SYMMETRY ENERGY AT SUPRA-SATURATION DENSITIES*

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Recent work on the symmetry energies of nuclear matter at supra-saturation densities by the *ab initio* Relativistic Brueckner–Hartree–Fock calculations as well as the nonrelativistic and relativistic state-of-the-art density functional theories is reviewed, which was motivated by the historical detection of gravitational waves from GW170817. By investigating the neutron star and the neutron drop, *i.e.*, a certain number of neutrons confined in an external field, strong correlations are found between the neutron star tidal deformability and the symmetry energies of nuclear matter at supra-saturation densities. From the correlations and the upper limit on the tidal deformability extracted from GW170817, the symmetry energy at twice saturation density is constrained by the *ab initio* Relativistic Brueckner–Hartree–Fock theory and the state-of-the-art density functional theories.

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1. Introduction

The relativistic nuclear density functionals start from effective nucleon–nucleon interactions or Lagrangians [1]. By fitting to the properties of nuclear matter and the ground or even excited states of selected nuclei, the relativistic nuclear density functionals can describe the ground and excited states for almost all nuclei in the whole nuclear chart very well and became important tools to study heavy nuclei and exotic nuclei far away from the stability region. Although the relativistic nuclear density functionals achieved great success in describing many properties of nuclear structure, ambiguities exist in the prediction for unstable nuclei without data and for nuclear

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matter at high densities. In such cases, *ab initio* calculations become very important and establish the link between the microscopic nucleon–nucleon interaction and nuclear structure properties. This will provide valuable information in describing exotic nuclei, nuclear matter under extreme conditions, and the effects of the tensor force, *etc.* [2].

The nuclear matter symmetry energy $E_{\rm sym}(\rho)$ characterizes the isospin dependence of the equation of state (EOS) for nuclear matter, with ρ the nuclear matter density. The investigation of symmetry energy is a long-standing problem in both nuclear physics and astrophysics. Although a lot of progress has been made to constrain the density dependence of symmetry energy from terrestrial laboratory measurements and astrophysical observations, large uncertainties still exist at supra-saturation densities [3–5].

A gravitational wave (GW) signal from a merger of binary neutron star (BNS) system was observed by the LIGO and Virgo collaborations on August 17, 2017, *i.e.*, GW170817 [6]. This observation has provided a crucial opportunity to investigate the properties of neutron stars. According to the GW170817 signal, one can extract the tidal deformability $\Lambda = 2/3\, k_2(c^2R/GM)^5$, which represents the mass quadrupole moment response of a neutron star to the strong gravitational field induced by its companion, where k_2 is the second Love number, M and R are the neutron star mass and radius, c and G are the speed of light and the gravitational constant, respectively [7]. For a neutron star with mass $1.4M_\odot$, the LIGO and Virgo collaborations provided an upper limit of $\Lambda_{1.4M_\odot} \leq 580$ with a credible level of 90% [8].

The neutron star tidal deformability provides new chances to investigate the EOS [9, 10]. By using the tidal deformability limit from GW170817, the neutron star radius and the neutron skin thickness of ^{208}Pb have been constrained in Ref. [11]. Moreover, a direct relation between the tidal deformability and L has been studied in Refs. [12, 13]. However, these works indicate that the tidal deformability, which probes the symmetry energy at around twice saturation density, may not provide a strong constraint on the nuclear matter properties at the saturation density.

2. Symmetry energy at supra-saturation densities

A neutron drop is very useful to probe the high-density behavior of EOS and it consists of a certain number of neutrons confined in an external field such as a harmonic oscillator [14]. By varying the number of neutrons and/or the strength of the external field for neutron drops, a variety of information for the drops at various densities can be obtained. The nuclear matter properties could be correlated to the neutron drop properties ranging from lower densities to higher densities [15].

Therefore, in the context of GW170817, it is interesting to link the nuclear EOS to the neutron drop properties. Starting with a bare nucleon–nucleon interaction, for the first time the relativistic Brueckner–Hartree–Fock (RBHF) equations are solved for finite nuclei in a Dirac–Woods–Saxon basis [16]. The full RBHF equations are solved for finite nuclei in a fully self-consistent basis which provides a relativistic *ab initio* calculation of the ground-state properties of finite nuclei without any free parameters [17]. By investigating the neutron drops confined in an external field, systematic and specific pattern due to the effects of the tensor forces is found in the evolution of spin–orbit splittings in neutron drops [18, 19]. The effects of the tensor forces on the evolution of spin–orbit splitting provide valuable guidance for the development of the state-of-the-art density functional theories (DFTs) [1, 2, 20–22]. The RBHF theory has been applied to investigate the spin symmetry in the Dirac sea [23], total masses and radii of neutron stars [24], and nuclear matter [25]. The symmetry energies at supra-saturation densities and neutron drop investigated with both *ab initio* RBHF and state-of-the-art density functional theories (DFTs) have been given in details in Ref. [15].

