

Nuclear symmetry energy: An experimental overview

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Abstract. The nuclear symmetry energy is a fundamental quantity important for studying the structure of systems as diverse as the atomic nucleus and the neutron star. Considerable efforts are being made to experimentally extract the symmetry energy and its dependence on nuclear density and temperature. In this article, the experimental studies carried out up-to-date and their current status are reviewed.

Keywords. Symmetry energy; density dependence; nuclear matter.

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1. Introduction

The nuclear matter symmetry energy, which is defined as the difference in energy per nucleon between the pure neutron matter and the symmetric nuclear matter, is an important quantity that determines the properties of objects such as the atomic nucleus and the neutron star [1]. The study of symmetry energy and its dependence on nuclear density and temperature is currently a subject of great interest [2]. Theoretically, the symmetry energy can be determined from microscopic calculations such as the Brueckner–Hartree–Fock (BHF) and the Dirac–Brueckner–Hartree–Fock (DBHF) calculations, or the phenomenological calculations such as the Skyrme Hartree–Fock (SHF) and the relativistic mean field (RMF) calculations [1]. These calculations currently predict wide range of symmetry energies for densities below and above normal nuclear density, $\rho_0 = 0.16 \text{ fm}^{-3}$ (figure 1). Experimentally, the symmetry energy is not a directly measurable quantity and has to be extracted indirectly from observables that are related to the symmetry energy. The experimental determination of the symmetry energy is therefore dependent on how reliable the model that describes the experimental observable is. So far, there has been very few experimental determination of the symmetry energy. These experimental studies are of two types:

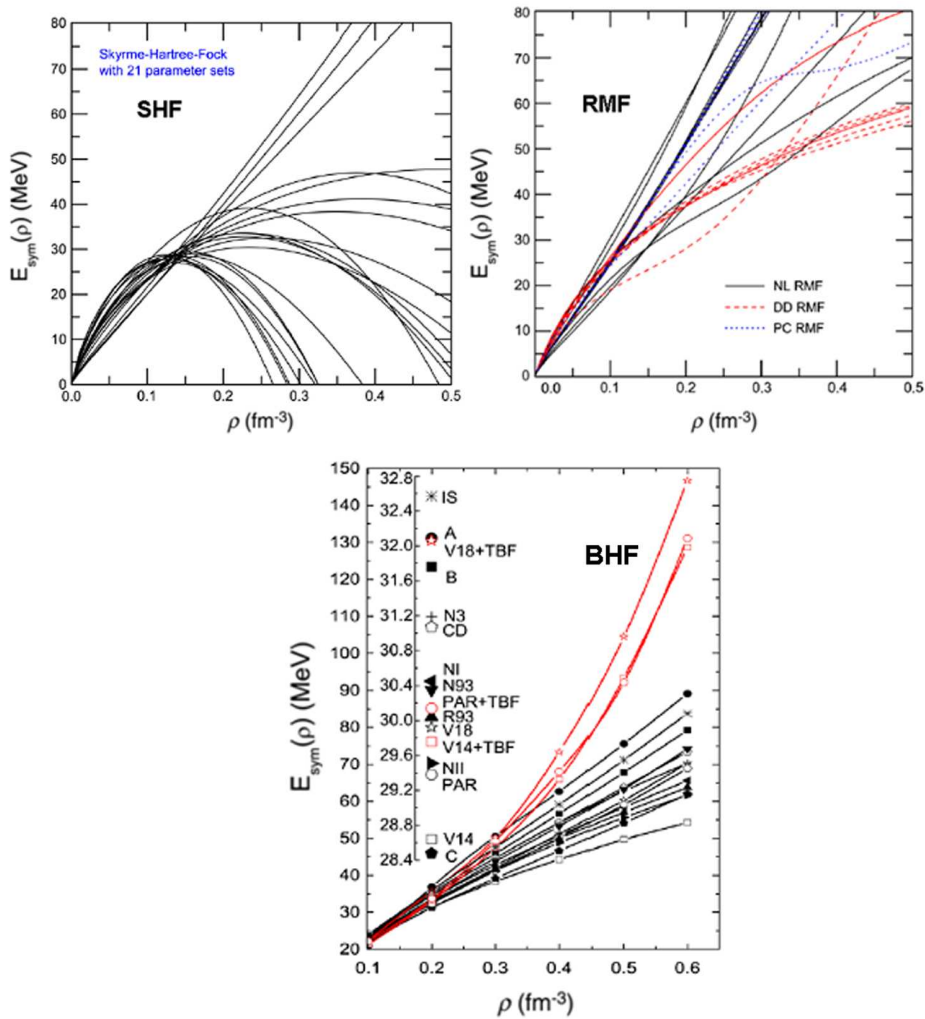


Figure 1. Density dependence of the symmetry energy as predicted by various theoretical calculations [1].

