Study of Equation of state of Symmetric Nuclear Matter and Pure Neutron Matter using Brueckner-Hartee-Fock approach

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Abstract: The properties of symmetric nuclear matter (SNM) and pure neutron matter (PNM) are of great importance in the development of nuclear many-body problem with application to nuclear as well as astrophysics. This paper reports microscopic calculations of the equation of state of Symmetric Nuclear Matter and pure Neutron Matter using Brueckner-Hartee-Fock (BHF) approach. Since the basic input in BHF is the nucleon-nucleon (NN) interaction hence we have used the most recent high quality NN potentials: Argonne v18, Reid 93 and Nijm II along with and without two types of three-body forces (TBFs): the Urbana IX model and the phenomenological density dependent three nucleon interaction (TNI) model of Lagris and Pandharipande [Nucl.Phys. A 359,349 (1981)]. The use of modern and recent available internucleon interactions coupled with the inclusion of TBFs helps us to achieve the saturation properties of SNM and PNM and tune them to be in agreement with the empirical values therefore taking care of the shortcomings of two body hard core potentials used earlier. Since the study pure neutron matter is important for the study of neutron stars, we have investigated the density dependence of PNM and the effect of TBFs on PNM.

Key words: SNM, PNM, Astrophysics, Nucleon, Neutron Star

Introduction

Equation of state (EOS) of nuclear matter is of great importance in nuclear physics for theoretical understanding of heavy ion collisions, supernova explosions and structure of neutron stars. One of the long standing problems in nuclear many-body theory is to obtain the nuclear matter binding energy and saturation properties in conformity with empirical estimates, starting from a realistic nucleon-nucleon (NN) interaction. Microscopic nucleon optical potential is directly related through folding model to the mean field in nuclear matter and hence the EOS. In view of this Non-relativistic Brueckner-Hartree-Fock (BHF) theory as well as variational techniques have been extensively used to investigate equation of state (EOS) of symmetric and pure neutron matter (Jeukenne, et al,1976; Baldo et al, 1988, 1989, 1990; Zuo, 1998, 1999; Bombaci and Lombardo, 1991).

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These calculations are microscopic in the sense that the only input used is the realistic two nucleon potentials. To calculate the nucleon-nucleus optical potential in BHF one additionally requires point proton and neutron density distribution in the target. An appropriate EOS must predict the correct saturation point for symmetric nuclear matter (SNM); give symmetry energy compatible with phenomenology and values of compressibility in agreement with empirical estimates. In order to calculate the EOS of symmetric zero temperature nuclear matter and the microscopic optical potential we have used the Hamiltonian of the form:

$$H = \sum_i \frac{-\hbar^2}{2m}\nabla_i^2 + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} \qquad (1)$$

where vij is a two nucleon potential and Vijk is a three nucleon interaction. In this paper we present our calculations based on the self-consistent Brueckner-Hartee-Fock (BHF) approximation for the calculation of Binding energy of Symmetric nuclear matter (SNM) and Pure neutron matter (PNM) as a function of density or Fermi momemtum.

It is well known that no two-body potential is able to reproduce the saturation property of the symmetric nuclear matter using non-relativistic variational (Wiringa et al, 1988) or BHF (Baldo et al., 1997) approach. Hence it has become necessary to use three body forces. Further the two nucleon potentials under bind the 3He and 3H (Brandenberg et al, 1961; Kummel et al, 1978). It has been established that the Bethe-Brueckner-Goldstone (Baldo et al., 1997) expansion converges at the two-hole line level of approximation if a continuous choice for the self-consistent single particle potential is adopted for the intermediate states in the BHF approach. Hence there is no hope that the higher order terms in the Goldstone expansion with only two-body force would be able to reproduce the saturation properties of SNM. Hence it has become necessary to use three body forces. In order to avoid the complication of solving Bethe-Fadeev equation (Faddeev et al, 1961), averaged three nucleon interaction ((Friedman and Pandharipande, 1981; Pudliner et al, 1995) has recently been used to obtain the correct saturation property of SNM by adjusting few parameters.

