Properties of nuclear matter and finite nuclei with finite range simple effective interaction

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Abstract

The nuclear mean field as a function of momentum and density is the quantity of crucial relevance in the study of nuclear matter and the equation of state can be obtained from it at momentum equals to Fermi momentum. In order to simulate the momentum dependence of the mean field, the effective interaction is constructed in the simplest form and the parameters are fixed with proper care on the momentum dependent aspects of the mean fields in different kinds of nuclear matter. By fixing the parameters of the interaction, as discussed in the work, microscopic trends of nuclear matter properties and predictions in finite nuclei, not less than any other conventional interaction, could be obtained.

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1 Introduction

The study of nuclear matter (NM) and finite nuclei in a given model is a subject of contemporary interest in the area of nuclear research. The most fundamental *ab initio* calculations of Dirac-Brueckner-Hartree-Fock (DBHF), Brueckner-Hartree-Fock (BHF) and variational types [1–6] start from a Hamiltonian which is adjusted to reproduce the nucleon-nucleon (N-N) scattering phase shifts and properties of few nucleon bound systems. The predictions in the regime of nuclear matter of this kind of *ab initio* calculations are usually considered as a standard. However, the extension to finite nuclei of microscopic calculations has severe constraints due to the much involved theoretical and computational procedures. In general, effective mean field models, either in the relativistic [7–9] and non-relativistic [10–12] frameworks are widely used for the studies in finite nuclei. However, a global description of NM and finite nuclei with a single set of interaction parameters is not available in the literature. In this work, we have made an attempt to study starting from NM to finite nuclei using the finite range simple effective interaction (SEI) [13, 14] without readjustment of any of its parameters while going from NM to finite nuclei. Ten of its total twelve parameters are fixed from the NM studies. The finite nuclei results may be considered as the predictions and shall justify the procedure adopted in the adjustment of parameters in NM.

In section 2 we have outlined the formulation of NM with SEI and discussed the fixation of parameters required for the studies of *isospin* and *spin* asymmetric NMs. We have also examined the predictions of SEI in NM under extreme conditions in this section. In section 3 we have discussed the predictions of finite nuclei properties by fitting the two remaining parameters. The last section 4 contains the conclusions.

2 Formalism

The neutron and proton mean fields, $u^n(k, \rho_n, \rho_p)$, $u^p(k, \rho_n, \rho_p)$ which are functions of momentum k, neutron and proton densities ρ_n and ρ_p, are the quantities of crucial importance in the studies of *isospin* asymmetric nuclear matter (ANM). The studies of these nucleonic mean fields are performed in terms of isoscalar $u(k, \rho)$ and isovector $u_\tau(k, \rho)$ parts. The isoscalar part is the avarege of the neutron and proton mean fields, where as, the isovector part is their difference averaged over the isospin. It has been shown that the momentum dependent parts of the isoscalar and isovector parts of the mean fields can be separated out and the resulting expressions become [15],

$$u(k,\rho) = e(\rho) + \rho\frac{de(\rho)}{d\rho} - \frac{\hbar^2 k_f^2}{2m} + u^{ex}(k,\rho) \tag{1}$$

$$u^{ex}(k,\rho) = \frac{\rho}{2}\int [j_0(kr) - j_0(k_f r)] \frac{3j_1(k_f r)}{(k_f r)} \left[v_{ex}^l + v_{ex}^{ul}\right] d^3r \tag{2}$$

$$u_\tau(k,\rho) = 2E_s(\rho) - \frac{\hbar^2 k_f^2}{3m^*(k=k_f,\rho)} + u_\tau^{ex}(k,\rho) \tag{3}$$

$$u_\tau^{ex}(k,\rho) = \frac{\rho}{2}\int [j_0(kr) - j_0(k_f r)] \left[v_{ex}^l - v_{ex}^{ul}\right] j_0(k_f) d^3r \tag{4}$$

