TEMPERATURE DEPENDENCE OF NUCLEAR SYMMETRY FREE ENERGY*

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The nuclear symmetry free energy as well as its slope and curvature parameters within the lowest order constrained variational method using Argonne V18 two-body interaction and an Urbana type three-body force are calculated. Density and temperature dependence of the above quantities are studied and the effect of including the three-body interaction on these parameters is also discussed.

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1. Introduction

The nuclear symmetry energy (NSE) plays a crucial role in a variety of nuclear phenomena. Its density dependence is critical for understanding heavy-ion reactions [1], the structure of rare isotopes [2], and the liquid–gas phase transition in asymmetric nuclear matter. Determining the NSE is also of great interest in many other issues in astrophysics such as the properties of neutron stars and supernova explosion mechanism [3]. On the other hand, knowledge of the temperature dependence of the NSE is essential in the studies of isoscaling analyses in heavy-ion reactions and the formation mechanism as well as the dynamical evolution of neutron stars and the supernova explosion mechanisms [3]. Despite of both experimental and theoretical efforts in determining the NSE, it is still largely uncertain even for cold nuclear matter. Especially its values at super-normal densities are poorly known. The exact knowledge of the slope and curvature parameters is very important for finding the EOS around saturation density.

It is well known that the empirical saturation properties of cold asymmetric nuclear matter cannot be correctly reproduced when only two-body interactions are included in the Hamiltonian. Therefore, one has to assume

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that also three-body forces (TBF) must be taken into account in the Hamiltonian. In this work, we intend to determine the density and temperature dependence of nuclear symmetry free energy (NSFE) of infinite nuclear matter as well as to study the effect of three-body forces on NSFE by using the lowest order constrained variational (LOCV) method with AV18 [4] two-body potential. In order to include the TBF, we employed the Urbana-type (UIX) three-body force.

2. The nuclear symmetry free energy

The Helmholtz free energy per nucleon of asymmetric nuclear matter at given density and temperature can be extracted from

$$F(\rho,\alpha,T) = E(\rho,\alpha,T) - S(\rho,\alpha,T)T\,, \tag{1}$$

where $E(\rho,\alpha,T)$ and $S(\rho,\alpha,T)$ are the thermal energy and entropy per nucleon of asymmetric nuclear matter respectively. By expanding the free energy up to second order in isospin asymmetry parameter $\alpha = \frac{\rho_n-\rho_p}{\rho_n+\rho_p}$ (where ρ_n and ρ_p are the neutron and proton densities respectively), one can find the nuclear symmetry free energy as

$$F_{\rm sym}(\rho,T) = \frac{1}{2}\frac{\partial^2 F(\rho,\alpha,T)}{\partial\alpha^2}\bigg|_{\alpha=0}\,. \tag{2}$$

Thus at frozen system, $F_{\rm sym}$ is the same as usual nuclear symmetry energy $E_{\rm sym}$. $F(\rho,\alpha,T)$ is calculated within the LOCV method using Argonne V18 two-body interaction and an Urbana type TBF [5]. In this method, we use a trial wave function as a product of uncorrelated many body wave function and Jastrow type correlation functions. Then by cluster expanding of expectation value of Hamiltonian at finite temperature (up to two-body clusters), a functional variational process is performing respect to correlation functions. The normalization constraint is imposed in this procedure. So, one can find the correlation functions, thermal energy, distribution functions *etc.* — the detail of method is described in [6] and references therein.

As a good approximation, one can employ the parabolic approximation

$$F_{\rm sym}(\rho,T) = F(\rho,1,T) - F(\rho,0,T)\,. \tag{3}$$

Around the saturation density ρ_0, the nuclear symmetry free energy can be expanded up to second order in χ as

$$F_{\rm sym}(\rho,T) = F_{\rm sym}(\rho_0,T) + L\chi + \frac{K_{\rm sym}}{2}\chi^2 + O\left(\chi^3\right)\,, \tag{4}$$

where χ is a dimensionless variable which defines as $\chi = \frac{\rho-\rho_0}{3\rho_0}$. L and $K_{\rm sym}$ in equation (4) are the slope and curvature parameters, respectively, and characterize the density and temperature dependence of the NSFE around the saturation density ρ_0 and are written as follows:

$$L(T) = 3\rho_0 \left.\frac{\partial F_{\rm sym}(\rho,T)}{\partial\rho}\right|_{\rho=\rho_0}, \quad (5)$$

$$K_{\rm sym}(T) = 9\rho_0 \left.\frac{\partial^2 F_{\rm sym}(\rho,T)}{\partial\rho^2}\right|_{\rho=\rho_0}. \quad (6)$$