1. Where, a certain form of the density dependence of the symmetry energy is assumed in the theoretical calculation and the experimental observable reproduced using the dependence that best explains the data. Such studies [3–10] often make use of dynamical models such as the isospin Boltzmann Uehling Uhlenbech (IBUU04) [10], the improved quantum molecular dynamics (ImQMD) [11] and the antisymmetrized molecular dynamics (AMD) [12], to relate the symmetry energy to the experimental observable. The disadvantage in such studies is that they assume a single form of the symmetry energy for all densities, which may not be true. Such studies provide only a gross dependence of the symmetry energy without much insight into its evolution

with the density. Also, these studies are highly model-dependent as will be discussed in a later section.

2. Where, the form of the density dependence of the symmetry energy is not known *a priori* and the symmetry energy is studied by mapping its value at each density. Such studies [7,13,14] require a detailed understanding of the relation between the symmetry energy, excitation energy, density and temperature. They make use of the statistical multifragmentation model (SMM) [15,16] to relate the symmetry energy to the experimental observable. The advantage in such studies is that they provide a 'direct' means of studying the symmetry energy with density and temperature that can then be compared with any theoretical predictions. The difficulty in such studies is often the theoretical interpretation of the symmetry energy.

In this article, recent experimental studies on the symmetry energy and its density dependence obtained using the above two approaches are reviewed.

2. Nuclear matter symmetry energy below saturation density ($0.3\rho_0 \leq \rho \leq \rho_0$)

The symmetry energy below saturation density has been studied in heavy-ion multifragmentation reactions using fragments with $A > 4$. Observables such as the fragment yield, isoscaling parameter, isospin diffusion transport ratio, double neutron-proton ratio and $\langle N \rangle / Z$ have been used to extract the symmetry energy.

2.1 Symmetry energy from dynamical multifragmentation model comparison

The symmetry energy in this density region has been studied by comparing the experimental observables with the dynamical model calculations. Chen *et al* [4] compared the NSCL-MSU isospin diffusion data from $^{124}\text{Sn} + ^{112}\text{Sn}$ reaction at 50 MeV/A with the dynamical IBUU04 [10] calculation, and obtained a symmetry energy of the form, $E_{\text{sym}}(\rho) = 31.6(\rho/\rho_0)^\gamma$ with $\gamma = 1.05$. The NSCL-MSU isospin data were also compared with the IBUU04 by Li and Chen [5], that included the isospin dependence of the in-medium nucleon-nucleon cross-section, giving a symmetry energy of the form, $E_{\text{sym}}(\rho) = 31.6(\rho/\rho_0)^\gamma$ with $\gamma = 0.69$. Shetty *et al* [3,6,7] extracted the symmetry energy by comparing the isoscaling parameters from ^{40}Ar , $^{40}\text{Ca} + ^{58}\text{Fe}$, ^{58}Ni and ^{58}Fe , $^{58}\text{Ni} + ^{58}\text{Fe}$, ^{58}Ni reactions with the dynamical AMD model calculation [12], resulting in a symmetry energy, $E_{\text{sym}}(\rho) = 31.6(\rho/\rho_0)^\gamma$ with $\gamma = 0.69$. Famiano *et al* [8] studied the symmetry energy by comparing the experimental double neutron to proton ratio in $^{112}\text{Sn} + ^{112}\text{Sn}$ and $^{124}\text{Sn} + ^{124}\text{Sn}$ reactions with the BUU97 calculation [17] and obtained a symmetry energy, $E_{\text{sym}}(\rho) = 32(\rho/\rho_0)^\gamma$ with $\gamma = 0.5$. More recently, Tsang *et al* [9] compared the isospin diffusion and the neutron to proton double ratio for $^{124}\text{Sn} + ^{112}\text{Sn}$ reaction at 50 MeV/A with the ImQMD calculation [11] and obtained a symmetry energy of the form, $E_{\text{sym}}(\rho) = 12.5(\rho/\rho_0)^{2/3} + 17.6(\rho/\rho_0)^\gamma$ with $\gamma = 0.4-1.05$. The functional

dependence of the symmetry energy obtained from all these comparisons are very similar to each other.

