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Momentum and density dependence of the isospin part of nuclear mean field and equation of state of asymmetric nuclear matter

B. Behera [a], T.R. Routray [a,*], A. Pradhan [a], S.K. Patra [b], P.K. Sahu [b]

[a] *Department of Physics, Sambalpur University, Jyoti Vihar, Burla, Sambalpur, Orissa PIN-768019, India*
[b] *Institute of Physics, Sachivalaya Marg, Bhubaneswar, Orissa PIN-751005, India*

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Abstract

Momentum and density dependence of the isospin part of nuclear mean field $u_\tau(k,\rho)$ which is still, in part, the open problem of the old Lane potential is analysed using density dependent finite range effective interactions. The behaviour of $u_\tau(k=k_f,\rho)$ around the Fermi momentum k_f is found to be related to the density dependence of nuclear symmetry energy $J_\tau(\rho)$ and nucleon effective mass $M^*(k=k_f,\rho)/M$ in symmetric nuclear matter. The momentum dependence of $u_\tau(k,\rho)$ is separated out in terms of a simple functional $u_\tau^{ex}(k,\rho)$ which vanishes at $k=k_f$ and involves only the finite range parts of the exchange interactions between pairs of like and unlike nucleons. Depending on the choice of the parameters of these exchange interactions two conflicting trends of momentum dependence are noticed which lead to two opposite types of splitting of neutron and proton effective masses. The equation of state of asymmetric nuclear matter and the high density behaviour of nuclear symmetry energy $J_\tau(\rho)$ are studied by constraining the additional parameters involved on the basis that pure neutron matter should not be predicted to be bound by any reasonable nuclear interaction. Emphasis is also given on the need of experimental data sensitive to the differences between neutron and proton transport properties in highly asymmetric dense nuclear matter and its analysis to constrain the high density behaviour of nuclear symmetry energy as well as to resolve the controversy on the two opposite types of splitting of neutron and proton effective masses.

* Corresponding author.
E-mail addresses: phy_su@rediffmail.com, trr1@rediffmail.com (T.R. Routray).

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1. Introduction

The equation of state (EOS) of nuclear matter under extreme conditions has become a major area of research in nuclear physics in the past decade. Currently an increasing attention is being given to the study of EOS of highly isospin asymmetric dense nuclear matter because of its implications and connections beyond standard nuclear physics, such as, astrophysical phenomena like supernova explosion and neutron star structure.

The most important quantity in the calculation of EOS of asymmetric nuclear matter (ANM) is the isospin part of the nuclear mean field $u_\tau(k,\rho)$ as function of momentum k and total nucleon density $\rho = \rho_n + \rho_p$. It is defined as the difference between zero-temperature neutron and proton mean fields, $u^n(k,\rho,Y_p)$ and $u^p(k,\rho,Y_p)$, as functions of k, ρ and the proton fraction $Y_p = \rho_p/\rho$ normalized to the asymmetry $(1-2Y_p)$,

$$u_\tau(k,\rho) = \frac{u^{n-p}(k,\rho,Y_p)}{2(1-2Y_p)} = \frac{u^n(k,\rho,Y_p) - u^p(k,\rho,Y_p)}{2(1-2Y_p)}. \tag{1}$$

In other words it is just the famous Lane potential; $\upsilon_1 = 4u_\tau(k,\rho)$ [1]. A study of momentum and density dependence of $u_\tau(k,\rho)$ is a very important topic for fundamental reasons, better knowledge of the isospin part of the in medium interaction as well as for the new experimental possibilities offered by the radioactive beam facilities. The growing experimental facilities for the study of nuclear reactions induced by high energy intense radioactive ion beams and their analysis in terms of transport model calculations have provided an opportunity for the first time to explore the EOS of highly asymmetric dense nuclear matter experimentally [2–12]. However, the progress in this direction seems to be rather low and the momentum and density dependence of $u_\tau(k,\rho)$ is still largely unknown [6,7,9–12] particularly at high density and at high momentum.

The various theoretical approaches used in the study of EOS of ANM include Dirac–Brueckner–Hartree–Fock (DBHF) calculations [13–20], Brueckner–Hartee–Fock (BHF) approximation to Brueckner–Bethe–Goldstone (BBG) calculations [21–24] and variational methods [25–27]. Besides these microscopic approaches, effective theories such as relativistic mean field (RMF) approximations [28–37] and non-relativistic effective interactions [38–44] have also been used extensively to study the EOS and mean field properties of asymmetric nuclear matter. In the simulations of dynamical evolution of high energy heavy ion collisions using isospin dependent transport models, usually very simple parametrizations of the energy density and mean fields are used [2–4,9–12].

The momentum and density dependence of the isospin part of nuclear mean field $u_\tau(k,\rho)$ predicted by these different theoretical model calculations are rather extremely divergent and even contradicting. All theoretical results on the behaviour of $u_\tau(k,\rho)$ around the Fermi surface $k = k_f$ which is directly connected with the density dependence of nuclear symmetry energy $J_\tau(\rho)$ can be roughly classified into two groups, i.e., a group