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Probing Nuclear Symmetry Energy and its Imprints on Properties of Nuclei, Nuclear Reactions, Neutron Stars and Gravitational Waves

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Abstract. Significant progress has been made in recent years in constraining nuclear symmetry energy at and below the saturation density of nuclear matter using data from both terrestrial nuclear experiments and astrophysical observations. However, many interesting questions remain to be studied especially at supra-saturation densities. In this lecture note, after a brief summary of the currently available constraints on nuclear symmetry energy near the saturation density we first discuss the relationship between the symmetry energy and the isospin and momentum dependence of the single-nucleon potential in isospin-asymmetric nuclear medium. We then discuss several open issues regarding effects of the tensor force induced neutron-proton short-range correlation (SRC) on nuclear symmetry energy. Finally, as an example of the impacts of nuclear symmetry energy on properties of neutron stars and gravitational waves, we illustrate effects of the high-density symmetry energy on the tidal polarizability of neutron stars in coalescing binaries.

1. Introduction
The Equation of State (EOS) of neutron-rich nucleonic matter can be written within the parabolic approximation in terms of the binding energy per nucleon at density $\rho$ as

$$E(\rho, \delta) = E(\rho, \delta = 0) + E_{\text{sym}}(\rho)\delta^2 + O(\delta^4),$$

where $\delta \equiv (\rho_n - \rho_p)/(\rho_p + \rho_n)$ is the neutron-proton asymmetry and $E_{\text{sym}}(\rho)$ is the density-dependent nuclear symmetry energy. The latter is among the most uncertain properties of dense, neutron-rich nucleonic matter. It has important ramifications for many interesting questions in both astrophysics and nuclear physics. Thanks to the hard work of many people in both astrophysics and nuclear physics communities, significant progress has been made in recent years in constraining the density dependence of nuclear symmetry energy using data from both terrestrial nuclear experiments and astrophysical observations. A deeper understanding about the underlying physics governing the density dependence of nuclear symmetry energy was also obtained from various theoretical studies. However, many challenging questions remain to be answered. As an illustration of our current understanding about nuclear symmetry
Figure 1. Density slope versus the magnitude of the symmetry energy at saturation density extracted from analyzing terrestrial experiments (left window) and astrophysical observations (right window). The analyses of terrestrial experiments include (1) analyses of isospin diffusion experiments with $^{124}$Sn+$^{112}$Sn at 50 MeV/A within the Isospin-Dependent Boltzmann-Uehling-Ulenbeck (IBUU04-2005)[1, 2], (2) the isospin diffusion and neutron/proton ratio of pre-equilibrium nucleon emissions in $^{124}$Sn+$^{112}$Sn reactions at 50 MeV/A within the Improved Molecular Dynamics (ImQMD-2009) model [3, 4, 5], (3) $^{124}$Sn+$^{112}$Sn reactions at 35 MeV/A within the Improved Molecular Dynamics (ImQMD-2010) model [6], (4) isoscaling (isoscaling-2007) [7], (5) energy shift of isobaric analogue states within liquid drop model (IAS+LDM-2009)[8], (6) neutron-skins of several heavy nuclei using the droplet model (DM+n-skin (2009))[9, 10], or the Skyrme-Hartree-Fock (SHF+n-skin) approach [11], or the phenomenological approach (n-skin 2012) [12], (7) pygmy dipole resonances (PDR 2007 and 2010) in $^{209}$Pb, $^{68}$Ni and $^{132}$Sn [13, 14], (8) the nucleon global optical potentials (Optical Pot. 2010) [15], (9) atomic masses analyzed by Myers and Swiatecki using the Thomas-Fermi model (TF+Nucl. Mass (1996) [16], (10) atomic masses analyzed by Möller et al. using the finite-range droplet model (FRDM) [17], (11) atomic masses analyzed by Liu et al. (Nucl. Mass (2010) [18], (12) atomic masses analyzed by Lattimer and Lim (Nucl. Mass (2012) [19], (13) Anti-symmetrized Molecular Dynamics (AMD) analyses of transverse flow of inter mediate mass fragments (Trans. Flow (2010)) [20], (14) empirical value of the symmetry energy at $\rho = 0.1\,\text{fm}^{-3}$ ($E_{\text{sym}}(\rho = 0.1\,\text{fm}^{-3})$ (2011) [21]. The analyses of astrophysical observations include (15) the mass-radius correlation of neutron stars (NSstar analysis1 and analysis2) [22, 23], (16) gravitational binding energy of neutron stars (Newton & Li; 2009) [24], (17) torsional oscillations of neutron star crust analyzed by Gearheart et al. [25] and Sotani et al. [26], (18) the r-mode instability of neutron stars analyzed by Wen et al. [27] and Vidana [28]. Similar plots from selecting different sets of constraints available in the literature at the time can be found in Refs. [15, 29, 30, 31].
energy near saturation density $\rho_0$, shown in Fig. 1 are the available constraints on the slope $L(\rho_0) \equiv 3\rho \frac{\partial E_{\text{sym}}(\rho)}{\partial \rho} \bigg|_{\rho_0}$ versus symmetry energy $E_{\text{sym}}(\rho_0)$ at $\rho_0$ from analyses of both terrestrial nuclear experiments and astrophysical observations. Besides experimental error bars, there are some model dependences in most analyses and not all model assumptions are equally valid. Even assuming all published results are equally physical, given the still widely scattered constraints it is difficult to calculate a community-average of the $E_{\text{sym}}(\rho_0)$ and $L(\rho_0)$ with physically meaningful error bars at this time. With all due respects to conclusions others may have drawn, in our obviously biased opinion, $E_{\text{sym}}(\rho_0) = 31 \pm 2$ MeV and $L(\rho_0) = 50 \pm 20$ MeV are probably the best empirical values with the optimistic error bars we can currently conclude.

