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A Microscopic Calculation of Incompressibility of Asymmetric Nuclear Matter*

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Abstract: We have investigated the incompressibility of asymmetric nuclear matter within the Brueckner-Hartree-Fock approach extended to include a microscopic three-body force. The isospin-dependence and density-dependence of the nuclear incompressibility have been obtained and discussed. It is shown that the incompressibility at a fixed density increases monotonically as a function of isospin asymmetry. The isospin asymmetry dependence of the equilibrium properties of asymmetric nuclear matter is also predicted and compared with the results of other theoretical approaches.

Key words: incompressibility; asymmetric nuclear matter; nuclear equation of state; Brueckner-Hartree-Fock approach

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1 Introduction

One of the main aims of heavy ion collisions (HIC) induced by radioactive beams is to extract reliable information about the equation of state (EOS) of asymmetric nuclear matter, especially the high density behavior of symmetry energy[1−2]. Nuclear matter incompressibility is an important property to characterize the EOS of nuclear matter. An accurate information of the nuclear matter compressibility is not only crucial for describing many basic properties of finite nuclei and the dynamics of HIC, but also plays a key role in understanding the neutron star structure and supernova explosion[3−5]. Experimentally, the incompressibility around saturation density can be extracted from the giant monopole resonances[4, 6−7] and HIC at intermediate energies.

Up to now, the incompressibility and other most important physical quantities related to the EOS of nuclear matter have been extensively studied by using different theoretical approaches, such as non-relativistic[8−10] and relativistic[11−13] Hartree-Fock (HF) models, variational approach[14−15], Thomas-Fermi approximation[16−17] and the chiral sigma model[18]. Most of the previous investigations about the incompressibility have been

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concentrated on symmetric nuclear matter and/or the isospin dependence of the incompressibility of asymmetric nuclear matter at equilibrium densities. The incompressibility K_{eq} of symmetric nuclear matter at saturation density predicted by different authors can be divided into two categories, i. e. , the soft one (around 200 MeV) and the stiff one (around 300 MeV or higher). For example, $K_{eq}=185$[8], 216.6[15], 209[15], 202[15], 238[14], 370.3[15], and 355.3 MeV[15]. In Ref. [10], Khoa et al. calculated the incompressibility of asymmetric nuclear matter in a wide range of density and up to high isospin-asymmetry by using the HF approach with the phenomenological M3Y effective interaction. They found that both the density-dependence and isospinasymmetry dependence of the predicted nuclear incompressibility depend strongly on the adopted parameters of the M3Y effective interaction. In Ref. [16] it was shown by K. Kolehmainen that the incompressibi- lity at saturation $K_{eq}(\beta)$ is a linear function of β^2 (where β is the isospin asymmetry of asymmetric nuclear matter). Other authors got similar results[8, 14-16]. In Ref. [19], it was shown that the predicted neutron density distribution of neutron-rich nuclei depends sensitively on the isospin-dependence of the equilibrium density of asymmetric nuclear matter. A slower decreasing of the equilibrium density as a function of asymmetry (for example, the result by the Skyrme-Hartree-Fock (SHF) model using the parameter set SIII) may lead to a higher central density of neutron-rich nuclei, while a faster decreasing of the equilibrium density with isospin symmetry results in a smaller central density[19]. In Ref. [9], Lopez-Quelle showed that the equilibrium density $\rho_{eq}(\beta)$ is also a linear function of β^2 up to the asymmetry where the equilibrium point exists.

In the present paper, we shall investigate the isospin-dependence and density-dependence of the incompressibility of asymmetric nuclear matter in a wide density range within the Brueckner-Hartree-Fock (BHF) approach extended to include a microscopic three-body force. The isospin-asymmetry dependence of the equilibrium properties of asymmetric nuclear matter are also predicted and discussed. The present paper is organized as follows. We will describe briefly the adopted theoretical approach in Section 2. The numerical results are presented and discussed in Section 3. In Section 4 a summary of the present work is given.