In this paper we first describe our results concerning nuclear matter with only two-body and then with the additional use of two types of three-body forces. Since the basic input in BHF (Day, 1967) is the nucleon - nucleon (NN) interaction hence we have used the most recent high quality NN potentials: Argonne v18 (Wiringa et al, 1995) (AV-18), Reid 93 and NijmII (Stoks et al, 1994). The saturation points obtained using only two body NN interactions in non relativistic BHF are found to lie within a narrow band, called Coester band (Coester et al, 1970). In order to improve upon the situation we have to include three body forces in BHF calculations. We have used two models of TBF in our calculations. The Urbana VII (UVII) three nucleon potential (Baldo and Ferreira, 1999; Carlson et al, 1983) and the phenomenological density dependent three nucleon interaction (TNI) model of Lagris, Friedman and Pandharipande (Kummel, 1978; Faddeev, (1961) in our effective interaction code to calculate EOS of SNM and PNM. Study of Neutron matter is important for estimating neutron star sizes and hence we have made BHF calculations for pure neutron matter.

Method of calculation

The microscopic Brueckner-Bethe-Goldstone description of nuclear matter is based on a linked cluster expansion of the energy per nucleon of the nuclear matter (Day, 1967). The basic ingredient is the Brueckner reaction matrix G, which is the solution of the Bethe Goldstone equation,

$$G[\omega;\rho] = V + \frac{|k_a k_b\rangle\langle k_a k_b|}{\omega - e(k_a) - e(k_b) + i\varepsilon} G[\omega;\rho] \tag{2}$$

where V is the realistic nucleon–nucleon interaction, ρ is the nuclear matter density, and w the starting energy. The single particle energy is

$$e(k) = e(k;\rho) = \frac{k^2}{2m} + U(k;\rho) \tag{3}$$

and the propagation of the intermediate nucleon pairs is constrained above the Fermi momentum kF . The BHF approximation for the single-particle potential U(k; ρ) using the continuous choice prescription is:

$$U(k;\rho) = \mathrm{Re} \sum_{k' \le k_F} \langle kk'|G|e(k)+e(k');\rho]|kk'\rangle_a \tag{4}$$

where the subscript a refers to antisymmetrization of the matrix elements. Because of U(k; ρ) in Eq. (3), Eqs. (2–4) constitute a set of coupled equations that needs to be solved self-consistently. In the BHF approximation the average energy per nucleon in nuclear matter is given by:

$$\frac{B}{A} = \frac{3}{5}\frac{k_F^2}{2m} + \frac{1}{2\rho}\mathrm{Re}\sum_{k' \le k_F} \left\langle kk' | G | e(k) + e(k'); \rho] | kk' \right\rangle_a \quad (5)$$

In the following section we present a brief account of the NN interactions used in our calculations.

Nucleon-Nucleon (NN) Potential Models

In this section we briefly describe the mathematical structure of the NN interactions: Argonne v18 (Wiringa et al, 1995), Reid93 and Nijm II (Stoks et al, 1994), which have been employed in the present study for calculating the equation of state of SNM and PNM.

Argonne v18 inter-nucleon potential

Traditionally, nucleon-nucleon (NN) potentials are constructed by fitting np data for T=0 states and either np or pp data for T=1 states. Examples of potentials fit to np in all states are Argonne v14 (Wiringa et al, 1984), Urbana v14 (Lagris and Pandharipande, 1981), and most of the Bonn potentials (Machleidt et al, 1987). Unfortunately, potential models which fit only the np data often give a poor description of pp data (Stokes and Swart, 1993; Li et al, 2006), even after applying the necessary Coulomb correction. On the other hand potentials fit to pp data in T=1 states give only mediocre description of np data. Fundamentally, this problem is due to charge-independence breaking in the strong interaction.

Argonne v18 (Wiringa et al, 1995) is a high quality, non relativistic, local nucleon-nucleon interaction with explicit charge dependence and charge asymmetry. The model has a charge independent part with 14 operator components, three additional charge-dependent and one charge-asymmetric operator have also been added. This NN interaction gives an excellent fit to both pp and np scattering data, as well as to low-energy nn scattering and deuteron binding energy. Compared to older Urbana 14 (Lagris and Pandharipande, 1981) and Argonne v14 (Wiringa et al, 1984) potentials, this potential has a weaker tensor force, which will generally lead to more binding in light nuclei and less rapid saturation in nuclear matter. This is counteracted by the weaker attraction in T=1 because of the mix of pp and np components Av 18 gives a χ2 per datum of 1.09 for pp and np data in the energy range 0-350MeV. The Argonne V18 potential is written as a sum of an electromagnetic (EM) part, a one-pion exchange (OPE) part, and intermediate- and short-range phenomenological part.