where, $e(\rho) = H(\rho)/\rho$ is the energy per particle in symmetric nuclear matter (SNM), $H(\rho)$ being the energy density, $\rho = \rho_n + \rho_p$ is the total density, $k_f = \frac{(3\pi^2\rho)^{1/3}}{2}$ is the Ferrmi momentum, j_0 is the spherical Bessel function of zeroth order, m^* is the effective mass in SNM and $E_s(\rho)$ is the symmetry energy. v_{ex}^l and v_{ex}^{ul} are the exchange interactions acting between pairs of like (l) and unlike (ul) nucleons. The functionals $u^{ex}(k,\rho)$ and $u_\tau^{ex}(k,\rho)$ in eqs.(2) and (4) are the momentum dependent contributions to the isoscalar and isovector parts of the nucleonic mean field, which vanishes at the Fermi momentum k=k_f and connection to the nuclear matter equation of state (EOS) can be obtained from eqs.(1) and (3). Further, these functionals, given by eqs.(2) and (4), have non-vanishing contributions only for finite range exchange interactions, while zero-range interactions do not contribute to the momentum dependence of the mean fields. So, in the simplest form one can consider a single finite range term of any of the conventional form *Yukawa/ Gaussian/ exponential* in the interction and examine how far it can account for the mean field properties. The finite range effective interaction (SEI) thus constructed in the simplest form containing a single finite range term is given as,

$$\begin{aligned} v_{eff}(r) &= t_0(1+x_0P_\sigma)\delta(r) + \frac{t_3}{6}(1+x_3P_\sigma)\left(\frac{\rho(\mathbf{R})}{1+b\rho(\mathbf{R})}\right)^\gamma \delta(r) \\ &+ (W + BP_\sigma - HP_\tau - MP_\sigma P_\tau) f(r), \end{aligned} \tag{5}$$

where, $f(r)$ is the functional form of the finite range interaction containing the single range parameter α and can be of any conventional form *Yukawa/*

Gaussian/exponential. Here, we have made explicit studies for the Gaussian and Yukawa forms.The SEI in eq.(5) contains of 11-parameters, namely, t_0, x_0, t_3, x_3, b, W, B, H, M, γ and α (the spin-orbit strength parameter W_0 will enter in the formulation of finite nuclei). The energy density of ANM, $H(\rho_n, \rho_p)$, and neutron (proton) mean field $u^{n(p)}(k, \rho_n, \rho_p)$ for the Gaussian form of $f(r)$ are given in Refs. [16,17] and for Yukawa form in Refs. [18,19].

The complete study of ANM requires the knowledge of altogether nine parameters, namely, b, γ, α, ε^l_{ex}, ε^{ul}_{ex}, ε^l_γ, ε^{ul}_γ, ε^l_0 and ε^{ul}_0. For the sake of simplicity, the formulation has been based on the fact that the range between a pair of like or unlike nucleons is the same but they differ in their strengths. The connection between the parameters of ANM and the interaction parameters is given in the earlier works [16, 18]. The knowledge of the nine parameters that characterize the ANM can be obtained from the independent studies of spin saturated SNM and pure neutron matter (PNM). The parameters γ, b and α along with the combinations of the strength parameters $(\frac{\varepsilon^l_0+\varepsilon^{ul}_0}{2}) = \varepsilon_0$, $(\frac{\varepsilon^l_\gamma+\varepsilon^{ul}_\gamma}{2}) = \varepsilon_\gamma$ and $(\frac{\varepsilon^l_{ex}+\varepsilon^{ul}_{ex}}{2}) = \varepsilon_{ex}$ are the six parameters needed for a complete description of the mean field properties and the EOS in SNM. In determining these parameters, we have first constrained the range α and finite range strength parameter ε_{ex} those governs the momentum dependence of the mean field in SNM. These two parameters are determined by adopting a simultaneous optimization procedure with the constraint that the attractive optical potential changes sign for a kinetic energy $\frac{\hbar^2 k^2}{2m}$=300 MeV of the incident nucleon (see Ref. [13] for details), a result extracted from the analysis of nucleon-nucleus scattering data in intermediate energy range [20,21]. The values thus obtained are ε_{ex}=-96.24 MeV, α=0.7596 fm for the Gaussian and ε_{ex}=-129.25 MeV, α=0.4044 fm for the Yukawa form, where we have used as input only the standard values of the nucleon mass m=939 MeV, Fermi kinetic energy $\hbar^2 k^2_{f_0}/2m$=37 MeV (that corresponds to the saturation density ρ_0=0.161 fm^{-3}) and energy per particle at saturation in SNM $e(\rho_0)$= -16.0 MeV. The momentum dependence of the nuclear mean field in SNM, $u^{ex}(k, \rho)$, computed using this SEI with Gaussian form at three different densities, ρ=0.1, 0.3, and 0.5 fm^{-3}, is shown in figure 1 of Ref [16] and agree very well over a wide range of momentum with the prediction of the realistic interaction UV14+UVII [22]. The same comparison is shown in the lower panel of the same figure in Ref. [16] for the Gogny D1 and D1S sets with the microscopic results [22]. The conclusion regarding the comparison in case of Yukawa form with the microscopic prediction is the same.