It must be mentioned that while both the IBUU04 and ImQMD comparisons lead to similar form of the density dependence of the symmetry energy for the isospin diffusion observable, the IBUU04 fails to adequately explain the neutron-to-proton ratio [18]. Furthermore, these comparisons lead to very different results for densities above saturation density [19,20] (as discussed in §5). The determination of the symmetry energy from the dynamical model comparison is therefore highly model-dependent, and the assumption of a single form of the symmetry energy at different densities questionable.

2.2 Symmetry energy from statistical multifragmentation model comparison

The symmetry energy has also been studied by comparing the experimental observables with the statistical multifragmentation model (SMM) calculation [15] in this density region. In multifragmentation, a nucleus expands with increasing excitation energy and its equilibrium density is reduced from the ground state density. Such a decrease should essentially map the density dependence of the symmetry energy. A detailed understanding of the relationship between excitation energy, density and temperature is however required. An attempt has recently been made by Shetty *et al* [7,13] from the study of isoscaling parameters in ^{58}Fe , $^{58}\text{Ni} + ^{58}\text{Fe}$, ^{58}Ni reactions at 30, 40 and 47 MeV/A. In this work, the symmetry energy was studied by correlating the experimentally observed decrease in the isoscaling parameter, density and the flattening of temperature (caloric curve), with the increase in excitation energy.

The decrease in the symmetry energy with increasing excitation energy was also observed in the fragmentation of excited target residues following $^{12}\text{C} + ^{124}\text{Sn}$, ^{112}Sn reactions at 300 and 600 MeV/A by Le Fevre *et al* [21]. It was also observed in ^{40}Ar , $^{40}\text{Ca} + ^{58}\text{Fe}$, ^{58}Ni reactions at 25, 33, 45 and 53 MeV/nucleon by Iglío *et al* [22], and by Shetty *et al* [3,23]. But in these work, a detailed understanding of the relation between temperature, excitation energy and nuclear density was not undertaken. Recently, Ogul *et al* [24] compared the MSU experimental isoscaling data ($\alpha = 0.36$ and $\beta = -0.39$) from ^{112}Sn , $^{124}\text{Sn} + ^{112}\text{Sn}$ reaction with the SMM calculation, and observed that a significant reduction of the symmetry energy is necessary to reproduce the experimental data. Geraci *et al* [25] studied $^{124}\text{Sn} + ^{64}\text{Ni}$ and $^{112}\text{Sn} + ^{58}\text{Ni}$ reactions at 35 MeV/A and observed a similar decrease in the symmetry energy with increasing excitation energy.

The reduction in the symmetry energy has also been observed in the projectile fragmentation of $^{64}\text{Ni} + ^{64}\text{Ni}$, $^{86}\text{Kr} + ^{64}\text{Ni}$, ^{124}Sn , ^{208}Pb reactions at 25 MeV/A using the observable $\langle Z/A \rangle$ by Souliotis *et al* [26,27]. More recently, Hudan *et al* [28] studied the projectile fragmentation in $^{124}\text{Xe} + ^{112}\text{Sn}$ reaction at $E/A = 30$ MeV and measured the $\langle N \rangle / Z$ and isotope distribution of fragments with $Z > 6$. They observed that a reduced value of the symmetry energy from 25 to 14 MeV was essential for explaining the data. They further showed that fragments with $Z > 6$ were even more sensitive to the variation in symmetry energy and could be an important probe for studying symmetry energy. A decrease in the symmetry energy

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was also implied by Wuenschel *et al* [29] in the study of $^{86,78}\text{Kr} + ^{64,58}\text{Ni}$ reactions at 35 MeV/A.