In the following, using three examples we illustrate some recent progress in understanding the underlying physics governing the density dependence of nuclear symmetry energy, why the symmetry energy is still very uncertain, and how to probe the high density behavior of nuclear symmetry energy. The materials presented here are mostly taken from our recent work published originally in Refs. [15, 25, 32, 33, 34, 35, 36, 37, 38, 39, 40].

2. The relationship between nuclear symmetry energy and single-nucleon mean-field potential

What is the direct relationship between the symmetry energy and the isoscalar and isovector parts of the single-nucleon potential $U_{n/p}(\rho, \delta, k)$? An answer to this question helps us better understand why the symmetry energy is still very uncertain. To our best knowledge, this question was first studied by Brueckner, Dabrowski and Haensel [41, 42, 43, 44] using K-matrices within the Brueckner theory in the 1960’s. More recently, it was studied by Xu et al. [33] and Chen et al. [34] using the Hugenholtz-Van Hove (HVH) theorem [45]. This is an important question for several reasons. First of all, in both nuclear physics and astrophysics, one of the ultimate goals is to understand the isospin dependence of strong interaction. Both the symmetry energy and the single-particle potential are determined by the same underlying strong interaction. Their relationship can thus help us better understand why the symmetry energy is still very uncertain, and connect with the QCD theory of nuclear strong interaction.

Theoretically, one usually derives both the single-nucleon potential and the symmetry energy from a model energy density functional constrained by empirical properties of nuclear matter and finite nuclei. However, the single-nucleon potential is often the one directly tested by comparing model calculations with experimental data. For example, the single-particle potential is the input for shell model calculations of nuclear structure and transport model simulations of nuclear reactions. Therefore, being able to know directly the corresponding symmetry energy from the single-particle potential without first going through the procedure of constructing the energy density functional is advantageous. For example, from nucleon-nucleus scattering and (p, n) charge exchange experiments one can directly extract from the data both the isoscalar and isovector nucleon optical potentials at normal density. One can then easily calculate the symmetry energy and its density slope at normal density directly from the optical potentials as demonstrated recently in Ref. [15].

According to the well-known Lane potential [46], the neutron/proton single-particle potential $U_{n/p}(\rho, k, \delta)$ can be well approximated by

$$U_{n/p}(\rho, k, \delta) \approx U_0(\rho, k) \pm U_{\text{sym}}(\rho, k)\delta,$$

where the $U_0(\rho, k)$ and $U_{\text{sym}}(\rho, k)$ are, respectively, the isoscalar and isovector (symmetry) potentials for nucleons with momentum $k$ in nuclear matter of isospin asymmetry $\delta$ at density $\rho$. It has been shown that the nuclear symmetry energy can be explicitly expressed as
where $t(k) = \hbar^2 k^2 / 2m$ is the kinetic energy and $k_F = (3\pi^2 \rho / 2)^{1/3}$ is the nucleon Fermi momentum in symmetric nuclear matter at density $\rho$. The slope of nuclear symmetry energy at an arbitrary density $\rho$ can be written as [15, 33, 34]

$$L(\rho) = 3\rho \frac{\partial E_{\text{sym}}(\rho)}{\partial \rho}\bigg|_{\rho} = \frac{1}{6} \left. \frac{\partial (t + U_0)}{\partial k} \right|_{k_F} \cdot k_F + \frac{1}{2} \left. \frac{\partial^2 (t + U_0)}{\partial k^2} \right|_{k_F} \cdot k_F^2 + \frac{3}{2} \left. U_{\text{sym}}(\rho, k_F) \right|_{k_F} \cdot k_F + \frac{1}{6} \left. \frac{\partial U_{\text{sym}}}{\partial k} \right|_{k_F} \cdot k_F.$$  