$$v(NN) = v^{EM}(NN) + v^{\pi}(NN) + v^{R}(NN) \quad (6)$$

The interaction potential can be projected in the operator format with 18 terms:

$$v_{ij} = \sum_{p=1,18} v_p(r_{ij}) O_{ij}^p \quad (7)$$

$$O_{ij}^{p=1,14} = 1, \tau_i.\tau_j, \sigma_i.\sigma_j, (\sigma_i.\sigma_j)(\tau_i.\tau_j), S_{ij}, S_{ij}(\tau_i.\tau_j), L.S$$
$$L.S(\tau_i.\tau_j), L^2, L^2(\tau_i.\tau_j), L^2(\sigma_i.\sigma_j), L^2(\sigma_i.\sigma_j)(\tau_i.\tau_j)$$
$$(L.S)^2, (L.S)^2(\tau_i.\tau_j)$$

The first 14 components mentioned above are charge independent and are denoted by abbreviations:

$$c, \tau, \sigma, \sigma\tau, t, t\tau, ls, ls\tau, l2, l2\tau, l2\sigma, l2\sigma\tau, ls2 \text{ and } ls2\tau$$

The four additional operators break charge independence and are given by:

$$O_{ij}^{p=15,18} = T_{ij}, \tau_i.\tau_j, (\sigma_i.\sigma_j)T_{ij}, S_{ij}T_{ij}, (\tau_{zi} + \tau_{zj})$$

$Tij = 3\tau_{zi}\tau_{zj} - \tau_i.\tau_j$ is the isotensor operator, defined analogous to the Sij operator. The terms are abbreviated as T, σT, T and τz. The T, σT and tT operators are charge dependent and τz is charge asymmetric.

Reid 93 and Nijm II inter-nucleon potentials

Reid 93 and Nijm II (Stoks et al, 1994) are regularized, updated and purely local versions of old Nijm78 and Reid68 potentials respectively. Reid93 is an updated high quality and a regularized version of the old Reid potential, where the singularities have been removed via the inclusion of a dipole form factor. With this choice, the tensor potential now also vanishes at the origin, as it should. An important feature of these potential models is that in the one-pion-exchange (OPE) part of the potential, there is an explicit distinction between the neutral-pion and charged-pion exchange. The pion masses used are mπ0 =134.9739 MeV and mπ± = 139.5675 MeV. Almost all other potentials in the literature use mean pion mass. In these other models the isovector np phase parameters are larger in magnitude than the corresponding pp phase parameters.

Results and discussion

BHF results for SNM (only two-body forces)

In this section we present our results for binding energy of symmetric nuclear matter in the non relativistic BHF approach with the three modern NN interactions: Argonne v18, Reid93 and NijmII inter-nucleon interactions. Fig 1 shows our BHF results of the EOS for SNM using only 2-body NN interaction. The figure reveals that, with only two-body interaction potentials the Hamada Johnston underestimates, whereas AV18, UV14, AV14, Reid93 and NIJM overestimates the nuclear binding energy per nucleon at higher saturation densities. Empirical saturation point (Day, 1996) (ρ=0.17±0.01 fm-3, kF=1.35±0.05fm-1, E0/A = -16±1MeV) of nuclear matter lies inside the rectangular box shown in the figure.

We observe from the figure that the energy per nucleon first decreases with increasing density ρ until it reaches the minimum (saturation) then it increases with increasing density ρ as it should. Our detailed results concerning saturation property are given in Table I. We note that the lowest order Brueckner theory using Argonne v18 interaction gives rise to a nuclear matter which saturates at ρ=0.22 fm-3 (i.e kF =1.50fm-1) with E/A= -17.013MeV.Our results using Argonne v18 are closer to empirical values as compared with those using Urbana v14 softcore potential (Lagris and Pandharipande, 1981) and Hamada-Johnston hardcore potential (Hamada and Johnston, 1962). Our results are also in better agreement as compared with those of Li et. al, (2006), Vidana and Constanca, (2009) and Hassaneen et al (2011).Use of Reid93 in BHF leads to ρ=0.27 fm-3 (i.e kF =1.60fm-1) with E/A= -18.43MeV. Nijm II results in =0.27 fm-3 (i.e kF =1.60fm-1) with E/A= -18.78MeV. Our results using both Reid 93 and NijmII NN interactions are again in closer agreement with the empirical values as compared to those deduced by Li et al (2006), Vidana and Constanca (2009) and Hassaneen et al (2011).