With the knowledge of these two parameters, range α and exchange

Table 1: Values of the effective mass and mean field in SNM at normal nuclear matter density for various limiting values of the momentum k togather with the rearrangement energy for Gaussian and Yukawa forms of SEI.

Properties	Yukawa	Gaussian
$\frac{m^*}{m}(k = k_{f0}, \rho_0)$	0.686	0.709
$\frac{m^*}{m}(k = 0, \rho_0)$	0.609	0.660
$u(k = \infty, \rho_0)$ MeV	35.89	12.68
$u(k = 0, \rho_0)$ MeV	-73.1	-70.05
$u_R(\rho_0)$ MeV	15.93	16.91

strength ε_{ex}, we can make a study of mean field, $u(k, \rho_0)$ and effective mass, m^*/m, properties in SNM at saturation density ρ_0. The predictions of m^*/m and $u(k, \rho_0)$ at different limiting values of k, and the rearrangement energy $u_R(\rho_0)$ are given in Table 1 for both Yukawa and Gaussian forms. However, the calculation of the mean field properties at densities other than saturation density and EOS of SNM, requires the knowledge of the rest four parameters b, ε_γ, ε_0, and γ. The parameter b is fixed to avoid the supraluminous behaviour in SNM [23]. The condition reads $b\rho_0 = \left[\left(\frac{mc^2}{T_{f0}/5 - e(\rho_0)}\right)^{\frac{1}{(\gamma+1)}} - 1\right]^{-1}$,with $T_{f0} = \frac{\hbar^2 k_{f0}^2}{2m}$. Its calculation requires again the knowledge of the NM values ρ_0, $e(\rho_0)$ and the parameter γ only. The two parameters, ε_γ and ε_0, are obtained from the saturation conditions, that is, from the values of $e(\rho_0)$ and ρ_0. The stiffness parameter γ is kept open and its admissible values are constrained by the condition that the pressure-density curve lies within the region extracted from the analysis of flow data in heavy-ion collisions (HIC) at intermediate and high energies [24]. With the knowledge of the two parameters α and ε_{ex} determined from the momentum dependence of isoscalar mean field at normal density ρ_0, the complete study of SNM can be performed for a given γ if one assumes only the standard NM values of ρ_0, $e(\rho_0)$ and m. To extend the study to ANM, one needs to know how ε_{ex}, ε_γ and ε_0 split into like and unlike isospin channels. The splitting of ε_{ex} into ε_{ex}^l and ε_{ex}^{ul} is decided using the physical constraint resulting from the studies of the thermal evolution of NM properties [19]. This study predicts a critical value of the splitting of ε_{ex} for which the thermal evolution of NM properties as well as the entropy per particle in PNM does not exceed that of SNM. The resulting critical value of the splitting is $\varepsilon_{ex}^l = \frac{2}{3}\varepsilon_{ex}$. The n-p effective mass splitting predicted with this choice of ε_{ex}^l nicely coincides with the results of DBHF calculations [2] as has been shown in the previous work [16]. The splitting of the remaining two parameters, namely ε_γ and ε_0, is obtained by assuming a standard value of symmetry energy $E_s(\rho_0)$ at saturation and a value of its derivative $E_s'(\rho_0) = \rho_0 \frac{dE_s(\rho_0)}{d\rho_0}$ for which the asymmetric contribution of the nucleonic part of the energy density in charge neutral beta-stable $n + p + e + \mu$ matter becomes maximum. This choice predicts a density dependence of the symmetry energy which is neither very stiff nor soft and does not allow the direct URCA process to occur in neutron stars, in agreement with the predictions of the population synthesis models [25] based on cooling calculations [26]. The SEI with the parameters obtained in this way is able to reproduce the microscopic trends of the density dependence of the EOS and the momentum dependence of the mean fields in ANM [18,27]. With the knowledge of all nine parameters of ANM, the neutron star matter EOS has been calculated by solving the charge neutral beta-stability conditions and neutron star bulk properties are obtained from the solution of the Tolman-Oppenheimer-Volkov (TOV) equation. In the Figures 1, we show the mass-radius relations predicted for different sets of SEI corresponding to five different values of γ.

