Equation of state of Symmetric Nuclear matter and Neutron matter with Three Body Forces

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Introduction

Microscopic optical potential calculated within first order Brueckner theory has been extensively used to calculate saturation properties of zero temperature symmetric nuclear matter (SNM), pure neutron matter(PNM) and analyze the nucleon scattering data. In this paper we confine ourselves to only the saturation property of SNM and PNM. We have used soft core Urbana v14 (UV14) [1] and Hard core Hamada Johnston (HJ) [2] inter-nucleon potential in the present work. No inter-nucleon potential has been successful in obtaining the correct binding energy and saturation density in the non relativistic BHF approximation.

In view of the failure of the two-body forces to predict the correct saturation properties of nuclear matter it has become essential to use the three-body forces (TBF). We have used two models of TBF. The Urbana VII (UVII) three nucleon potential [3], and a phenomenological density dependent three nucleon interaction(TNI) model of Lagris, Friedman, and pandharipande [4] in our effective interaction code to calculate EOS of SNM and PNM.

General Theory

We have followed the method of Brueckner and Gammel [5] to solve the integral equation to obtain g-matrix for all inter-nucleon states up to 1=5. Integral equation for the reaction matrix is defined as

$$g(w = e(j) + e(k)) = v - v\frac{Q}{e(k_1) + e(k_2) - w}g \qquad (1)$$

where the single particle energy e(k) is given by

$$e(k) = \frac{\hbar^2 k^2}{2m} + V(k) \qquad (2)$$

The nucleon-nucleus optical potential in nuclear matter is defined as the antisymmetrized matrix elements of the reaction matrix g

$$V_{NM}(k, E) = \sum_j n_{\langle}(j)\langle \vec{k}, \vec{j}|\, g(E + e(j))\,|\vec{k}, \vec{j}\rangle_A \qquad (3)$$

The energy per nucleon for infinite neutron matter is given by

$$E/A = \frac{\int_0^{k_F}\left[\frac{\hbar^2 k^2}{2m} + \frac{1}{2}V(k)\right]k^2 dk}{\int_0^{k_F} k^2 dk}$$

Three-Body Forces (TBF)

(a) UrbanaVII (UVII) model

The UVII three-nucleon potential [3] has a long range attractive two-pion exchange part and an intermediate-range repulsive part:

$$V_{ijk} = V_{ijk}^{2\pi} + V_{ijk}^{R} \; .$$

The two- pion exchange part is a cyclic sum of the following commutatoe and anti-commutator terms:

:

$$V_{ijk}^{2\pi} = \sum_{cyc} A(\{x_{ij}, x_{ik}\}\{\tau_i\cdot\tau_j, \tau_i\cdot\tau_k\} + \tfrac{1}{4}[x_{ij}, x_{ik}][\tau_i\cdot\tau_j, \tau_i\cdot\tau_k]) \, ,$$

The repulsive part is taken as

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

The constants A and U are treated as parameters. For the use in BHF calculations, this TBF is reduced to an effective, density dependent, two-body force by averaging over the third nucleon in the medium, taking account of the nucleon-nucleon correlations by means of the BHF defect function *g*.

$$v_3^{eff}(r_{ik}) = \rho \sum_{\sigma_j,\tau_j} \int d^3r_j V_{ijk}[1-g(r_{ij})]^2[1-g(r_{jk})]^2,$$

For Further details see Ref[3].

(b)<u>Three Nucleon Interaction (TNI)</u>

The UV14 plus TNI model [4] approximates the effect of three-body force by adding two density dependent terms: a three nucleon repulsive (TNR) and a three nucleon attractive (TNA) term. TNR is treated microscopically while the effect of TNR is added to the resulting EOS.

$$v_{14} + \text{TNR} = \sum_{p=1}^{14} [v_\pi^p(r_{ij}) + v_I^p(r_{ij})\exp(-\gamma_1\rho) + v_S^p(r_{ij})]O_{ij}^p\ ,$$

$$\text{TNA} = \gamma_2\rho^2\exp(-\gamma_3\rho)(3-2\beta^2)$$

where β = (N – Z) /A. where N and Z are numbers of neutrons and protons. We follow ref. [6] and calculate E (k_F, v_{14}+TNR) with the interaction (eq.3.17) using BHF method, and add the TNA contribution (eq.3.18) to obtain the nuclear matter energy. For Further details see Ref [4].

Results

In Fig. 1 we show calculated binding energy per nucleon for SNM. Solid and dash dot lines show our results for UV14 and HJ (two body forces), while dash and dotted dot lines show results using three body force namely UV14 plus UVII and UV14 plus TNI respectively. We see that nuclear matter with UV14 saturates at ρ =0.256 fm^{-3} ,E/A=-19.01 MeV and with HJ saturates at ρ =0.148,E/A=-12.4 MeV. Empirical saturation point (ρ=0.17±1fm-3, E/A=-16±1 MeV) of nuclear matter lies inside the rectangular box. With three body force (UV14 plus UVII) SNM saturation at =0.178 fm-1,E/A=-14.62 MeV and UV14 plus TNI gives saturation at ρ =0.157 fm^{-3}, E/A = -16.6 MeV. Thus with three body foces SNM saturates at a value which is quite close to the empirical value. In order to reproduce the correct saturation of SNM we found our values are A= -0.0058 and U=0.0016 in Urbana Model and in TNI model are γ_1=0.15 fm^{-3}, γ_2=-260 $MeVfm^6$ and γ_3=11fm^3. Fig.2 shows the calculated binding energy per nucleon for neutron matter using UV14, HJ, UV14 plus UVII and UV14 plus TNI interaction.

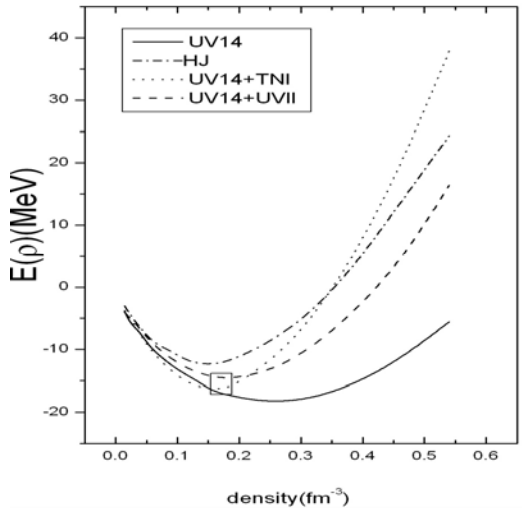

Fig.1

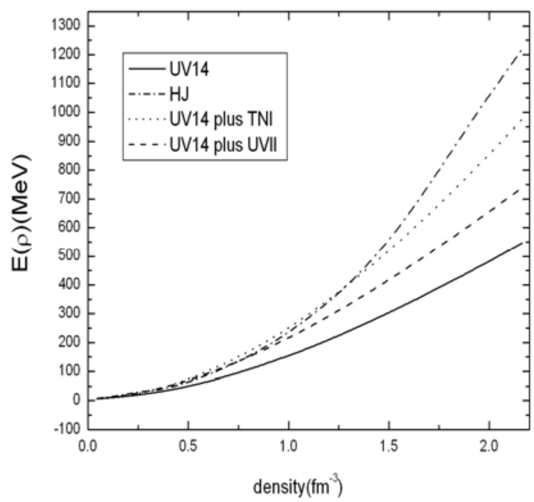

Fig.2

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