2 Theoretical Approach

Our investigation is based on the Brueckner-Bethe-Goldstone (BBG) theory for asymmetric nuclear matter[20-22]. The extension of the BBG scheme to include three-body forces (TBF) can be find in Refs. [23-24]. Here we give a brief review for completeness. The starting point of the BBG scheme is the Brueckner reaction G matrix, which satisfies the following Bethe-Goldstone (BG) equation,

$$G(\rho, \beta; \omega)=\upsilon_{NN}+\upsilon_{NN}\times \sum_{k_1k_2}\frac{|k_1k_2\rangle Q(k_1k_2)\langle k_1k_2|}{\omega-\varepsilon(k_1)-\varepsilon(k_2)+i\eta}G(\rho, \beta; \omega) , \quad (1)$$

where $k_i\equiv(\boldsymbol{k}, \sigma_i, \tau_i)$ denotes the momentum, the z-component of spin and isospin of a nucleon, respectively. ω is the starting energy and $Q(k_1k_2)=[1-n(k_1)][1-n(k_2)]$ is the Pauli operator which prevents the two intermediate nucleons from being scattered into the states below the Fermi sea. The isospin asymmetry parameter is defined as $\beta=(\rho_n-\rho_p)/\rho$, ρ_n, ρ_p, and ρ being the neutron, proton and total nucleon number densities, respectively. The BHF single particle (s. p.) energy is given by $\varepsilon(k)=\hbar^2k^2/2m+U^{bhf}(k)$. In solving the BG equation for the G-matrix, we adopt the continuous choice for the s. p. potential $U^{bhf}(k)$ since it has been proved to provide a much faster convergency of the hole-line expansion for the energy per nucleon of nuclear matter up to high densities than the gap choice[25]. In addition, under the continuous choice, the s. p. potential describes physically at the BHF level the nuclear mean field felt by a nucleon in nuclear medium[26] and is calculated from the real part of the on-shell G-matrix, i. e.

$$U^{\rm bhf}(k)=\sum_{k'} n(k')\,{\rm Re}\,\langle kk'|G[\varepsilon(k)+\varepsilon(k')]|kk'\rangle_A. \quad (2)$$

The realistic nucleon-nucleon (NN) interaction $v_{\rm NN}$ in the present calculation contains two parts, i. e., the Argonne V18 (AV18) two-body interaction[27] plus the contribution of the microscopic TBF described in Ref. [23]. Two kinds of TBFs have been adopted in the BHF formalism[23, 28-29]. One is the semi-phenomenological TBF[30] which has two or few adjustable parameters determined by reproducing the empirical saturation density and energy of symmetric nuclear matter in the BHF calculations[29]. The other is the microscopic TBF based on meson exchange coupled to the intermediate virtual excitations of nucleon-tinucleon pairs and nucleon resonances[23, 28]. The TBF adopted in the present calculation was originally proposed by Grange et al.[28] based on the meson-exchange current approach. The parameters of the TBF, i. e., the coupling constants and the form factors, have been redetermined recently in Ref. [23] from the one-boson-exchange potential (OBEP) model to meet the self-consistent requirement with the adopted AV18 two-body force. The values of the parameters are given in Ref. [23]. A more detailed description of the TBF model and the related approximations can be found in Ref. [28].

In our BHF calculation, the TBF contribution has been included by reducing the TBF to an equivalently effective two-body interaction via a suitable average with respect to the third-nucleon degrees of freedom according to the standard scheme as described in Ref. [28]. In r-space, the equivalent two-body force $V_3^{\rm eff}$ reads[23-24],

$$\langle \boldsymbol{r}_1' \boldsymbol{r}_2'|V_3^{\rm eff}|\boldsymbol{r}_1 \boldsymbol{r}_2\rangle = \frac{1}{4}{\rm Tr}\sum_n\int {\rm d}\boldsymbol{r}_3\,{\rm d}\boldsymbol{r}_3'\,\phi_n^*(\boldsymbol{r}_3')[1-\eta(r_{13}')]\times [1-\eta(r_{23}')]W_3(\boldsymbol{r}_1'\boldsymbol{r}_2'\boldsymbol{r}_3'|\boldsymbol{r}_1\boldsymbol{r}_2\boldsymbol{r}_3)\times \phi_n(\boldsymbol{r}_3)[1-\eta(r_{13})][1-\eta(r_{23})], \quad (3)$$