Moreover, the relative neutron-proton effective mass is

$$\frac{m_n^* - m_p^*}{m} = -2\hbar^2 \frac{m}{\hbar^2 k_F} \frac{dU_{\text{sym}}}{dk} \bigg|_{k_F} \left[ 1 + 2 \left( \frac{m}{\hbar^2 k_F} \frac{dU_0}{dk} \bigg|_{k_F} \right) \right].$$

We emphasize that this relationship is valid only at the mean-field level. Taking into account the tensor force induced neutron-proton short range correlation, the kinetic part of the symmetry energy might be reduced significantly from the Fermi gas model prediction as we shall discuss in detail in the next section. The above expressions for $E_{\text{sym}}(\rho)$ and $L(\rho)$ in terms of the isoscalar and isovector single-particle potentials are particularly useful for extracting the symmetry energy and its density slope from terrestrial nuclear laboratory experiments. While the density and momentum dependence of the isoscalar potential $U_0(\rho, k)$ has been relatively well determined up to about 4 to 5 times the normal nuclear matter density $\rho_0$ using nucleon global optical potentials from nucleon-nucleus scatterings as well as kaon production and nuclear collective flow in relativistic heavy-ion collisions [47, 48], our current knowledge about the symmetry potential $U_{\text{sym}}(\rho, k)$ is rather poor especially at high density and/or momenta [40, 49, 50, 51, 52, 53]. Experimentally, there is some constraints on the symmetry potential only at normal density from low energy nucleons up to about 100 MeV obtained from nucleon-nucleus and (p, n) charge exchange reactions [15]. Shown in the left window of Fig. 2 are all the energy dependent symmetry potentials in the literature [15]. Assuming that these various global energy dependent symmetry potentials are equally accurate and all have the same predicting power beyond the original energy ranges in which they were analyzed, an averaged symmetry potential of

$$U_{\text{sym}}(\rho_0, E) = 22.75 - 0.21E$$

was obtained (thick solid line in the left window of Fig. 2). It represents the best fit to the global symmetry potentials constrained by the world data up to date. With this best estimate for the $U_{\text{sym}}(\rho_0, E)$, Xu et al. found that $E_{\text{sym}}(\rho_0) = 31.3 \pm 4.5$ MeV and $L(\rho_0) = 52.7 \pm 22.5$ MeV. Shown in the right window of Fig. 2 are the various contributions to the $E_{\text{sym}}(\rho_0)$ and $L(\rho_0)$. The $E_{\text{sym}}(1) = \frac{1}{2} \hbar^2 k_F^2$ denotes the kinetic energy term with the effective mass $m_0^*$ and the $E_{\text{sym}}(2) = \frac{1}{2} U_{\text{sym}}(\rho_0, k_F)$ is the symmetry potential contribution. It is seen that the two terms are comparable. Their respective uncertainties are marked by the red boxes. The $L(\rho_0)$ has three terms: $L(1) = \frac{2}{3} \hbar^2 k_F^2$, $L(2) = \frac{1}{2} U_{\text{sym}}(\rho_0, k_F)$ and $L(3) = \left. \frac{\partial U_{\text{sym}}(\rho, k_F)}{\partial k} \right|_{k_F} k_F$. While both the $L(1)$
and $L(2)$ are positive, the $L(3)$ is negative because of the decreasing symmetry potential with increasing energy. To our best knowledge, extracting the symmetry energy and its density slope directly from the optical potential is probably the most straightforward approach available in the literature. However, the major challenge of using this approach is our poor knowledge about the momentum dependence of the isovector potential. From the symmetry potential given in Eq. \[(6)\], Xu et al. extracted a neutron-proton effective mass splitting of $(m_n^* - m_p^*)/m = (0.32 \pm 0.15)\delta$. Interestingly, from the dispersive optical model analysis of some new data on neutron-nucleus scattering, R. Charity recently also found a value of $(m_n^* - m_p^*)/m = 0.32\delta$ with an error bar to be determined \[54\]. The extracted constraint on $E_{sym}(\rho_0)$ versus $L(\rho_0)$ from the global nucleon optical potentials are compared with constraints extracted from other approaches \[31\] in Fig. 1. It is consistent with the ones from most other approaches.

