ interactions can be neglected in a first approximation in the dilute limit relevant for present discussion; the influence of interactions on the physics discussed above needs further assessment.

- Note that the medium effects, not considered here, will make the formation of a quantum condensate more difficult at high densities because Pauli-exclusion principle will act among the nucleons and because the $\alpha-\alpha$ interactions will reduce the condensate fraction in $\alpha$ matter. It should be kept in mind that $\alpha$ condensate will likely exist in a transient form and will disappear in thermodynamic equilibrium, as the matter will tend to form heavier clusters. Therefore, dynamical (nonequilibrium) treatment of the onset of $\alpha$ condensation may be of great interest on its own right.

- BEC of $\alpha$ particles may be also of interest under inhomogeneous conditions, where heavier nuclei form a separate phase.

The change in the composition of matter as the temperature is lowered from $T \simeq 10$ MeV to a few MeV may have interesting implications in astrophysics of compact star mergers and supernovas. The dynamical properties of matter such as electron transport or neutrino propagation may be affected by the crossover from matter dominated by nucleons to matter dominated by $\alpha$ particles, assuming that heavy nuclei have not been formed. Consequently, the computations of neutrino opacity [56] or electronic MHD resistivity [57].
should include such transformations. The $\alpha$ particle BEC and its influence on the physical processes in these contexts remain to be studied.

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