Equation of state; Symmetric Nuclear Matter two and three body forces

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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.

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:

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

,

where v_{ij} is a two nucleon potential and V_{ijk} is a three nucleon interaction. In this paper we present our results for the self-consistent Brueckner-Hartee-Fock (BHF) 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 [1] or BHF [2] approach. Hence it has become necessary to use three body forces.

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[3], Reid93 and NijmII[4] inter-nucleon interactions. Fig.1 shows energy per nucleon as a function of density ρ using all the three NN interactions described above. For comparison we have also shown the results for the energy per nucleon for SNM from Ref. [5]. Empirical saturation point [6] (ρ=0.17±0.01 fm^{-3}, k_F=1.35±0.05fm^{-1}, E_0/A = -16±1MeV) of nuclear matter lies inside the rectangular box shown in Fig 1.

We observe from the Fig.1 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. We note that the lowest order Brueckner theory using Argonne v18 interaction gives rise to a nuclear matter which saturates at ρ=0.23 fm^{-3} (i.e k_F =1.50fm^{-1}) with E/A= -17.013MeV. Our results using for E/A Argonne v18 are closer to empirical values as compared with those using Urbana v14 softcore potential (E/A=-19.01) and Hamada-Johnston hardcore potential (E/A=-12.4). Our results are also in better agreement as compared with those of Z.H.Li *et.al*,[5], Isaac Vidana *et. al* [7] and K.S.A Hassaneen [8].

Use of Reid93 in BHF leads to ρ=0.27 fm^{-3} (i.e k_F =1.60fm^{-1}) with E/A= -18.43MeV. Nijm II results in =0.27 fm^{-3} (i.e k_F =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 Refs. [5,7,8].

All the results using three different two- body NN interactions in BHF give rise to saturation at higher density and an over bound nuclear matter. Since it is evident that no two body force is able to reproduce the saturation properties of symmetric nuclear matter,Hence it becomes necessary to study the effect of three body forces.

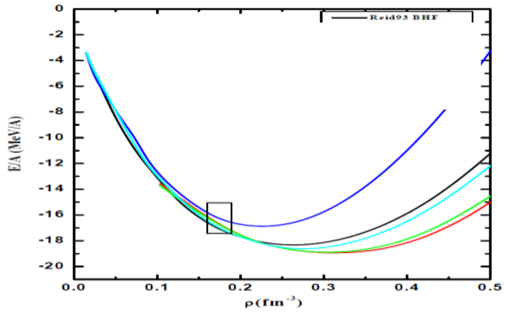

Fig 1. Black solid line shows our result using Reid 93, green line for Nijm II and blue line for Av18. Red dashed and green dashed line show the results of Ref.[5] for NijmII and Reid93 respectively.

We incorporated two types of three body forces in BHF using Argonne v18, Urbana VII model[9] and phenomenological density dependent three nucleon interaction model (TNI) of Lagris, Friedman and Pandharipande [10].

Our results for binding energy of symmetric nuclear matter obtained after including both UVII and TNI models are presented in Fig.2. Solid red curve is the result for calculated binding energy per nucleon E (ρ)/A for symmetric nuclear matter as a function of density using Argonne v18 plus UVII model for TBF. The green curve shows our result when phenomenological TNI is added to the two body Av 18 potential. We have also plotted our result for E/A for Argonne v18 using only two body potential (solid black curve) only. For comparison we have also included in Fig.2, the results of the BHF calculations by Z.H.Li et. al. (Blue curve) [5].

We observe from Fig. 2 that the introduction of UVII three body model in Av 18 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}, k_F=1.4fm^{-1} and E/A= -15.38MeV a result close to the empirical value .

The green line in the Fig.2 shows our results for the E(ρ)/A for symmetric nuclear matter (SNM) using Av 18 plus TNI. We note that the symmetric nuclear matter with Av18 plus TNI saturates at ρ=0.158, E/A= -16.50MeV.We also observe that our results are closer to the empirical values than those obtained in Ref. [5]. We can conclude that the inclusion of three body forces in the NN interactions brings the saturation point closer the empirical value.

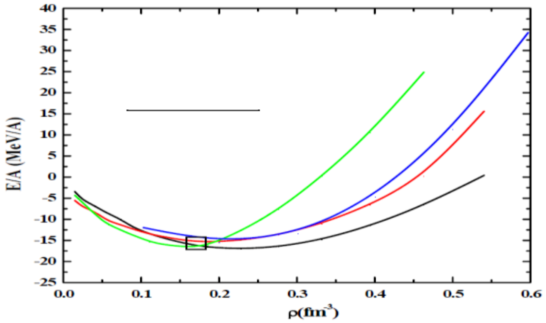

Fig.2. Black solid line shows our results using only Argonne v18 two body force.Red line shows our results using Av18 plus UVII. Green line shows our results for Av18 plus TNI. Blue line shows the results from Ref. [5].

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References:

[1]R.B.Wiringa,V.Fiks and A.Fabrocini, Phys. Rev. C **38**, 1010 (1988).

[2]M.Baldo, I.Bombaci, and G.F Burgio, Astron. Astrophys**. 328**, 274 (1997).

[3]R. B. Wiringa, V. G. J. Stoks, and R. Schiavilla, Phys. Rev. C**51**, 38 (1995).

[4] V. G. J. Stoks, R. A. M. Klomp, C. P. F. Terheggen, and J. J. deSwart, Phys. Rev. C **49**, 2950 (1994).

[5].Z.H.Li,U.Lombardo,H.J.Schulze,W.Zuo,L.W .Chen, and H.R.Ma Phys.Rev.C **74**,047304 (2006).

[6]B.D. Day, Comm. Nucl. Part. Phys. **11**,115 (1983); W.D. Myers and W.J. Swiatecki, Nucl. Phys. A**601**, 141 (1996).

[7]Isaac Vidana and Constanca Providencia Phys. Rev.C **80**,045806(2009).

[8]Kh.S.A.Hassaneen,H.M.AboElsebaa,E.A.Sultan,H.M.M. Mansour Annals of Physics **326** (2011) 566-577.

[9]M. Baldo and L. S. Ferreira, Phys. Rev. C **59**, 682 (1999).

[10]I.E. Lagris and V.R. Pandharipande, Nucl. Phys. **A 359**, 349 (1981).