3. Effects of tensor force induced neutron-proton short-range correlation on nuclear symmetry energy

From Fig. 1 and the related references, it is clear that there are still appreciable uncertainties about the density dependence of nuclear symmetry energy even around the saturation density. Moreover, at supra-saturation densities, even the tendency of the symmetry energy remains controversial \[40\]. So, why is the nuclear symmetry energy, especially at supra-saturation densities, so uncertain? Of course, the answer itself is model dependent. Generally, besides our poor knowledge about the isospin dependence of strong interaction in dense neutron-rich medium, different approaches used in treating nuclear many-body problems in various models contribute to the divergence of the predicted symmetry energy especially at supra-saturation densities. Nonetheless, there are several key and commonly used physics ingredients that can affect the predicted $E_{sym}(\rho)$ in all theories. For instance, the symmetry energy has a kinetic part. Often, it is assumed to be the one predicted by the free Fermi gas model, i.e., $E_{sym}^{kin}(FG) (\rho) \equiv (2^2 - 1) \frac{k^2}{5} \frac{\rho}{2m} \approx 12.5(\rho/\rho_0)^{2/3}$. Interestingly, it was first found recently within a phenomenological model \[55\] that the tensor force induced high momentum tail in the single-nucleon momentum distribution in symmetric nuclear matter (SNM) reduces significantly the $E_{sym}^{kin}(\rho)$ to values much smaller than the $E_{sym}^{kin}(FG) (\rho)$. In fact, the $E_{sym}^{kin}(\rho)$ can become zero or even negative if more than about 15% nucleons populate the high-momentum tail above the Fermi surface as indicated by the recent experiments done at the Jefferson National Laboratory.

Figure 2. Left Window: Energy dependence of the nuclear symmetry potential $U_{sym}(\rho, E)$ at normal density from different global optical model fits. The solid lines are in the energy ranges where the original analyses were made while the dashed parts are extrapolations. Right Window: The magnitude of each term in the nuclear symmetry energy $E_{sym}(\rho_0)$ and its density slope $L(\rho_0)$ at normal nuclear density. Taken from Ref. \[15\].
(J-Lab) by the CLAS Collaboration \cite{56}. This finding was recently confirmed qualitatively by three independent studies using the state-of-the-art microscopic many-body theories \cite{57, 58, 59}. As discussed in detail by Xu et al. in Ref. \cite{55}, the high momentum tail in SNM increases the

![Figure 3.](image)

**Figure 3.** Left Window: The average kinetic energy per nucleon $E_{\text{kin}}$ for pure neutron matter and symmetric nuclear matter with different percentages of correlated nucleons ($\theta_{k>k_F}$) as a function of Fermi momentum. Right Window: The kinetic energy part of nuclear symmetry energy with different percentages of correlated nucleons ($\theta_{k>k_F}$) as a function of Fermi momentum. Taken from Ref. \cite{55}.

average kinetic energy of nucleons to values above the free Fermi gas model prediction. While in PNM (pure neutron matter), the Fermi gas prediction is a good approximation. Shown in the left window of Fig. 3 is the the average kinetic energy as a function of Fermi momentum for PNM and SNM with the percentage of high momentum nucleons to be $\theta_{k>k_F} = 0\%$, $5\%$, $10\%$, $15\%$, and $20\%$, respectively. As one expects, the SRC increases the $E_{\text{kin}}$ significantly for SNM. More quantitatively, for SNM at the saturation density corresponding to $k_F = 1.33$ fm$^{-1}$, the $E_{\text{kin}}$ with $\theta_{k>k_F} = 20\%$ ($E_{\text{kin}}(k_F) \approx 40$ MeV) is about twice of that ($E_{\text{kin}}(k_F) \approx 22$ MeV) for the free Fermi gas. However, the $E_{\text{kin}}$ for PNM is the same as for the free Fermi gas. Consequently, the tensor force induced high momentum tail in SNM affects the kinetic part of the nuclear symmetry energy. In particular, if about 15% nucleons in SNM are in the high momentum tail, it is seen that the average kinetic energy is about the same in PNM and SNM. This leads to an approximately zero kinetic symmetry energy as shown in the right window of Fig. 3. In many studies in both nuclear physics and astrophysics, it is customary to write the total symmetry energy as $E_{\text{sym}}(\rho) = 12.5(\rho/\rho_0)^{2/3} + E_{\text{sym}}^{\text{pot}}(\rho)$ where the first term is the Fermi gas prediction for the $E_{\text{sym}}^{\text{kin}}(\rho)$ and the $E_{\text{sym}}^{\text{pot}}(\rho)$ is the potential contribution. In doing so, however, one neglects completely effects of the tensor force on the $E_{\text{sym}}^{\text{kin}}(\rho)$. For example, in transport model analyses of heavy-ion reactions, the $E_{\text{sym}}^{\text{pot}}(\rho)$ is normally parameterized as a function of density. The corresponding single-particle potential based on some energy density functions is used as input to transport models. Thus, heavy-ion reactions test directly the single nucleon potential. The kinetic part of the symmetry energy based on the Fermi gas model prediction is normally added by hand to the $E_{\text{sym}}^{\text{pot}}(\rho)$ in fixing parameters in the EOS. The results shown in Fig. 3 raise serious questions about this practice. Moreover, many interesting questions regarding effects of the tensor-force induced isospin dependence of short-range nucleon-nucleon correlations and the uncertain short-range behavior of tensor force due to the $\rho$ meson exchange on the density dependence of nuclear symmetry energy remain to be studied more systematically and self-consistently \cite{32, 60, 61}.
4. Probing the high-density symmetry energy with the tidal polarizability of neutron stars

