Abstract. Understanding the equation of state (EOS) of neutron-rich matter is a central goal of nuclear physics that cuts across a variety of disciplines. Indeed, the limits of nuclear existence, the collision of energetic heavy ions, the structure of neutron stars, and the dynamics of core-collapse supernova all depend critically on the nuclear-matter EOS. In this contribution I focus on the EOS of cold baryonic matter with special emphasis on its impact on the structure, dynamics, and composition of neutron stars. In particular, I discuss how laboratory experiments on neutron skins as well as on Pygmy and Giant resonances can help us elucidate the structure of these fascinating objects.

1. Motivation
One of the four overarching questions framing the recent report by The Committee on the Assessment of and Outlook for Nuclear Physics is “How does subatomic matter organize itself?” [1]. This question has been at the core of nuclear physics since Rutherford’s century-old discovery of the atomic nucleus in 1911. The number of electrons—which equals the number of protons in a neutral atom—determines the chemistry of the atom. And it is this chemistry that is responsible for binding atoms into molecules and molecules into both traditional and fascinating new materials. But how does matter organize itself at densities significantly higher than those found in everyday materials; say, from $10^4 - 10^{15}$ g/cm$^3$. Recall that in this units nuclear-matter saturation density equals $\rho_0 = 2.48 \times 10^{14}$g/cm$^3$. Indeed, relative to every day life these densities are so high that atoms become pressure ionized. Understanding what novels phases of matter emerge under these extreme conditions of density is both fascinating and unknown. Moreover, it represents one of the grand challenges in nuclear physics. Remarkably, most of these exotic phases—Coulomb crystals, nuclear pasta, color superconductors—can not be realized under normal laboratory conditions. Yet, whereas most of these phases have a fleeting existence in the laboratory, they attain stability in neutron stars due to the presence of enormous gravitational fields. In this manner neutron stars become the catalyst for the formation of unique states of matter and provide unique laboratories for the characterization of the ground state of cold matter over an enormous range of densities. Note that an unavoidable consequence of both charge neutrality and beta equilibrium is that neutron-star matter is necessarily neutron rich. This follows naturally from the very low electron mass which in turn results in a high electron chemical potential.

2. Neutron-star structure
To appreciate the enormous dynamic range and richness displayed by these fascinating objects we discuss briefly the anatomy of a neutron star. For a fairly accurate rendition of the structure
Figure 1. A scientifically-accurate rendition of the structure and the various phases predicted to exist in a neutron star (courtesy of Dany Page).

and phases of a neutron star see Fig. 1. Neutron stars contain a non-uniform crust above a uniform liquid core that is comprised of a uniform assembly of neutrons, protons, electrons, and muons in chemical equilibrium and packed to densities that may exceed that of normal nuclei by up to an order of magnitude. The highest density attained in the stellar core depends critically on the equation of state of neutron-rich matter, which at those high densities is poorly constrained. However, for soft equations of state, namely, those with a pressure that rises slowly with density, the highest density attained at the core may be high enough for the emergence of new exotic phases, such as pion or kaon condensates [2, 3], strange quark matter [4], and color superconductors [5, 6]. Nothing further will be said in this contribution about such high-density phases.

At the other extreme, namely, at densities of about half of nuclear-matter saturation density, the uniform core becomes unstable against cluster formation. At these “low” densities the average inter-nucleon separation increases to such an extent that it becomes energetically favorable for the system to segregate into regions of normal density (nuclear clusters) and regions of low density (dilute, likely superfluid, neutron vapor). Such a clustering instability signals the transition from the uniform liquid core to the non-uniform crust. The solid crust is itself divided into an outer and an inner region. The outer crust spans a region of about seven orders of magnitude in density (from about $10^4$ g/cm$^3$ to $4 \times 10^{11}$ g/cm$^3$ [7, 8, 9, 10]). Structurally, the outer crust is comprised of a Coulomb lattice of neutron-rich nuclei embedded in a uniform electron gas. As the density increases—and given that the electronic Fermi energy increases rapidly with density—it becomes energetically favorable for electrons to capture into protons. This results in the formation of Coulomb crystals of progressively more neutron-rich nuclei. This progression starts with $^{56}$Fe—the nucleus with the lowest mass per nucleon—and is predicted to end with the exotic, neutron-rich nucleus $^{118}$Kr (see Fig. 2). Qualitatively, the most stable nucleus at a given crustal density emerges from a competition between the electronic Fermi energy (which favors low $Z$) and the nuclear symmetry energy (which favors $N \approx Z$ nuclei) [9, 10].
Quantitatively, however, nuclear-shell structure plays a critical role in the determination of the most stable nucleus.