All the results using three different two-body NN interactions in BHF give rise to a saturation at higher density and an over bound nuclear matter. Thus, with only two body forces, the nonrelativistic BHF fails to obtain either the magnitude or the density near the empirical estimates of the saturation property.

The equation of state (EOS) can be characterized in the thermodynamical context by the incompressibility coefficient, K, which is directly related to the curvature of the EOS. The incompressibility K can be easily calculated from the equation:

$$K = 9\rho^2 \frac{\partial^2 E_A(\rho)}{\partial \rho^2}\ ; \rho = \rho_0 \qquad (8)$$

The incompressibility K can be used to understand the stiffness of EOS. The empirical value of the incompressibility of symmetric nuclear matter at its saturation density ρ0 is estimated to be 210±30MeV (Haensel et al, 2007). We have calculated the incompressibility at the saturation points for all three interactions: Argonne V18, Reid93 and Nijm II NN interactions. Our results are given in Table I. We note that our results for K are in fair agreement with the empirical value from all the three potentials used here.

A nucleon in nuclear medium behaves like a quasi-particle characterized by the effective interaction and its effective mass.The effective mass describes the momentum dependence of the single particle potential in the nuclear medium. The effective mass m* can evaluated from the slope of U(k) at Fermi momentum (Lejeune et al, 1986).

$$\frac{m*}{m} = \left[1 + \frac{m}{\hbar^2 k} \frac{dU}{dk} \right]^{-1}_{k=k_F} \qquad (9)$$

The phenomenological value of $\frac{m*}{m} \approx 0.7$ (Jeukenne, 1976).

Our BHF results for the effective mass are presented in Table I. We note that our results using all the three above mentioned potentials are very close to the phenomenological value.

Three Body Forces (TBF)

Our results show that non relativistic calculations with only two body interactions fail to reproduce the correct saturation properties of symmetric nuclear matter, in conformity with a large number of earlier calculations (Wiringa et al, 1988; Baldo et al, 1997). Further two body potentials under bind 3H and 4He. It is generally accepted that in order to overcome this deficiency, one needs to introduce three body forces(TBF) in the NN interactions. Unfortunately, it seems not possible to reproduce the experimental binding energies of light nuclei along with correct saturation property accurately with a simple set of TBF. A phenomenological model for nuclear TBF has been introduced by the Urbana group (Baldo and Ferreira, 1999; Carlson et al, 1983) and an another density dependent three nucleon interaction(TNI) model has been introduced by Lagris, Friedman and Pandharipande (Friedman and Pandharipande, 1981; (Lagris and Pandharipande, 1981).These models are briefly described below.

UrbanaVII (UVII) model

The UVIX three nucleon potential has a long range attractive two pion exchange part and an intermediate range repulsive part.

$$V_{ijk} = V_{ijk}^{2\pi} + V_{ijk}^{R} \qquad (10)$$

The two pion exchange term $V_{ijk}^{2\pi}$ is attractive and is a cyclic sum over the nucleon indices i, j, k of products of commutator and anticommutator terms.

$$V_{ijk}^{2\pi} = A \sum_{cyc} (\{X_{ij}, X_{jk}\}\{\tau_i.\tau_j, \tau_j, \tau_k\} + \frac{1}{4}[X_{ij}, X_{jk}][\tau_i.\tau_j, \tau_j.\tau_k]\} \qquad (11)$$

$$V_{ijk}^{R} = U \sum_{cyc} T(r_{ij})^2 T(r_{ik})^2 \qquad (12)$$

The detailed expressions for the effective two body interactions are given by Baldo and Ferreira (1999).

Three Nucleon Interaction (TNI)

As shown by Lagaris and Pandharipande (1981), realistic two-nucleon interaction seem to overbind nuclear matter very significantly at kF >1.5 fm-1, whereas at low kF <1.3 fm-1 nuclear matter is an underbound, this strongly suggest the need for more attraction at low densities and higher repulsion at high densities. Lagris and Pandharipande (1981) have taken a phenomenological point of view, and add contribution of TNI to the Urbana v14 (Lagris and Pandharipande, 1981) model to get the correct E (kF) around kF=1.33 fm-1.