where the trace is taken with respect to the spin and isospin of the third nucleon. The function $\eta(r)$ is the defect function[28, 31]. A detailed description and justification of the above scheme can be found in Ref. [28]. Due to its dependence on the defect function the effective two-body force $V_3^{\rm eff}$ is calculated self-consistently along with the G-matrix at each step of the iterative BHF procedure.

The incompressibility of nuclear matter is defined as:

$$K(\rho,\beta)=9\frac{\partial P(\rho,\beta)}{\partial\rho}, \quad (4)$$

where ρ is the total nucleon number density, P is the nuclear pressure and can be calculated by:

$$P(\rho,\beta)=\rho^2\frac{\partial E_{\rm A}(\rho,\beta)}{\partial\rho}, \quad (5)$$

where $E_{\rm A}(\rho,\beta)$ denotes the EOS of asymmetric nuclear matter (i. e., the energy per nucleon of asymmetric nuclear matter). For asymmetric nuclear matter, the incompressibility K can be split into two contributions[10, 32], i. e.,

$$K(\rho,\beta)=K_0(\rho)+K_{\rm asy}(\rho)\beta^2, \quad (6)$$

where K_0 denotes the iso-scalar part of the incompressibility and $K_{\rm asy}$ describes the iso-vector part. According to the microscopic investigations[20-21, 24, 33], the energy per nucleon of asymmetric nuclear matter fulfills satisfactorily a quadratic dependence on isospin asymmetry β in the whole asymmetry range $0\leqslant\beta\leqslant1$, i. e., $E_{\rm A}(\rho,\beta)=E(\rho,\beta=0)+E_{\rm sym}(\rho)\beta^2$. Here, $E_{\rm sym}$ is the nuclear symmetry energy. Consequently, the isovector contribution $K_{\rm asy}$ can be calculated as follows:

$$K_{\rm asy}(\rho,\beta)=9\rho^2\frac{\partial^2 E_{\rm sym}(\rho,\beta)}{\partial\rho^2}+18\rho\frac{\partial E_{\rm sym}(\rho,\beta)}{\partial\rho}. \quad (7)$$

3 Results and Discussion

In order to calculate reliably the nuclear incompressibility, we parameterize first the obtained EOS of symmetric nuclear matter $E(\rho, \beta=0)$ and the symmetry energy $E_{sym}(\rho)$ as functions of density by smooth curves. The obtained parameterizations are given by the following formulas:

$$E^0(\rho) = -181.65\rho + 681.78\rho^2 - 955.19\rho^3 + 984.55\rho^4 + 82.69\rho^5 - 378.27\rho^6, \quad (8)$$

$$E_{sym}(\rho) = +316.41\rho - 1257.22\rho^2 + 3222.88\rho^3 - 2254.48\rho^4 - 536.68\rho^5 + 1053.40\rho^6. \quad (9)$$

The numerical results and the corresponding parameterizations are shown and compared in Fig. 1.

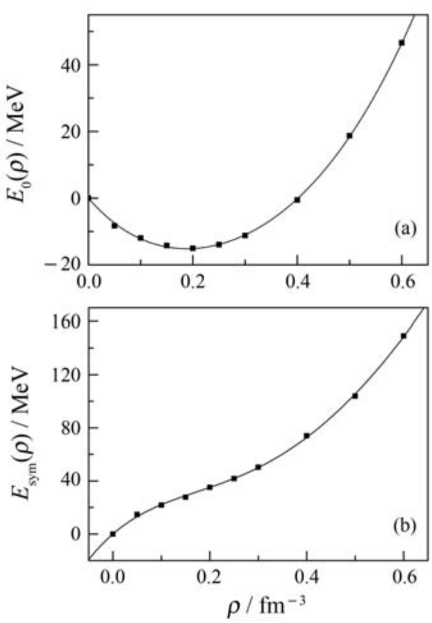

Fig. 1 The solid squares stand for theoretical results with Argonne 18 potential and the lines are fitting results.

