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The role of three-body forces in nuclear symmetry energy and symmetry free energy

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Abstract

Within the framework of lowest-order constrained variational (LOCV) method using AV18 two-body interaction supplemented by UIX three-body force, equation of state of asymmetric nuclear matter at both zero and finite temperature is studied. Density dependence of the nuclear symmetry energy as well as its partial wave decomposition is also investigated. It is shown that all saturation properties of the cold symmetric nuclear matter, including the symmetry energy and its slope, can be correctly reproduced if the three-body force is used in the LOCV formalism. Furthermore, density and temperature dependence of the symmetry energy and symmetry free energy in hot neutron rich matter is studied. An opposite temperature dependence for the symmetry energy and symmetry free energy is found.

Keywords: Nuclear matter; Nuclear symmetry energy; Nuclear symmetry free energy; Three-body forces

1. Introduction

One of the aims of nuclear science is to understand the properties of strongly interacting bulk matter at nuclear levels. In this regard, properties of symmetric nuclear matter (SNM) has been studied for a long time and its equation of state (EOS) around saturation density ρ_0 is known rather well. On the other hand, the EOS of highly isospin asymmetric nuclear matter, particularly

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pure neutron matter (PNM), has not been established well despite of its crucial role in both nuclear physics and astrophysics. Motivated by this fact, studying the nuclear symmetry energy E_{sym} which mostly governs the PNM EOS is currently an active field of research in nuclear physics.

Since the symmetry energy can not be directly measured, it is of fundamental importance to identify observables which strongly correlate with E_{sym} and its density slope L to impose constraints on these quantities. Additional information on the value and density dependence of symmetry energy can be extracted from the astrophysical observations of compact objects, namely neutron stars. Among the terrestrial laboratory observables, the neutron skin thickness is widely studied [1–6] during last decades. Nowadays, there are many other observables such as isospin fractionation, neutron–proton differential flow, nuclear mass systematics, low-lying E1 mode, etc., which are believed to be sensitive to symmetry energy and particularly, its density slope. We refer to references [7–11] and references therein quoted for more details. Density dependence of this quantity also relates the heavy-ion reactions [12–18], stability of superheavy nuclei [19], cooling [20–24] and the mass-radius relations of neutron stars [25,26], and properties of nuclei involved in r-process nucleosynthesis [27]. On the other hand, the symmetry energy or symmetry free energy of hot neutron-rich matter is important for understanding some physical and astrophysical phenomena such as the liquid-gas phase transition of asymmetric nuclear matter, the dynamical evolution of massive stars and the supernova explosion mechanisms [28].

In order to theoretically predict the symmetry energy, asymmetric nuclear matter is studied in the framework of various microscopic and phenomenological approaches by using a variety of microscopic and phenomenological two-nucleon forces and phenomenological three-body forces. Such many-body techniques include the Brueckner–Hartree–Fock (BHF) [7,29] and its relativistic counterpart Dirac–Brueckner–Hartree–Fock (DBHF) [30] frameworks, the self-consistent Green's function method [31], variational approaches [32,33], mean-field model [34], the Quantum Monte Carlo (QMC) technique [35], extended relativistic mean field (ERMF) model [36], and Skyrme–Hartree–Fock (SHF) method [37]. There are also some recent calculations for the symmetry energy of finite nuclei (see e.g. [38] and references therein). Recent progress and challenges in both theoretically and experimentally measuring the symmetry energy and its density dependence, specially at supra nuclear densities, are also reviewed in Refs. [39–43]. On the other hand, less theoretical and experimental attention is so far devoted to studying the temperature and density dependence of the symmetry energy or symmetry free energy of nuclear matter as well as finite nuclei [44–50].

Despite of numerous attempts that were made to determine the symmetry energy properties, especially the value of $E_{sym}(\rho_0)$ and its density slope L at saturation density ρ_0, these quantities are still uncertain. Results are strongly dependent on different experimental techniques and many-body approaches as well as nuclear interaction models. Especially, the density dependence of symmetry energy is poorly known. The high density prediction of many-body models for the symmetry energy are extremely diverse and sometimes contradictory. On the other hand, although the semi-empirical value of the symmetry energy is known to be in the range of $\sim 31.6 \pm 2.66$ MeV [41], explorations on L show wide variations. The obtained theoretical lower limit is ~ 20 MeV [51] and the upper one is even higher than 170 MeV [52]. However, recent surveys of analyses of terrestrial nuclear laboratory experiments and astrophysical observations found that the mean semi-empirical value of the slope parameter at saturation density lies in the range of 58.9 ± 16.0 MeV [41,11].

In the present work, within the self-consistent lowest order constrained variational (LOCV) approach using the Argonne V18 two-body potential [53] supplemented by an Urbana type three-

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