The Urbana v14 plus TNI model approximates the effect of Vijk by adding two density dependent terms to the Urbana v14 two-body potential: a three Nucleon repulsion (TNR) term and a three nucleon attractive term. The TNR term is taken as the product of an exponential of the density i.e. exp ($-\gamma_1\rho$) with the intermediate range part of the potential. The primary effect if this term is the reduction of the intermediate range attraction of the two nucleon potential with three-body interactions effectively contributing $-\gamma_1\rho v_I^P$.

The attractive Vijk interaction is not treated microscopically by FP (Lagris and Pandharipande, 1981). They assume that its contribution to the nuclear matter has the form

$$TNA = \gamma_2\rho^2 \exp(-\gamma_3\rho)(3-2\beta^2) \qquad (13)$$

where β = (N – Z) /A, N and Z are numbers of neutrons and protons.

We follow Friedman and Pandharipande (1981) and calculate E (kF, Av18+TNR) with the interaction using BHF method, and add the TNA contribution to obtain the nuclear matter energy.

The effect of the attractive Vijk on the wave function is also neglected by FP. The values of γ_1, γ_2 and γ_3 used by FP (Lagris and Pandharipande, 1981) are 0.15 fm-3,-600 MeV fm6 and 13.6 fm3 respectively.

BHF results for SNM (two plus three body force)

The equation of state of symmetric nuclear matter has been investigated within Brueckner-Hartee-Fock approach adopting the charge-dependent Argonne V18 plus Urbana VII model and phenomenological density dependent three nucleon interaction model (TNI) of Lagris, Friedman and Pandharipande (1981).

To incorporate the Urbana VII model in Brueckner scheme we followed the method proposed by Lejeune et al, (1986) to reduce the TBF to an effective two-body force by averaging over the spin, isospin of the third particle (j) and folding over the coordinates rj with the product of the two-body correlation functions; (1-gij)2 and (1-gjk)2. These correlation functions express the probability of finding the jth particle at a distance rij,rik from the ith and kth particle respectively. g(r) is the two body defect function obtained in BHF calculations..

Our results for binding energy of symmetric nuclear matter obtained after including both UVII and TNI models are presented in Fig. 1(a). We observe that the introduction of UVII three body model in AV18 significantly improves the agreement between our results and the empirical value of the saturation of symmetric matter. We notice that symmetric matter with UVII three body force saturates at ρ=0.185fm-3, kF=1.4fm-1 and E/A= -15.38MeV a result close to the empirical value (Day, 1996). We note that the symmetric nuclear matter with AV18 plus TNI saturates at ρ=0.158, E/A= -16.50MeV. We conclude that the inclusion of three body forces in the NN interactions brings the saturation point closer the empirical value.

In Fig. 2 we show different components; VS, VT and VR of the averaged BHF three body force potential in symmetric matter kF =1.4fm-1. The final form of the effective two-body force is given in equation (11).We find that A= -0.0333 and U= 0.00038 give the appropriate saturation point. Our results are very close to those derived by Zhou et al, (2004).

Pure Neutron Matter

Pure neutron matter (PNM) is defined as an idealized infinite, homogeneous system of neutrons. At a given density the properties of such a system, treated as a gas of interacting fermions at T= 00K, are determined by the neutron-neutron interaction.

To calculate the EOS of neutron matter we follow the procedure given by Østgaard. 1970), and remove all T = 0 interactions, and also T=1, T3= 0 interaction. The Fermi momentum kF is related to the density ρ of neutron matter:

$$\rho = \frac{k_F^3}{3\pi^2} \qquad (14)$$

We have calculated energy per nucleon of pure neutron matter E (ρ) as a function of density in first orders Brueckner theory using Argonne V18, Reid93 and Nijm II soft-core potentials. We have also studied the effect of introducing three body force of Urbana UVII type with the two-body Argonne V18 potential on PNM.

In Fig.3 we show the results for energy per particle EA (E/A) with density (ρ) for pure neutron matter using Argonne V18. We have also compared our results with those of Zhou et al, (2004) in the same figure.

We observe from the figures that the pure nuclear matter EOS is unbound with energy per nucleon rising approximately monotonically with increasing density or Fermi momentum, which is in agreement with most of the many-body calculations (Arntsen and Østgaard. 1984). We also observe that our results are in a reasonable agreement with those of Arntsen and Østgaard. (1984) for Argonne V18.

To study the effect of inclusion of three body force in the NN interaction we incorporate Urbana VII (Baldo and Ferreira, 1999; Carlson et al, 1983) in Argonne V18 and calculate the energy of pure neutron matter.