It is seen that the fitting results are in excellent agreement with the numerical data. For symmetric nuclear matter, the predicted saturation density is around 0.19 fm^{-3} which is slightly larger than the empirical value 0.17 fm^{-3}, and the corresponding saturation energy is about −16 MeV in quite good agreement with the experimental value. From the lower panel of Fig. 1, one may notice that the symmetry energy shows a relatively soft density-dependence at low densities, while its density-dependence becomes stiff at high densities, which was also derived in Ref. [34] with the BHF method using different nucleon-nucleon interactions complemented with TBF.

Around the saturation density of symmetric nuclear matter ρ_0, the symmetry energy can be expanded to second-order in density[35], i. e.,

$$E_{sym} = E_{sym}(\rho_0) + \frac{L(\rho_0)}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}(\rho_0)}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2, \quad (10)$$

where $L(\rho_0)$ and $K_{sym}(\rho_0)$ are defined as:

$$L(\rho_0) = 3\rho \left.\frac{\mathrm{d}E_{sym}(\rho)}{\mathrm{d}\rho}\right|_{\rho_0},$$
$$K_{sym}(\rho_0) = 9\rho^2 \left.\frac{\mathrm{d}^2E_{sym}(\rho)}{\mathrm{d}\rho^2}\right|_{\rho_0}, \quad (11)$$

L and K_{sym} are related directly to the slope and curvature of symmetry energy, respectively and thus are two most important quantities for describing the density-dependence of symmetry energy. The value of the slope parameter at saturation density $L(\rho_0)$ plays a significant role in understanding the properties of neutron-rich nuclei and heavy nuclei. For example, it had been shown in Refs. [36−38] that $L(\rho_0)$ is correlated linearly to the neutron skin thickness of heavy nuclei. Experimentally, the value of L around saturation can be extracted by studying the isospin observables in HIC and the obtained value is $L(\rho_0)=(88\pm25)$ MeV[35]. From our calculation, we get a value of $L(\rho_0)=70$ MeV which turns out to be in quite good agreement with the value extracted from HIC. In Fig. 2, we display the calculated slope parameter $L(\rho)$ vs. density. It is seen that the slope parameter L

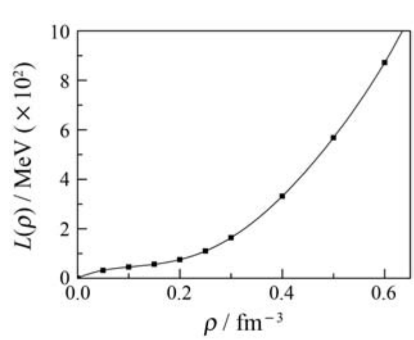

Fig. 2 The predicted density dependence of the slope parameter $L(\rho)$ of symmetry energy.

increases monotonically as a function of density. At relatively low densities, the increasing of $L(\rho)$ vs. density is rather slow, while above $\rho=0.25$ fm^{-3}, the increasing rate of $L(\rho)$ vs. density becomes very large as the density increases. For the curvature parameter K_{sym}, we have got a similar density dependence.

By using the parameterizations Eqs. (8) and (9), we can calculate the incompressibility of asymmetric nuclear matter $K(\rho, \beta)$. Shown in Fig. 3 is the obtained $K(\rho, \beta)$ vs. density at several isospin asymmetries $\beta=0$, 0.4, 0.6, 0.8, 1. From the figure, one can clearly see the density and isospin-asymmetry dependence of the incompressibility. At a fixed asymmetry, the predicted $K(\rho, \beta)$ increases continuously as the density increases; at a fixed density the $K(\rho, \beta)$ turns out to be an monotonically increasing function of isospin-asymmetry. In the high density region, it is seen that the predicted $K(\rho, \beta)$ rises up very fast as the asymmetry increases. The above results imply that it becomes more difficult and much more energy is required to compress asymmetric nuclear matter at a larger density and/or a higher isospin asymmetry.

