Spin Polarized Nuclear Matter and Finite Nuclei with Simple Finite Range Effective Interaction

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Introduction

The study of nuclear matter (NM) and finite nuclear matter in a given model is an area of current research interest in Nuclear physics. The study of NM in the microscopic theory, namely, Dirac–Brueckner–Hartree–Fock (DBHF), Brueckner– Hartree–Fock (BHF) and variational calculations using realistic interaction are considered to be standard references in the regime of NM. However the extension of these calculations to study of finite nuclei has not progressed much due to severe computational and analytical constraints. The effective theory namely relativistic mean field theory (RMF) and non-relativistic theory using phenomenological effective forces are quite successful in the study of finite nuclei. However, it has not been possible to reproduce all the trends of the microscopic calculations in NM from a given effective mean field model calculation. In this work, we shall examine the ability of the finite range simple effective interaction (SEI) in reproducing the microscopic trends in NMs of various types and finite nuclei results as well.

Formalism

The finite range SEI is given by

$$v_{eff}(r) = t_0(1 + x_0P_\sigma)\delta(r) + \frac{t_3}{6}(1 + x_3P_\sigma)\left(\frac{\rho(\boldsymbol{R})}{1+b\rho(\boldsymbol{R})}\right)^{\gamma} + (W + BP_\sigma - HP_\tau - MP_\sigma P_\tau)f(r) \quad \ldots(1)$$

where, $f(r)$ is the form factor of the finite-range interaction containing the single range parameter, α. Here we consider $f(r)$ to be of Gaussian form exp $(-r^2/\alpha^2)$. The other terms have their usual meaning. The isospin asymmetric nuclear matter (ANM) and the bulk properties of finite nuclei have been studied earlier [1] and have been found to give all the trends of microscopic calculation in the domain of ANM. We shall now examine the predictions of the SEI in spin polarized NM. The energy per particle expressions in symmetric nuclear matter (SNM) with the SEI are given as

$$H(\rho)=\frac{3\hbar^2k_f^2}{10M}+\frac{(\varepsilon_0^l+\varepsilon_0^{ul})}{4\rho_0}\rho+\frac{(\varepsilon_\gamma^l+\varepsilon_\gamma^{ul})}{4\rho_0{}^{\gamma+1}}\rho\left(\frac{\rho(\boldsymbol{R})}{1+b\rho(\boldsymbol{R})}\right)^{\gamma} + \frac{(\varepsilon_{ex}^l+\varepsilon_{ex}^{ul})}{4\rho_0}\rho\left[\frac{3\Lambda^6}{16k_f^6}-\frac{9\Lambda^4}{8k_f^4}+\left(\frac{3\Lambda^4}{8k_f^4}-\frac{3\Lambda^6}{16k_f^6}\right)e^{\frac{-4k_f^2}{\Lambda^2}}+\frac{3\Lambda^3}{2k_f^3}\int_0^{\frac{2k_f}{\Lambda}}e^{-t^2}\,dt\right] \quad \ldots(2)$$

Results and Discussion

The SEI in equation (1) contains 11-parameters, namely t_0,x_0,t_3,x_3, γ, b, W, B, H, M and α. The complete study of SNM, PNM and ANM requires nine parameters, namely γ, b, ε_0^l, ε_0^{ul}, ε_γ^l, ε_γ^{ul}, ε_{ex}^l, ε_{ex}^{ul} and α keeping two interaction parameters open. The connections of the new parameters to the interaction parameters can be found in the Ref.[1]. The two open parameters considered in the last work [1] are t_0 and x_0 and are fixed from the finite nuclei. These two alongwith the spin-orbit strength W_o were fixed from the binding energies (BE) of ^{40}Ca, ^{208}Pb and $1P_{3/2}$-$1P_{1/2}$ level splitting in ^{16}O. Thus with knowledge of all the 11- parameters of SEI the study of BEs and radii of 161 even-even nuclei have been made and found to give results to the degree no less than the other traditional interactions. However, it is now found that the method of determination of x_0 and W_o from the BE of ^{208}Pb and $1P_{3/2}$-$1P_{1/2}$ level splitting in ^{16}O does not fix these two parameters in an unique way. One can find other sets of values of x_0 and W_o for which the finite nuclei results remains practically the same. For example, x_0=0.6 and W_0=115 give the results of the 161 nuclei with root mean square deviations (*rms*) 1.54 MeV and 0.015 fm for BEs and radii, respectively. Another set is x_0=0.2 and W_0=116 that also reproduces the BE of ^{208}Pb and $1P_{3/2}$-$1P_{1/2}$ level splitting in ^{16}O and reproduces the results of the 161 nuclei with *rms* deviations 1.47 MeV and 0.015 fm. Several sets of x_0 and W_o are practically possible, all will be giving the same results in isospin asymmetric nuclear matter as well as similar results in finite nuclei. Due to this uncertainty in the value of the parameter x_0, the contributions in the four channels of nucleon-nucleon (N-N) interaction become uncertain which manifests in the spin property of NM.