It has been argued [30] that the decrease in the symmetry energy to reproduce the experimental observables in these studies might not be necessary if the surface corrections to the symmetry energy were included in the mass parametrization used in the SMM model calculation. The possibility of the modification of symmetry energy and the surface energy coefficient of nuclear matter was studied recently by Ogul *et al* [24]. They found that the isoscaling parameters were affected very little by the surface energy variation and are very sensitive to the symmetry energy. A decrease in the symmetry energy is therefore essential to explain the experimental data. Ye *et al* [31] also studied the influence of the surface entropy on the isoscaling using the extended compound nucleus (ECN) model and found that although the surface entropy increased the numerical values of isoscaling parameters, it had only minor effect on the extracted symmetry energy. A clear theoretical interpretation of the symmetry energy in statistical model is therefore important.

2.3 Symmetry energy from other studies

The nuclear symmetry energy has also been studied from observables other than those studied using heavy-ion reactions. Centelles *et al* [32] have studied the symmetry energy using the experimental neutron skin measured in 26 antiprotonic atoms. Klimkiewicz *et al* [33] have studied the symmetry energy from correlation between the symmetry pressure and the symmetry energy using the properties of pygmy dipole resonance (PDR) in ^{208}Pb nuclei. Trippa *et al* [34] have studied the symmetry energy from the correlation between the symmetry energy and the experimental centroid energy of the giant dipole resonance (GDR) in ^{208}Pb nuclei. Khoa *et al* [35,36] have studied the symmetry energy from the folding model analysis of the charge exchange $p(^6\text{He}, ^6\text{Li})n$ reaction measured at 41.6 MeV/A. Danielewicz [37] has studied the symmetry energy by constraining the binding energy, neutron skin and the isospin analogue state of finite nuclei. The symmetry energy has also been studied by fitting the binding energy of 1654 nuclei using the Thomas-Fermi model of Myers and Swiatecki [38,39]. The results of these independent studies are shown in figures 2 and 3 and discussed in §4.

3. Nuclear matter symmetry energy below $\rho < 0.3\rho_0$

Symmetry energy at very low densities $(0.01-0.05)\rho_0$ has been studied by Kowalski *et al* [14] in heavy-ion collision of $^{64}\text{Zn} + ^{92}\text{Mo}$, ^{197}Au reactions at 35 MeV/A. It was shown that isoscaling analysis of the light clusters ($A \leq 4$) could be used to study the symmetry energy at such low densities. They observed that the experimental symmetry energy was somewhat higher than those expected from the mean-field calculations. At such low densities cluster formation became important and mean field calculations did not take into account such effects. Recently, Natowitz *et al* [40] have shown that the symmetry energy at such low densities could be explained by quantum statistical calculation that included cluster correlation in nuclear medium. At densities higher than $0.2-0.3\rho_0$, the many-body correlation disappeared and

the symmetry energy followed the dependence predicted by the mean-field calculations.

4. Current status of the density dependence of the symmetry energy for $\rho \leq \rho_0$

The symmetry energies obtained from the studies discussed above are as shown in figure 2. The orange box in the extreme left of figure 2 corresponds to the values of symmetry energy extracted by Kowalski *et al* [14] and Natowitz *et al* [40]. The green and the red solid points are the symmetry energies extracted from the correlation between temperature, density, isoscaling parameter and the excitation energy by Shetty *et al* [7,13]. The blue solid point in the figure corresponds to the symmetry energy obtained by constraining the experimental energy of giant dipole resonance (GDR) in ^{208}Pb by Trippa *et al* [34]. The square solid point in the figure corresponds to the symmetry energy obtained by fitting the experimental differential cross-section data in a charge exchange reaction using the isospin-dependent interaction of the optical potential by Khoa *et al* [35,36]. The green solid curve in the figure is the one obtained from the dynamical AMD model comparison of the experimental isoscaling data assuming the sequential decay effect to be small [3,6]. The symmetry energy extracted from the IBUU04 comparison of isospin diffusion results by Li and Chen [5], and the ImQMD comparison by Tsang *et al* [9] are similar to the green curve. The solid black curve is the symmetry energy extracted from the double neutron to proton ratio by Famiano *et al* [8], using the BUU97 model calculation. The red dashed curve corresponds to the one obtained from an accurately calibrated relativistic mean field calculation by Todd-Rutel and Piekarewicz [41] for describing the giant monopole resonance (GMR) in ^{90}Zr and ^{208}Pb , and the isovector giant dipole resonance (IVGDR) in ^{208}Pb . The shaded region in the figure corresponds to those obtained by constraining the binding energy, neutron skin thickness and isospin analogue state in finite nuclei using the mass formula by Danielewicz [37]. The yellow curve corresponds to the parametrization adopted in the studies of neutron star [42]. Current studies in the region, $0.3\rho_0 \leq \rho \leq \rho_0$, can therefore be parametrized by a ‘stiff’ form of the symmetry energy, $E_{\text{sym}}(\rho) = 31.6(\rho/\rho_0)^\gamma$, with $\gamma = 0.5\text{--}0.7$. This parametrization is in good agreement with the mean-field calculation. In the density region, $\rho < 0.3\rho_0$, the experimental symmetry energy is observed to deviate from the mean-field calculation due to the importance of cluster formation, and is in good agreement with the quantum statistic calculation [40].