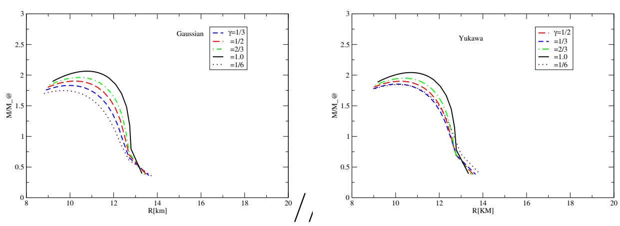

Figure 1: Mass-radius relations predicted for Gaussian (left panel) and Yukawa (right panel) for the EOSs having γ=1/6, 1/3, 1/2, 2/3 and 1.0.

We have still two parameters open which we have taken to be t_0 and x_0. These two parameters, along with the spin-orbit strength W_0, were determined by a simultaneous fit to the experimental binding energies of ^{40}Ca and ^{208}Pb and to the splitting of the $1p$ single-particle levels in ^{16}O in our work on finite nucleus in Ref. [16]. However, in a subsequent work [17], it is shown that the x_0 and W_0 parameters are, actually, correlated and different combinations of them leave the *rms* deviations of binding energies and charge radii practically unchanged but predict very different behavior in spin polarized matter, which is sensitive to the value of x_0. To determine x_0 we consider the particular case of spin polarized neutron matter. Its description requires to know how the strength parameters ε_0^l, ε_γ^l and ε_{ex}^l of spin saturated neutron matter splits into the two channels of like (parallel, "l,l") and unlike (anti-parallel, "l,ul") spin orientations subject to the constraints, ε_0^l=$(\varepsilon_0^{l,l} + \varepsilon_0^{l,ul})/2$, ε_γ^l=$(\varepsilon_\gamma^{l,l} + \varepsilon_\gamma^{l,ul})/2$ and ε_{ex}^l=$(\varepsilon_{ex}^{l,l} + \varepsilon_{ex}^{l,ul})/2$. The parameters $\varepsilon_{ex}^{l,l}$ and $\varepsilon_{ex}^{l,ul}$ determine the momentum dependent aspects of the mean field in polarized neutron matter. From a fit to the DBHF predictions on effective mass splitting between spin-up and spin-down neutrons in spin polarized neutron matter [28], it is found that the SEI predictions agrees well with the DBHF ones for $\varepsilon_{ex}^{l,l} = \varepsilon_{ex}^l/3$, as shown in Ref. [17]. This consideration allows to determine x_0 in a unique way as,

$$x_0 = 1 - \frac{2\varepsilon_0^l - \varepsilon_{ex}^l}{\rho_0 t_0}, \tag{6}$$

subject to the condition that t_0 is known. The two only open parameters, t_0 and W_0, were fitted to reproduce the binding energies of ^{40}Ca and ^{208}Pb, respectively.