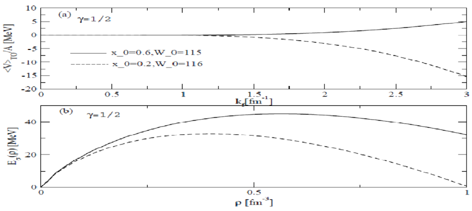

Fig.1: (a) (*upper panel*): TO state contribution to interaction energy per particle in SNM as a function of density for the two EOSs having x_0=0.6, W_0=115 and x_0=0.2, W_0=116. (b) (*lower panel*): The spin symmetry energy as a function of density for the two EOSs as in (a).

This is shown in the Figure 1 where the triplet-odd (TO) state contribution to the energy per particle in SNM is shown in the upper panel for the two EOSs corresponding to γ=1/2 (NM incompressibility K(ρ_0)=245 MeV) but for the two sets of x_0 and W_o. In the lower panel, the spin symmetry energy is shown for these two EOSs that differ widely showing that the predictions in the spin channel of NM shall be divergent with the uncertainty associated with x_0. These two EOSs give the same results for symmetry energy and neutron-proton effective mass splitting in ANM. The predictions of the BEs and radii of the 161 even-even nuclei with these two EOSs, as can be seen from Figure 2, are quit similar where the difference between the calculated and the experimental values of BEs and charge radii of these nuclei are shown in the upper and lower panels, respectively. Thus it evident that by fixing the two open parameters t_0 and x_0 of SEI along with W_o from finite nuclei does not allow us to predict the spin polarized NM in a unique way, although the predictions in ANM are not associated with any uncertainty. The spin polarized NM has crucial relevance in the context of astrophysical phenomena, in particular, the high magnetic field observed in pulsars.

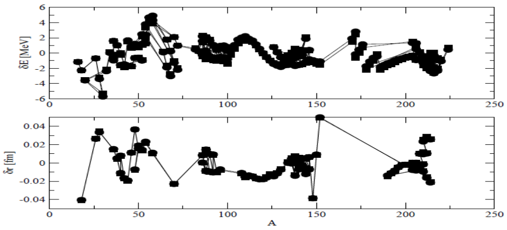

Fig.2: (a) (*upper panel*): The difference of the calculated and experimental values of energies of the 161 even-even nuclei for the two EOSs having x_0=0.6, W_0=115 (filled circle) and x_0=0.2, W_0=116 (filled square) as a function of mass number A. (b) (*lower panel*): Same as (a), but for charge radii.

In view of the above we have attempted to constrain one more parameter of SEI, x_0, from suitable adjustment of the momentum dependence of the mean fields in spin polarized PNM to reproduce the results of effective mass splitting of the microscopic DBHF calculation [2]. In doing this we, now, determine 10- out of 11- parameters of SEI from NM studies keeping only one parameter t_0 open. So with the determination of t_0 from finite nucleus along with the spin-orbit parameter W_o we, in principle, could predict the SNM, PNM, ANM, spin polarized NM and finite nuclei with the SEI in a definite manner. However, the method shall be effective if it can still predict the finite nuclei results with same precision as well as the quality of the predictions in spin polarized NMs of different types as compared to other standard models. The study has been performed considering EOSs over a wide range of NM incompressibility and the momentum and density dependence aspects of spin polarized NMs of different types are studied. It is also found that the finite nuclei results in case of the different EOSs considered could be obtained with similar precision.

References

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