Fig. 4 shows energy of PNM with and without three body force. We observe that the inclusion of three body forces stiffens the equation of state as is expected (Baldo and Ferreira, 1999).

The pressure P(ρ) and energy density ε(ρ) of the pure neutron matter are obtained from E(ρ) ,where E(ρ) is the energy per nucleon, ρ is the number density (Wiringa et al, 1988):

$$\varepsilon(\rho) = \rho(E(\rho) + M_N C^2) \qquad (15)$$

$$P(\rho) = \rho^2 \frac{\partial E(\rho)}{\partial \rho} \qquad (16)$$

Velocity of sound in neutron matter (in units of c) is given by:

$$S(\varepsilon) = \sqrt{\frac{\partial P(\varepsilon)}{\partial \varepsilon}} \qquad (17)$$

Our results for ε (ρ), P (ρ) and s(ε) using Argonne V18 are presented in Fig. 5. Our results are in close agreement with Wiringa et al, (1988) using Urbana v14.

Symmetry Energy

The neutron matter EOS combined with that of symmetric nuclear matter provides us with information on the isospin effects (Zuo et al, 1997) in particular on the symmetry energy (Esym). A number of studies had been carried out by to determine the exact value of Esym (ρ0) and its density slope L at the saturation. The empirical valueof Esym(ρ0) is

Table 1: Saturation properties of Nuclear Matter obtained from different potentials.

	$k_F^0(fm^{-1})$	$\rho_0(fm^{-3})$	$-E/A(MeV)$	$E_{sym}(MeV)$	$K(MeV)$	m^*/m	$L(MeV)$
Empirical Values	1.35±0.05	0.17±0.01	16±1	30.5±3	210±30	0.7	52.5±20
Av18	1.50	0.228	17.013	33.2	206.024	0.68	53.34
Av18+UVII	1.40	0.185	15.38	30.93	244.3		
Av18+TNI	1.33	0.158	16.50				
Reid 93	1.60	0.28	18.43	35.39	205.27	0.67	61.31
NijmII	1.60	0.28	18.78	34.32	210.73	0.67	64.72
Lagris and Pandharipande (1981)	-	0.259	17.30	29.9	-	-	-
Stokes and Swart (1993)	-	0.24	17.30	35.8	213.6		63.1
Li et al, (2006)	1.627		11.29	20.11	189.51	189.5	

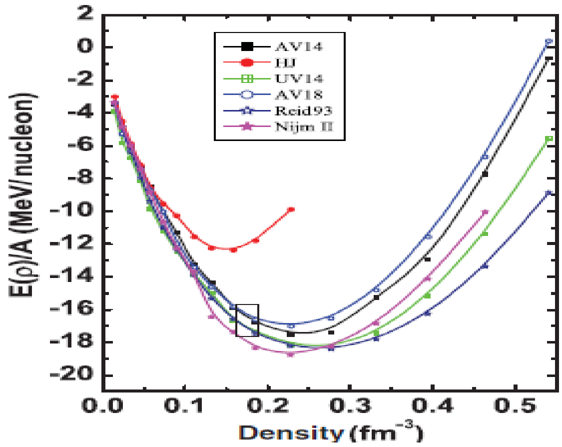

Fig 1. Energy per nucleon as a function of density for SNM by using only 2-body force

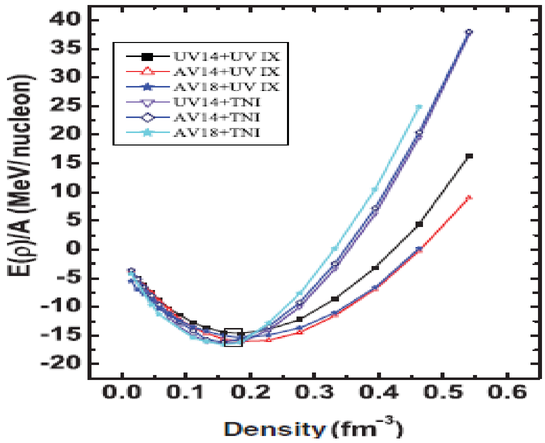

Fig 1(a) Energy per nucleon as a function of density with three body force

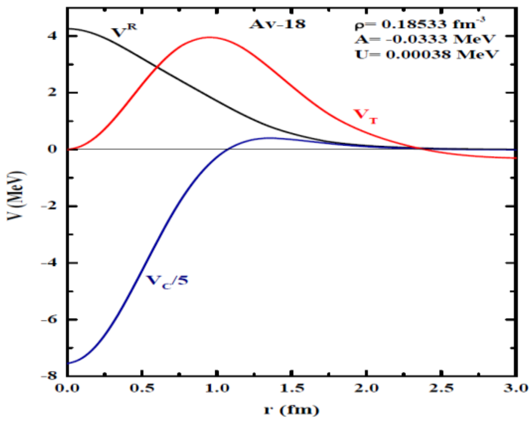

Fig 2. Components of effective two-body potential after taking the average over the third nucleon in UVII model [20,21] of three body force.