3 Finite nuclei

It is clear from the discussions of the last section that the study from infinite NM to finite nuclei requires only the NM parameters $e(\rho_0)$, ρ_0 and $E_s(\rho_0)$ for a given stiffness γ of SNM. The values of these NM parameters are not uniquely defined and their emperical values lies with in certain ranges. The values of these three NM parameters used in different model calculations broadly cover the ranges, $-15.8MeV \leq e(\rho_0) \leq -16.02MeV$, $0.14fm^{-3} \leq \rho_0 \leq 0.18fm^{-3}$ and $27MeV \leq E_s(\rho_0) \leq 38MeV$. In the last section the studies have been made for the values of these parameters $e(\rho_0)$=-16 MeV, ρ_0=0.161fm^{-3} and $E_s(\rho_0)$=30 MeV. But computation of finite nuclei with a set of values of these three NM parameters chosen arbitrarily does not ensures the best description of binding energies and charge radii for interaction with a given γ.In order to verify this point we have calculated the binding energies and charge radii of 161 even-even spherical nuclei using the EOSs corresponding to γ=1/6, 1/3, 1/2 and 2/3 but having same $e(\rho_0)$=-16 MeV, ρ_0=0.161fm^{-3} and $E_s(\rho_0)$=33 MeV. Finite nuclei calculations with the SEI have been performed in the framework of the Density Functional Theory by constructing a quasi-local energy density functional obtained from a Thomas-Fermi approach of the density matrix [29, 30] plus a BCS treatment of pairing correlations,as discussed in details in Ref. [16].

The results of the deviations of the predicted charge radii, $\delta r_{ch} = {r_{ch}}^{th} - {r_{ch}}^{expt}$, of 86 even-even spherical nuclei whose values are experimentally measured are shown in Figure 2. It can be seen that for γ=1/6, the calculated results are overestimated, whereas, it is underestimated for γ=1/2 and 2/3. These results are found to be very weakly sensitive to the

Table 2: Critical values of the NM parameters $e(\rho_0)$, ρ_0 and $E_s(\rho_0)$ for the four sets of EOSs of SEI corresponding to γ=1/6, 1/3, 1/2 and 2/3. The *rms* deviations of energies, δE_{rms}, of 161 and radii, δr_{rms} of 86 spherical nuclei for the four sets of EOSs are given. The corresponding *rms* values for the same set of nuclei obtained for SLy4 Skyrme set [31] and D1S and NL3 RMF set are given for comparison.

γ	T_{f0} MeV	ρ_0 fm^{-3}	$E_s(\rho_0)$ MeV	δr_{rms} fm	δE_{rms} MeV
1/6	37.2	0.1623	36.0	0.0189	1.6993
1/3	36.8	0.1597	35.5	0.0170	1.6754
1/2	36.4	0.1571	35	0.0155	1.8518
2/3	36.1	0.1552	35	0.0152	1.8297
SLy4				0.024	1.71
D1S				0.020	2.41
NL3				0.020	3.58

variations of $e(\rho_0)$ and $E_s(\rho_0)$ with in their ranges, and depend very strongly on the value of ρ_0. The results of energies of the 161-nuclei for these four EOSs show that the energies are overestimated for γ=1/6 and underestimated for γ=2/3 and the results are sensitive to the value of $E_s(\rho_0)$ rather than to the variations of $e(\rho_0)$ and ρ_0. So we have fixed the value of $e(\rho_0)$=16 MeV and varied ρ_0 and $E_s(\rho_0)$ with in their ranges and found out the characteristic values of these two NM parameters for each γ for which the charge radii of the 86 and energies of 161 even-even spherical nuclei are reproduced with minimum *rms* deviations. The vaules are given in Table 2.