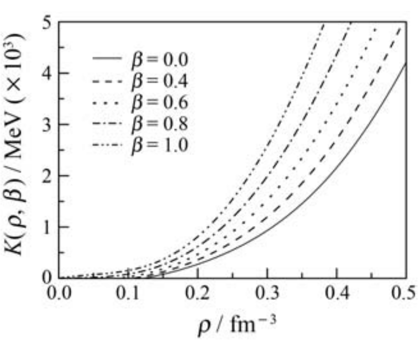

Fig. 3 The density dependence and isospin dependence properties of incompressibility are clearly illuminated in this figure.

Our predicted incompressibility by the microscopic BHF approach shows a quite different density-dependence or isospin-asymmetry dependence as compared to the results given in Ref. [10] by using the HF approximation and the semi-phenomenological M3Y effective interaction. By using the DDM3Y1 parameter set, Khoa et al.[10] found that increasing the isospin-asymmetry makes the EOS of asymmetric nuclear matter stiffer at all densities. Such an isospin behavior of $K(\rho, \beta)$ is comparable with our result. However, they predicted a decreasing $K(\rho, \beta)$ as a function of density at a fixed asymmetry in the high density region above two times nuclear matter saturation density and their $K(\rho, \beta)$ is much smaller than ours at high density. By using the BDM3Y1 parameter set, the $K(\rho, \beta)$ they obtained increases monotonically with density, in consistence with our result. While, as compared to our present result, they obtained an opposite isospin dependence of $K(\rho, \beta)$ at high density, i. e., their $K(\rho, \beta)$ becomes a decreasing function of isospin-asymmetry at high densities.

Before summary, we shall discuss the isospin-dependence of the equilibrium properties (i. e., the saturation properties) of asymmetric nuclear matter. Here, by "equilibrium properties" we denote the properties at the equilibrium density where the energy per nucleon of asymmetric nuclear matter reaches its minimal. We have calculated the equilibrium density of asymmetric nuclear matter for several values of isospin asymmetry. It is found that the obtained equilibrium density $\rho_{\text{eq}}(\beta)$ is a monotonically decreasing function of β and depends almost linearly on β^2 (see Fig. 4), which is in agreement with the result of Lopez-Quelle et al.[9] using the Dirac-Hartree-Fock (DHF) method. By fitting the numerical results with a linear function, we obtain $\rho_{\text{eq}}(\beta^2)=\rho_{\text{eq}}(0)(1-b\beta^2)$ with $b=0.935$. The coefficient b describes the decreasing rate of the equilibrium density with increasing asymmetry. In Table 1, we compare the values of b obtained using different theoretical approaches and different nucleon-nucleon forces. Our result is given in the last column. It is noticed that the value of b we obtained is close to that of Lopez-Quelle et al. using the DHF method including both isoscalar and isovector mesons (indicated by DHF (e) in the table) and slightly smaller than the value obtained from the BHF approaches using Paris nucleon-nucleon interaction without considering the TBF[8] (indicated by DHF(e) in the table Paris in the table). However, it turns out to be much larger than those predicted by the Skryme-HF approach using the SI' and SII parameter sets[39].

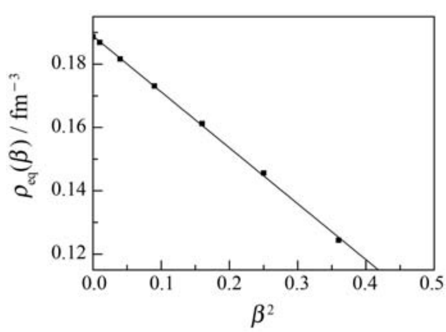

Fig. 4 Equilibrium density $\rho_{eq}(\beta)$ of asymmetric nuclear matter vs. isospin asymmetry. The solid squares are the calculated values of $\rho_{eq}(\beta)$ at different isospin asymmetries and the straight line is the fitting result.