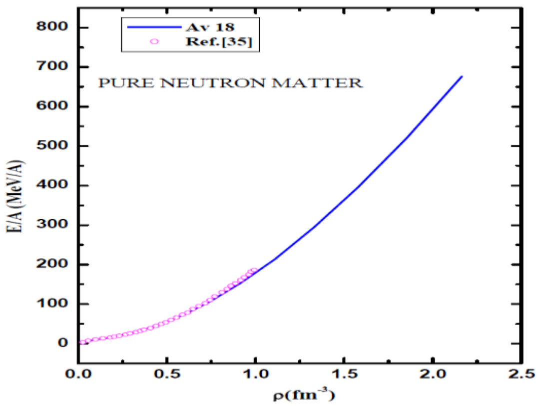

Fig 3. Energy per nucleon for Pure Neutron matter as a function of density using Argonne V18. .Red line shows the results of Ref[33].

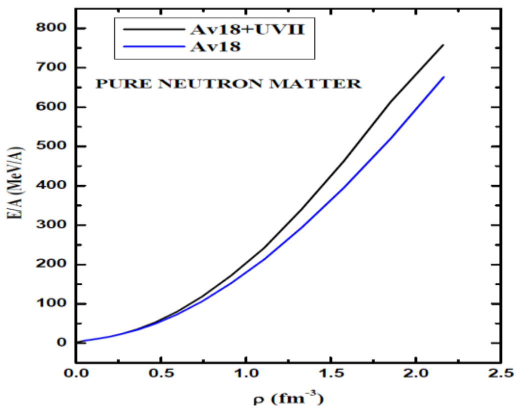

Fig.4. Energy per nucleon for Pure Neutron matter as a function of density using Argonne V18.Blue line show results using two body forces only and black line shows the result after inclusion of three body forces (UVII).

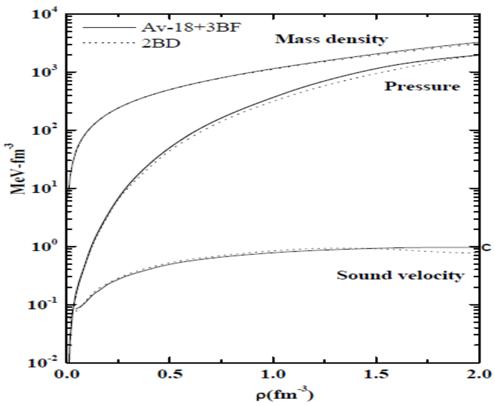

Fig.5. Mass density, Pressure and Sound velocity for Neutron Matter using Argonne V18

30.5±3MeV. (Haustein, 1988) and L is 52±20MeV (Chen, 2011). The symmetry energy can be expressed in terms of the difference between the binding energy of pure neutron matter EA (ρ, 1) and that of symmetric nuclear matter EA(ρ,0) i.e.

$$E_{sym}(\rho) = E_A(\rho,1) - E_A(\rho,0)$$

The density slope parameter L is defined as given by Vidana and Constanca (2009):

$$L = 3\rho_0 \frac{dE_{sym}}{d\rho};\ \rho = \rho_0 \qquad (23)$$

The values of symmetry energy and density slope at saturation point are listed in Table I. We observe from the table that our results are quite close to the empirical values.

Conclusion

We have investigated the effect of using three different modern high quality nucleon-nucleon potentials on the EOS calculated in BHF. We observe that our results with only two body force reconfirm the Coester band.

We have been able to include the effect of two types of three-body forces in our BHF calculations. We note that the inclusion of three body forces in BHF improves the agreement between our results and the empirical values. Further the EOS turns out to be stiffer when TBF is included in the BHF calculations as given by Baldo and Ferreira (1999).

Our results for incompressibility, effective mass and symmetry energy are in a good agreement with their empirical estimates.

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