![Neutron Star Crust:](image)

**Figure 2.** A scientifically-accurate rendition of the composition of the stellar crust (courtesy of Sanjay Reddy).

Eventually, however, the neutron-proton asymmetry becomes too large for the nuclei to absorb any more neutrons and the excess neutrons go into the formation of a dilute—likely superfluid—neutron vapor; this signals the transition from the outer to the inner crust. At a neutron-drip density of about $4 \times 10^{11}$ g/cm$^3$, $^{118}$Kr is unable to retain any more neutrons. As alluded earlier, at densities approaching nuclear-matter saturation density ($\approx 2.5 \times 10^{14}$ g/cm$^3$) uniformity in the system will be restored. Yet the transition from the highly-ordered crystal to the uniform liquid is both interesting and complex. This is because distance scales that were well separated in both the crystalline phase (where the long-range Coulomb interaction dominates) and in the uniform phase (where the short-range strong interaction dominates) become comparable. This unique situation gives rise to “Coulomb frustration.” Frustration, a phenomenon characterized by the existence of a very large number of low-energy configurations, emerges from the impossibility to simultaneously minimize all elementary interactions in the system. Indeed, as these length scales become comparable, competition among the elementary interactions results in the formation of a myriad of complex structures radically different in topology yet extremely close in energy. Given that these complex structures—collectively referred to as “nuclear pasta”—are very close in energy, it has been speculated that the transition from the highly ordered crystal to the uniform phase must proceed through a series of changes in the dimensionality and topology of these structures[11, 12]. Moreover, due to the preponderance of low-energy states, frustrated systems display an interesting and unique low-energy dynamics that has been studied using a variety of techniques including numerical simulations[13, 14, 15, 16, 17, 18]. In Fig. 3 we display snapshots of two such simulations at a density of $\rho = 0.01$ fm$^{-3}$—where the system still resembles a collection of “spherical” clusters immersed in a dilute neutron vapor—and at $\rho = 0.025$ fm$^{-3}$, where some of the exotic shapes are starting to emerge[13].
3. Nuclear structure
The main goal of this contribution is to invoke nuclear-structure observables to constrain the structure, dynamics, and composition of neutron stars. Nuclear structure plays a critical role because in order to prevent the collapse of the star, the enormous gravitational fields must be balanced by the pressure support of its underlying constituents. To illustrate this point we note that spherically-symmetric neutron stars in hydrostatic equilibrium satisfy the Tolman-Oppenheimer-Volkoff (TOV) equations, which are the extension of Newton’s laws to the domain of general relativity. The TOV equations may be expressed as a coupled set of first-order differential equations of the following form:

\[
\frac{dP}{dr} = -G \frac{\mathcal{E}(r) M(r)}{r^2} \left[ 1 + \frac{P(r)}{\mathcal{E}(r)} \right] \left[ 1 + \frac{4\pi r^3 P(r)}{M(r)} \right] \left[ 1 - \frac{2GM(r)}{r} \right]^{-1},
\]

\[
\frac{dM}{dr} = 4\pi r^2 \mathcal{E}(r),
\]

where \( G \) is Newton’s gravitational constant and \( P(r), \mathcal{E}(r), \) and \( M(r) \) represent the pressure, energy density, and enclosed-mass profiles of the star, respectively. Note that the three terms enclosed in square brackets in Eq. (1) are of general-relativistic origin. Notably, the only input that neutron stars are sensitive to is the equation of state (EOS), namely, the relation between the pressure \( P \) and energy density \( \mathcal{E} \). Indeed, no solution of the TOV equations is possible without a model for the equation of state. Conversely and remarkably, each EOS generates a unique mass-vs-radius relation [19]. In Fig. 4 we display mass-vs-radius relations as predicted by three relativistic mean-field models [20]. To a large extent, all three models—NL3 [21, 22], FSU [23], and IU-FSU [20]—are able to accurately reproduce a variety of ground-state observables (such as masses and charge radii) throughout the nuclear chart. Yet, the predictions displayed in Fig. 4 are significantly different. In what follows we identify the reason for such a large model dependence and elucidate how the measurement of certain critical laboratory observables may be used to constrain the structure, dynamics, and composition of neutron stars.