The slope parameter, $L = 3\rho_0(\partial E_{\text{sym}}(\rho)/\partial\rho)$, is an alternate way of constraining the symmetry energy near saturation density, ρ_0 . Figure 3 shows the slope parameter L , obtained from various studies discussed above. These comparison results in a constraint of $30 < L < 80$ MeV for the symmetry energy slope at saturation density [32,43].

5. Nuclear matter symmetry energy above saturation density ($\rho > \rho_0$)

At densities higher than the normal nuclear matter density, the theoretically determined symmetry energy as a function of density is largely unconstrained.

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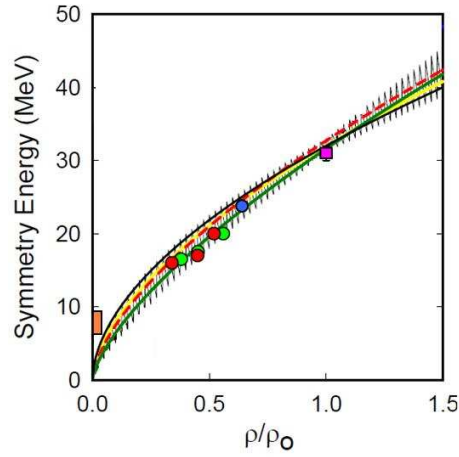


Figure 2. Density dependence of the symmetry energy extracted from different studies described in the text.

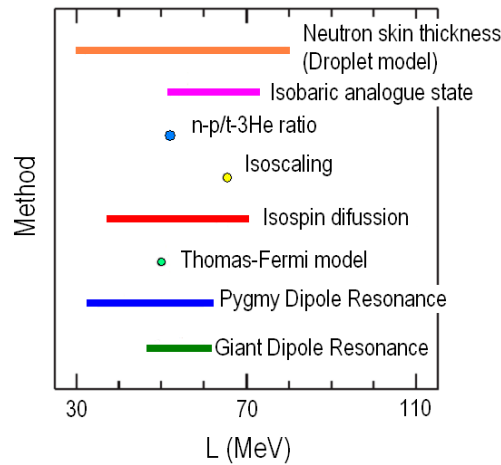


Figure 3. The slope parameter L , from various different observables as described in the text.

Experimental determination of the symmetry energies at such densities have been very few and they are all from dynamical model comparison. The results are highly model-dependent and contradicting. One observable that has recently been studied is the π^-/π^+ ratio in $^{40}\text{Ca} + ^{40}\text{Ca}$, $^{96}\text{Ru} + ^{96}\text{Ru}$, $^{96}\text{Zr} + ^{96}\text{Zr}$ and $^{197}\text{Au} + ^{197}\text{Au}$ reactions at GSI by the FOPI Collaboration [44]. A comparison [19] of these data with the transport model IBUU04 calculation shows that it can be reproduced with a ‘soft’ ($x = 1$) form of the density dependence of the symmetry energy. This is in contrast with those obtained from the low-density studies of the symmetry energy

where a ‘stiff’ ($x = 0$) form of the symmetry energy reproduced the data well. More recently, the π^-/π^+ GSI data were also compared with the ImQMD calculation by Feng *et al* [20]. The comparison favoured a much stiffer form of the symmetry energy than those obtained from the low-density studies, and in direct contradiction to those obtained from the IBUU04 model comparison. The symmetry energy results at such high densities are therefore currently controversial.