Table 1 The predicted $\rho_{eq}(\beta)$ and b in comparison with those obtained by other authors (see the text)

Force	$\rho_{eq}(0)$	b
Paris	0.289	1.115
SI'	0.1553	0.286
SII	0.1453	0.084
DHF(b)	0.1484	0.65
DHF(e)	0.1484	0.9
BHF(AV18+TBF)	0.1889	0.935

In order to study the isospin dependence of the incompressibility of asymmetric nuclear matter at the corresponding equilibrium densities, one may define the following quantity[8],

$$K_{eq}(\beta) = 9\rho^2 \left. \frac{\partial^2 E_A(\rho, \beta)}{\partial \rho^2} \right|_{\rho_{eq}(\beta)} . \qquad (12)$$

The resulting $K_{eq}(\beta)$ at $\beta=0$ and $\beta=1/3$ are given in the last column of Table 2 in comparison with the values reported in Refs. [8] (the first column), [15] (the 5th and 6th column), [16] (the second to 4th column), and [14] (7th column). It is seen that increasing the isospin asymmetry makes the $K_{eq}(\beta)$ become smaller and thus leads to a softening of the EOS of asymmetric nuclear matter at the corresponding equilibrium density, which is in agreement with all the results listed in Table 2.

Table 2 Parameters K_0 for the isospin dependence of the incompressibility at saturation

Force	$\rho_{eq(0)}$	K_0 (0)	K_0(1/3)
Paris	0.289	185	143.3
SKM*	0.16	216.6	168.7
SI'	0.1553	370.3	318.0
SIII	0.1453	355.3	305.0
AV14+UVII	0.194	209	158
UV14	0.175	202	156
FP	0.16	238	212
AV18	0.1889	225.2	202.7

4 Conclusion

In summary, we have investigated the incompressibility of asymmetric nuclear matter within the BHF framework extended to include the microscopic TBF. The isospin-dependence and density-dependence of the incompressibility have been obtained and discussed. The predicted incompressibility of asymmetric nuclear matter turns out to be a monotonically increasing function of both density and isospin asymmetry. The incompressibility obtained by the microscopic BHF approach shows a quite different density-dependence and/or isospin-asymmetry dependence as compared to the results in Ref. [10] using the HF approximation and the semi-phenomenological M3Y effective interaction with different parameters. The slope parameter L and the curvature parameters K_{sym} of the symmetry energy is shown to increase monotonically with increasing density. At the saturation density, the obtained values of L and K_{sym} are about 70 MeV and 45 MeV, respectively, which lie in the middle of other results[8, 14-16] and are comparable with the values extracted from the isospin observables in HIC[35]. The isospin-asymmetry depen- dence of the equilibrium properties of asymmetric nuclear matter are also discussed. The obtained equilibrium density $\rho_{eq}(\beta)$ is found to be a decreasing function of β and it depends almost linearly on β^2, in agreement with the result of Lopez-Quelle et al.[9] using the DHF method. By a linear fit, we get $\rho_{eq}(\beta^2)=\rho_0(0)(1-0.935\beta^2)$. The incompressibility of asymmetric nuclear matter at the corresponding equilibrium density turns out to be smaller at a higher asymmetry, which is in agreement with the previous results of Refs. [8, 15—16] using different theoretical approaches and/or different nucleon-nucleon interactions.

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非对称核物质不可压缩系数的微观计算*

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摘 要：在带微观三体力的 Brueckner-Hartree-Fock 方法下研究了非对称核物质的不可压缩系数，得到了不可压缩系数的同位旋以及密度依赖，并做了进一步的讨论。在一定密度下，不可压缩系数作为同位旋非对称度的函数随同位旋单调递增。预测了非对称核物质在平衡态的同位旋依赖性质并与其他理论方法做了比较。

关 键 词：不可压缩系数；非对称核物质；核状态方程；Brueckner-Hartree-Fock 方法

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