The starting point for the calculation of both nuclear and neutron-star structure is the interacting Lagrangian density of Ref. [26] supplemented by an isoscalar-isovector term first
Figure 4. (Color online) Mass-vs-Radius relation predicted by the three relativistic mean-field models [20]. The observational data that suggest very small stellar radii represent 1σ confidence contours for the three neutron stars reported in Ref. [24]. The two shaded areas that suggest larger radii are 1σ and 2σ contours extracted from the analysis of Ref. [25].

The Lagrangian density includes an isodoublet nucleon field (ψ) interacting via the exchange of two isoscalar mesons, a scalar (φ) and a vector (Vµ), one isovector meson (bµ), and the photon (Aµ) [28, 29]. In addition to meson-nucleon interactions, the Lagrangian density is supplemented by four nonlinear meson interactions with coupling constants (κ, λ, ζ, and Λv) that are included primarily to soften the equation of state of both symmetric nuclear matter and pure neutron matter. For a detailed discussion on the impact of these terms on various quantities of theoretical, experimental, and observational interest see Ref. [30].

Of significant relevance to the various trends displayed in Fig. 4 are the isoscalar-vector self-interactions (scaled by the parameter ζ) and the mixed isoscalar-isovector interaction (scaled by the parameter Λv). In particular, isoscalar-vector self-interactions may be tuned to primarily and almost exclusively modify the equation of state of symmetric nuclear matter at high densities. For example, Müller and Serot found it possible to build models with different values of ζ that reproduce the same observed properties at saturation density, yet predict maximum neutron star masses that may differ by almost one solar mass [26]. Indeed, by a fine tuning of ζ one was able to increase the maximum neutron star mass from 1.72 M⊙ (in the FSU model) to 1.94 M⊙ (in the IU-FSU model) without adversely affecting well-known properties of finite nuclei [20]. This last value is consistent with the recent Demorest et al., observation of a (1.97 ± 0.04) M⊙ neutron star [31]. Thus, we reach the inescapable conclusion that the only reliable constraint on
the high-density EOS of cold nuclear matter must come from the observation of massive neutron stars.

In contrast, laboratory experiments may play a critical role in constraining the size of neutron stars. This is because neutron-star radii are controlled by the density dependence of the symmetry energy in the immediate vicinity of nuclear-matter saturation density \([32]\). Recall that the symmetry energy represents the energy cost in converting protons into neutrons (or vice versa) and may be viewed as the difference in the energy between pure neutron matter and symmetric nuclear matter. A particularly critical property of the symmetry energy is its slope at saturation density—a quantity customarily denoted by \(L\) \([33]\). Unlike symmetric nuclear matter, the slope of the symmetry does not vanish at saturation density. Indeed, \(L\) is simple related to the pressure of pure neutron matter at saturation density. That is,

\[
P_0 = \frac{1}{3} \rho_s L .
\]

Although the slope of the symmetry energy is not directly observable, it is strongly correlated to the thickness of the neutron skin of heavy nuclei \([34, 35]\). Heavy nuclei develop a neutron skin as a consequence of a large neutron excess and a Coulomb barrier that hinders the proton density at the surface of the nucleus. The thickness of the neutron skin depends sensitively on the pressure of neutron-rich matter: the greater the pressure the thicker the neutron skin. And it is exactly this same pressure that supports neutron stars against gravitational collapse. Thus models with thicker neutron skins often produce neutron stars with larger radii \([27, 36]\). Thus, it is possible to study “data-to-data” relations between the neutron-rich skin of a heavy nucleus and the radius of a neutron star. We illustrate these ideas in Fig. 5 where the neutron-skin thickness of \(^{208}\text{Pb}\) \((\Delta r_{np})\) is plotted on the left-hand panel against the slope of the symmetry energy \((L)\) for a variety of nonrelativistic and relativistic models \([37]\). The correlation between these two quantities is extremely strong \((0.979)\) and indicates that the neutron skin of \(^{208}\text{Pb}\) may be used as a proxy for the determination of a fundamental property of the EOS. Also shown