The high-density behavior of nuclear symmetry energy has long been regarded as the most uncertain property of dense neutron-rich nucleonic matter [40, 62, 63]. While several observables have been proposed [40] and some indications of the high-density symmetry energy have been reported based on terrestrial nuclear experiments [64, 65], unfortunately, the conclusions remain controversial. Interestingly, it was recently proposed that the late time neutrino signal from a core collapse supernova [66] and the tidal polarizability [39] of canonical neutron stars in coalescing binaries are very sensitive probes of the high-density behavior of nuclear symmetry energy. Coalescing binary neutron stars are among the most promising sources of gravitational waves (GW). One of the most important features of the binary mergers is the tidal deformations of neutron stars, which give us precious information about the neutron-star matter EOS [67, 68, 69, 70, 71, 72, 73, 74]. At the early stage of an inspiral tidal effects may be effectively described through the tidal polarizability parameter \( \lambda \) [67, 68, 69, 72] defined via \( Q_{ij} = -\lambda \delta_{ij} \), where \( Q_{ij} \) is the induced quadrupole moment of a star in binary, and \( \delta_{ij} \) is the static external tidal field of the companion star. As an example, shown in the left window of Fig. 4 are two models chosen to have the same EOSs for both SNM and PNM using the IU-FSU RMF model and the SHF using the SkIU-FSU parameter set [38], i.e., they have the same symmetry energy at and below the saturation density. At supra-saturation densities, however, the symmetry energy with the IU-FSU RMF is significantly more stiff above about 1.5\( \rho_0 \). It is seen from the right window of Fig. 4 that the two models predict significantly different polarizability (\( \lambda \)) values in a broad mass range from 0.5 to 2\( M_\odot \). More quantitatively, for a canonical neutron star of 1.4\( M_\odot \), a 41.41\% change from \( \lambda = 2.828 \times 10^{36} \) (IU-FSU) to \( \lambda = 1.657 \times 10^{36} \) (SkIU-FSU) is observed. As it was discussed in detail in Ref. [39], the observed symmetry energy effect on the tidal polarizability is as strong as its effect on the late time neutrino flux from the cooling of proto-neutron stars [66]. Moreover, it is interesting to note that the narrow uncertain range for the proposed Einstein Telescope will enable it to tightly constrain the symmetry energy.
especially at supra-saturation densities.

5. Summary

In summary, significant progress has been made in recent years in constraining the symmetry energy mostly around and below the saturation density using both terrestrial nuclear laboratory data and astrophysical observations. However, to fully understand the nature of neutron-rich nucleonic matter and its equation of state especially at supra-saturation densities many interesting questions remain to be studied. In particular, the high-density behavior of the symmetry energy is still among the most uncertain properties of neutron-rich matter. Besides continuing the search of sensitive observables in terrestrial experiments and astrophysical observations, it is important to understand the underlying physics leading to the divergent predictions for the high-density symmetry energy. In particular, effects of the tensor-force induced short-range neutron-proton correlation and the short-range behavior of the tensor force itself on the high-density behavior of the symmetry energy deserve some special attention. Given the strong ongoing efforts and close collaborations of many people in both the nuclear physics and astrophysics communities, it is expected that more stringent constraints on the symmetry energy over a broad density range will come soon.

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