For asymmetric nuclear matter, the binding energy per nucleon can be generally expressed as a power series in the asymmetry parameter $\alpha = (\rho_n - \rho_p)/\rho$, where the total density $\rho = \rho_n + \rho_p$ with the neutron density ρ_n and proton density ρ_p

$$E(\rho, \alpha) = E(\rho, 0) + E_{\rm sym}(\rho)\alpha^2 + \mathcal{O}(4)\,, \tag{1}$$

where $E(\rho, 0)$ is the binding energy per nucleon for symmetric nuclear matter and $E_{\rm sym}(\rho)$ is the symmetry energy

$$E_{\rm sym}(\rho) = \frac{1}{2}\frac{\partial^2 E(\rho,\alpha)}{\partial\alpha^2}\bigg|_{\alpha=0}\,. \tag{2}$$

In Ref. [15], based on *ab initio* RBHF theory and state-of-the-art DFTs, strong correlations are found among the neutron star tidal deformability, the neutron star radius, the root-mean-square radii of neutron drops, and the symmetry energies of nuclear matter at twice saturation density. From these correlations and the upper limit on the tidal deformability extracted from GW170817, the symmetry energy at twice saturation density are constrained.

The symmetry energy of nuclear matter at twice saturation density $E_{\rm sym}(2\rho_0)$ and the r.m.s. radii $R_{\rm nd}$ of 20 neutrons in a harmonic oscillator with $\hbar\omega = 25$ MeV are calculated by the *ab initio* theory and DFTs. *Ab initio* calculations were carried out with the RBHF theory using the

Bonn potentials [25, 26]. The adopted DFTs range from nonrelativistic models (*e.g.*, SLy4 and those starting with S) [27], to relativistic models with the nonlinear meson exchange functionals (NL models, PK1, TM1), as well as the density-dependent meson exchange ones (DD-ME and RHF models, PKDD, TW99) [28, 29]. As shown in Fig. 1 (modified from Ref. [15]), the predictions from DFTs span a fairly wide range of the neutron drop radii $R_{\rm nd}$ because the isovector channels of DFTs are loosely determined in the fitting procedures.

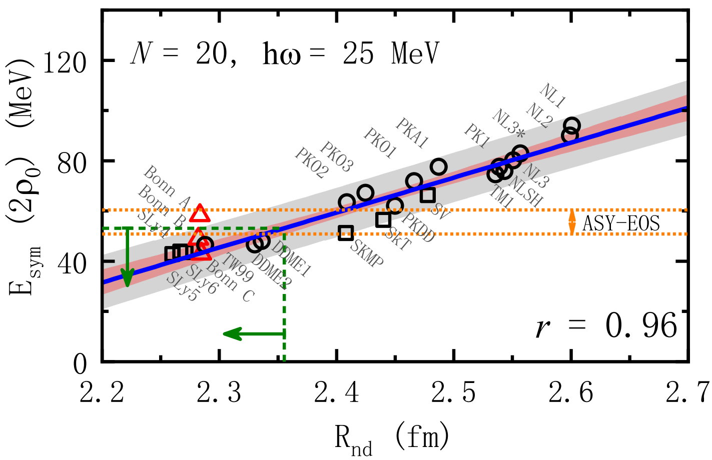

Fig. 1. (Color online) Correlations between the symmetry energy at twice saturation density and r.m.s. radii of 20 neutrons in a HO with $\hbar\omega = 25$ MeV, calculated by relativistic (circles), nonrelativistic (squares) density functional theories and *ab initio* methods (triangles). The thick black/blue line is the fit to the results of density functionals, and the inner (outer) colored regions depict the 95% confidence (prediction) intervals of the linear regression. The upper limit $R_{\rm nd} \leq 2.36$ fm deduced from the tidal deformability is shown with the horizontal arrow, which gives rise to an upper limit $E_{\rm sym}(2\rho_0) \leq 53.2$ MeV labeled with the vertical arrow. Modified from Ref. [15].

A strong correlation between $E_{\rm sym}(2\rho_0)$ and the neutron drop radius $R_{\rm nd}$ is established and Pearson's coefficient is $r = 0.96$ by fitting the DFTs results. This strong correlation is universal since it is based on widely different nuclear density functionals. Furthermore, the correlation predicted by DFTs is supported by the *ab initio* RBHF theory. It indicates that the neutron drop radii could set an important constraint on the symmetry energy at twice saturation density. The constraint $R_{\rm nd} \leq 2.36$ fm [15] deduced from neutron star tidal deformability gives $E_{\rm sym}(2\rho_0) \leq 53.2$ MeV, which is consistent with the recent ASY-EOS experimental results 50.8 MeV

$\leq E_{\rm sym}(2\rho_0) \leq 60.4$ MeV [30] and the predictions by *ab initio* RBHF theory. Accordingly, the ambiguity of the symmetry energy predicted at twice saturation density is remarkably reduced, and reveal a soft symmetry energy in the regime of high density.

3. Summary and perspective

In this contribution, a recent work motivated by the historical detection of gravitational waves from GW170817 on the symmetry energies of nuclear matter at supra-saturation densities by the *ab initio* Relativistic Brueckner–Hartree–Fock calculations as well as the nonrelativistic and relativistic state-of-the-art density functional theories is reviewed. By investigating the neutron star and the neutron drop, strong correlations are found between the neutron star tidal deformability and the symmetry energies of nuclear matter at supra-saturation densities. From the correlations and the upper limit on the tidal deformability extracted from GW170817, the symmetry energy at twice saturation density is constrained $E_{\rm sym}(2\rho_0) \leq 53.2$ MeV, which is consistent with the recent ASY-EOS experimental results and *ab initio* RBHF theory.

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