![Figure 5](image-url)
on the right-hand panel of Fig. 5 is a “data-to-data” relation between the neutron-skin thickness of $^{208}\text{Pb}$ and the radius of a canonical $1.4\text{M}_\odot$ neutron star as predicted by NL3 [21, 22] and FSU [23]. Although the “stars” in the figure indicate the predictions of these two accurately-calibrated models, a systematic variation of the isoscalar-isovector parameter $\Lambda_v$ has been done to generate the two solid lines. Such a systematic variation enables one to modify the density-dependence of the symmetry energy without affecting well-known nuclear properties, such as masses and charge radii. Our results establish a strong correlation between two quantities—the neutron skin and the stellar radius—that differ by 18 orders of magnitude! And although the correlation is strong, it is not model independent as the radius of a neutron star is sensitive to densities that are slightly higher than those relevant to finite nuclei. Finally, the point labeled as “phase transition” is meant to indicate that a large neutron skin in $^{208}\text{Pb}$ accompanied by a small neutron-star radius is likely to indicate a softening of the EOS at high densities, which may be suggestive of a phase transition to an exotic state of matter. Note that although we have focused exclusively on the correlation between $L$ and the stellar radius, the impact of $L$ extends to a myriad of other neutron-star observables[27, 36, 38, 39, 40, 41].

4. PREX: The Lead Radius Experiment

Given the instrumental role that the neutron-skin thickness of $^{208}\text{Pb}$ plays in constraining the equation of state, the Lead Radius Experiment (“PREX”) at the Jefferson Laboratory represents a true experimental milestone. The successfully commissioned Lead Radius Experiment has provided the first model-independent evidence of the existence of a significant neutron skin in $^{208}\text{Pb}$[42, 43]. Building on the strength of the enormously successful parity-violating program at the Jefferson Laboratory, PREX used parity-violating electron scattering to provide a largely model-independent determination of the neutron radius of $^{208}\text{Pb}$. Parity violation at low momentum transfers is particularly sensitive to the neutron distribution because the neutral weak-vector boson ($Z^0$) couples preferentially to the neutrons in the target [44]; the coupling to the proton is suppressed by the weak mixing angle ($1-4\sin^2\theta_W \approx 0.08$). Although very small, this purely electroweak measurement may be interpreted with as much confidence as conventional electromagnetic scattering experiments that have been used for decades to accurately map the proton distribution.

The Lead Radius Experiment collected enough high-quality data to provide a first constrain on the neutron radius of $^{208}\text{Pb}$. Although PREX achieved the systematic control required to perform this challenging experiment, unforeseen technical problems resulted in time losses that significantly compromised the statistical accuracy of the measurement. Thus, rather than achieving the original goal of a 3% uncertainty in the asymmetry—and a corresponding 1% error in the neutron radius—PREX had to settle for an error almost three times as large. This resulted in the following value for the neutron-skin thickness of $^{208}\text{Pb}$[42, 43]:

$$R_n - R_p = 0.33^{+0.16}_{-0.18}\text{ fm}. \quad (5)$$

Given that the determination of the neutron radius of a heavy nucleus is a problem of fundamental importance with far reaching implications in areas as diverse as nuclear structure [34, 35, 45, 46, 47], atomic parity violation [48, 49], heavy-ion collisions [50, 51, 52, 53, 54], and neutron-star structure [27, 36, 38, 39, 40, 41, 55], the PREX collaboration has made a successful proposal for additional beam time so that the original 1% goal (or $\pm 0.05\text{ fm}$) may be attained[56]. Unfortunately, the 12-GeV upgrade of the facility has pushed the timetable for the experiment all the way to 2014-15. And while the scientific case for such a pivotal experiment remains strong, the search for additional physical observables that may be both readily accessible and strongly correlated to the neutron skin (and thus also to $L$) is a worthwhile enterprise. It is precisely the exploration of such a correlation between the electric dipole polarizability and the neutron-skin thickness of $^{208}\text{Pb}$ that is at the center of the next section.
5. Pygmies and Giant Resonances