It can be seen from these values that as NM incompressibilty increases from 206 MeV (corresponding to γ=1/6) to 265 MeV (γ=2/3), the saturation density decreases from 0.1623 fm^{-3} to 0.1552 fm^{-3}, and symmetry energy decreases from 36 MeV to 35 MeV, respectively. The finite nuclei calculations of spherical even-even nuclei over the nuclear chart have performed for the four EOSs having γ=1/6, 1/3, 1/2 and 2/3 with their charecterstic values of the NM parameters, in Refs. [16,17]. The SEI predictions of binding energies, radii, single particle spectra, isotopic shift in ^{208}Pb, etc. of the spherical nuclei are found to be no less in quality than that of any other conventional interaction.The description of finite nuclei has been extended by performing full Hartree-Fock-Bogoliubov (HFB) calculations including deformation degrees of freedom using the SEI. The HFB formulation is restricted to axially symmetric geometry. The pairing interaction is the same as in Refs. [17]. The solution of the HFB equations has been recast as a minimization procedure of the energy density functional, where the HFB wave function of the Bogoliubov transformation is chosen to minimize the

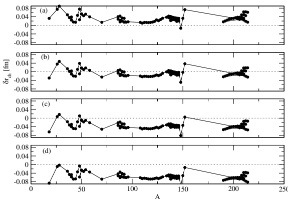

Figure 2: δr_{ch} as a function of mass number A for the 86 even-even spherical nuclei

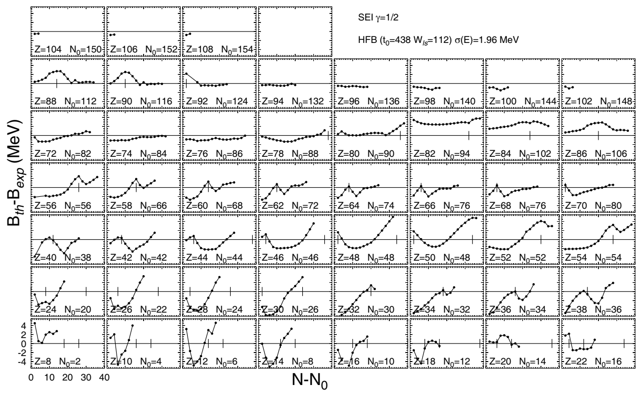

Figure 3: HFB results of $(B_{th} - B_{exp})$ of 620 even-even nuclei as a function of mass number A for the EOS of SEI having γ=1/2.

energy. We have minimized the binding energy *rms* deviation $\sigma(E)$ for the 620 even-even (spherical and deformed) nuclei with known experimental masses taken from Ref. [32]. The values of t_0 and W_0 corresponding to the minimum *rms* deviations $\sigma(E)$ turn out to be the same as found in the quasi-local energy density formulation in Ref. [17]. The energies of 620 nuclei could be reproduced with *rms* $\sigma(E)$=1.873 MeV and 1.958 MeV in the HFB calculation for the EOS having γ=1/3 and γ=1/2, respectively. The results of γ=1/2 are shown in Figure 3. In this figure, the binding energy difference $\Delta B = B_{th} - B_{exp}$, is plotted as a function of the neutron number N, shifted by N_0, which indicates the origin of the horizontal axis for the different isotopic chains displayed in this figure.

4 Conclusions

A global study from nuclear matter to finite nuclei is performed using the finite range simple effective interaction.Ten of the twelve parameters of the interaction are fixed in the regime of nuclear matter. Emphasis has been given to fix the parameters responsible for the momentum dependence of the mean fields in ANM and neutron matter from appropriate considerations.While going for the study of finite nuclei by adjusting the two open parameters t_0 and W_0 from the fits to the binding energies of two magic nuclei, the predictions with regards to the momentum dependence of the mean fields and EOSs in different types of nuclear matters remain unchanged.

It has been found that different properties of nuclear matter similar in trends as given by the microscopic calculations and results in finite nuclei similar in quality to the ones of the conventional interactions could be reproduced. The finite nuclei results can be considered as the predictions of the interaction, as is evident from the procedure of parameters determination. So it can be said that the momentum dependence of the mean field in nuclear matter is a crucial aspect and its appropriate consideration is an essential feature while making a unified study of nuclear matter and finite nuclei in a given model.

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