Another observable that has been suggested for probing the high-density behaviour of the symmetry energy is the relative and differential collective flow between triton and ^3He particles [45]. Preliminary calculation by Yong *et al* [45] suggested that a ‘stiff’ ($x = 0$) dependence of the symmetry energy would lead to a linear behaviour for the relative flow, whereas the ‘soft’ ($x = 1$) dependence would give a nonlinear behaviour with appreciable difference between the two. So it is expected that a measurement of this observable should provide important information on the high-density behaviour of the symmetry energy.

The theoretical determination of the symmetry energy at high density is a challenge. It is not known how reliable the dynamical model calculations can be at such high densities as it is not known how the quantum many-body effects can be treated in these calculations, or how the effects of spin–isospin for three-body force can be included. Also, the nuclear matter at such densities is not in a pure nucleonic state at thermodynamical equilibrium. The above comparison with the experimental data is therefore only a ‘circumstantial’ evidence [19] and much theoretical work needs to be done before a definitive conclusion can be reached.

6. How is the nuclear matter symmetry energy related to the symmetry energy of finite nuclei?

The symmetry energy of finite nuclei at saturation density is often extracted by fitting ground state masses with various versions of the liquid drop mass formula. For a finite nuclei it is important to decompose the symmetry term of liquid into bulk (volume) and surface contributions, and identify the volume symmetry energy coefficient as the symmetry energy derived from the nuclear matter at saturation density. Using the constraint obtained from the above studies on nuclear matter symmetry energy, the symmetry energy of a finite nucleus of mass A , $S_A(\rho)$, can be written as [13]

$$S_A(\rho) = \frac{\alpha(\rho/\rho_0)^\gamma}{1 + [\alpha(\rho/\rho_0)^\gamma/\beta A^{1/3}]}, \quad (1)$$

where $\alpha = 31\text{--}33$ MeV, $\gamma = 0.5\text{--}0.7$ and $\alpha/\beta = 2.6\text{--}3.0$. The quantities α and β are the volume and the surface symmetry energy at normal nuclear density. Presently, the values of α , γ and α/β remain unconstrained. The ratio of the volume symmetry energy to the surface symmetry energy (α/β), is closely related to the neutron skin thickness [37]. Depending upon how the nuclear surface and the Coulomb contribution is treated, two different correlations between the volume and the surface symmetry energy have been predicted [46] from fits to nuclear masses. Experimental masses and neutron skin thickness measurements for nuclei with $N/Z > 1$ should provide tighter constraint on the above parameters.

The above relation for the symmetry energy of finite nuclei has been compared [13] with the Thomas–Fermi calculation of Samaddar *et al* [47]. It was observed that this empirical relation compared very well with the Thomas–Fermi calculation for a wide range of nuclei. Future measurements of symmetry energy as a function of excitation energy for very light and heavy nuclei should provide further insight into the validity of this relation.

7. Future measurements of symmetry energy at rare isotope beam facilities

Currently, studies on the density dependence of the symmetry energy are being carried out using beams of stable nuclei. In order to study large isospin dependency, beams of neutron-rich nuclei are needed. A number of observables sensitive to the symmetry energy that can be experimentally tested has been suggested by Di Toro *et al* [2,48]. It is hoped that future facilities for rare isotope beams such as FRIB, FAIR and SPIRAL II should provide increased precision in the measurement of symmetry energy using these observables over a wide range of density. These facilities will allow studies to be carried out at 2–3 times the normal nuclear density.

New detectors such as the time projection chamber (TPC) at NSCL/MSU and the time projection chamber, SAMURAI at RIKEN/Japan are therefore being planned to study the symmetry energy and the nuclear equation of state. These detectors will significantly enhance our understanding of the nuclear symmetry energy and their relation to atomic nuclei and neutron stars.

8. Summary

In summary, the experimental determination of the nuclear symmetry energy is reviewed. It is observed that despite the model-dependent ways in which the symmetry energy is extracted, significant progress has been made. These studies are the first step in an effort to constrain the symmetry energy that is important for studying the structure of neutron stars and exotic nuclei. In the future, it is hoped that more measurements will be carried out where the symmetry energy is extracted for each densities and compared with theoretical calculations. These measurements using beams of neutron-rich nuclei and robust theoretical interpretation of the symmetry energy will help refine some of these results. Furthermore, they will help constrain the symmetry energy at densities above the normal nuclear density where experimental results are scarce.

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