3. Results and discussion

Density dependence of the NSFE for three values of temperature is reported in the left panel of Fig. 1. Solid and dashed curves indicate the results obtained by using the pure two-body force and two-body force plus the TBF, respectively. In general, the NSFE increases when the temperature and density increases. Since the TBF gives a repulsive contribution to the EOS of nuclear matter, adding this force will result in increasing the NSFE at a given density and temperature. All other following results are calculated when the TBF is included in nuclear Hamiltonian. The validity of linear dependence of NSFE on square of asymmetric parameter α is presented in the right panel of Fig. 1. It is seen that similar to the zero temperature case, the NSFE fulfills a quadratic dependence on α in the whole asymmetry range and different temperature and density which shows that the validity of the empirical quadratic law can be extended to the highest isospin asymmetry and to the case of finite temperature as well. The temperature dependence of NSFE at saturation density is shown in the left panel of Fig. 2. With increasing temperature, $F_{\rm sym}(\rho_0)$ decreases from its maximum (41.83 MeV) at $T = 0$ to its minimum (28.16 MeV) at limiting

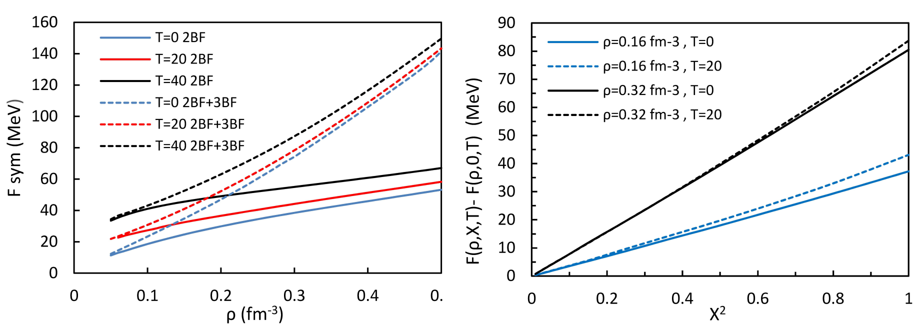

Fig. 1. The NSFE at different temperatures with and without three-body interaction (left panel) and quadratic dependence of the NSFE on α (right panel).

temperature, *i.e.*, $T_L = 14.73$ MeV. T_L is the temperature for which the free energy does not show a bound state. In the right panel of Fig. 2, we indicate the behavior of L and $K_{\rm sym}$ as a function of T. As the temperature increases, the slope parameter decreases from $L = 129.73$ MeV at $T = 0$ to $L = 68.79$ MeV at T_L. The curvature parameter also shows similar behavior as L and ranges from $K_{\rm sym} = 105.71$ MeV for cold nuclear matter to $K_{\rm sym} = 46.61$ MeV at T_L.

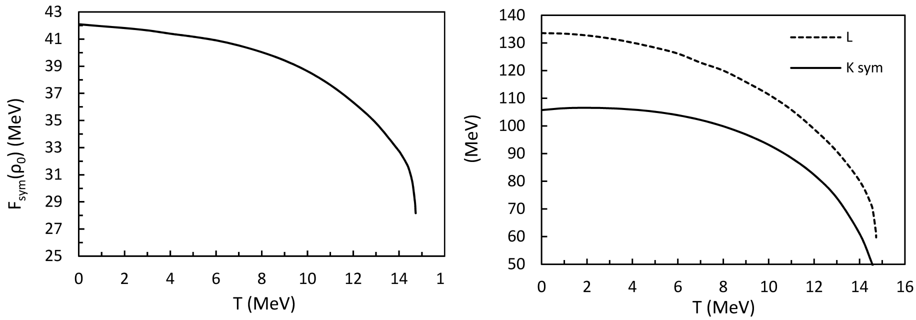

Fig. 2. Temperature dependence of NSFE at saturation density (left panel), slope and curvature parameters (right panel).

In conclusion, we have used the microscopic variational approach (LOCV) to study the temperature dependence of nuclear symmetry free energy. By adding a phenomenological three-body force to our Hamiltonian, we have calculated the NSFE and have shown that using TBF in addition to bare 2BF increases the NSFE at given temperature and density. Though the NSE at saturation point by including 3BF — because of its repulsive nature for nuclear matter, is overestimated from its empirical value, but its behavior is compatible with others techniques. Also it is shown that slope parameter and curvature parameters are decreasing function of temperature. Such calculation within a microscopical point of view at finite temperature is a good starting point for future studies.

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