A promising complementary approach to the parity-violating program relies on the electromagnetic excitation of the electric dipole mode [57]. For stable (medium to heavy) nuclei with a moderate neutron excess the dipole response is concentrated on a single fragment—the giant dipole resonance (GDR)—that exhausts almost 100% of the classical Thomas-Reiche-Kuhn (TRK) sum rule. For this mode of excitation—perceived as a collective oscillation of neutrons against protons—the symmetry energy acts as the restoring force. Models with a soft symmetry energy predict large values for the symmetry energy at the densities of relevance to the excitation of this mode. As a consequence, the stronger restoring force of the softer models generates a dipole response that is both hardened (i.e., pushed to higher excitation energies) and quenched relative to its stiffer counterparts. In the particular case of the first moment of the energy distribution, the quenching and hardening largely cancel each other, leading to an energy-weighted sum that is—as it should—fairly model independent. In contrast, the inverse energy-weighted sum, which is directly proportional to the dipole polarizability $\alpha_D$, is highly sensitive to the density dependence of the symmetry energy, as here the quenching and hardening act coherently [58]. Given that the neutron radius of a heavy nucleus is also sensitive to the density dependence of the symmetry energy, the electric dipole polarizability may be used to constrain the neutron skin. Indeed, this sensitivity suggests the existence of the following interesting correlation: the larger the neutron-skin thickness of $^{208}\text{Pb}$, the larger its electric dipole polarizability.

Figure 6. (Color online) Predictions from a variety of nuclear models for the electric dipole polarizability and neutron-skin thickness of $^{208}\text{Pb}$ are shown on the left-hand side of the figure. Also shown are constrains on the neutron-skin thickness from PREX [42, 43] and on the dipole polarizability from RCNP [60, 61]. On the right-hand side of the figure we show correlation coefficients between the neutron-skin thickness of $^{208}\text{Pb}$ and several observables as obtained from a covariance analysis based on the FSU interaction [64].

To test the validity of this correlation we display on the left-hand panel of Fig. 6 the dipole polarizability in $^{208}\text{Pb}$ as a function of its corresponding neutron-skin thickness as predicted by a large number of nuclear-structure models that have been calibrated to well-known properties.
of finite nuclei [59]. Once calibrated, these models without any further adjustment are used to compute both the neutron skin as well as the distribution of electric dipole strength. From such a distribution of strength \( R_{E1} \) the dipole polarizability is readily extracted from the inverse energy-weighted sum. That is,

\[
\alpha_D = \frac{8\pi e^2}{9} \int_0^\infty \omega^{-1} R_{E1}(\omega) \, d\omega .
\]  

(6)

At first glance a clear (positive) correlation between the dipole polarizability and the neutron skin is discerned. However, on closer examination one observes a significant scatter in the results—especially in the case of the standard Skyrme forces (denoted by the black triangles). In particular, by including the predictions from all the 48 models under consideration, a correlation coefficient of 0.77 was obtained. Also shown in the figure are experimental constraints imposed from PREX and the recent high-resolution measurement of \( \alpha_D \) in \(^{208}\)Pb [60, 61]. By imposing these recent experimental constraints, several of the models—especially those with either a very soft or very stiff symmetry energy—may already be ruled out. Evidently the correlation between \( \alpha_D \) and \( R_n - R_p \) is model dependent and deserves to be investigated further.

However, to establish how the dipole polarizability may provide a unique constraint on the neutron-skin thickness of neutron-rich nuclei and other isovector observables we display on the right-hand panel of Fig. 6 correlation coefficients computed using a single underlying model, namely, FSU [23]. For details on the implementation of the required covariance analysis we refer the reader to Refs. [62, 63, 64]. According to the model, an accurate measurement of the neutron skin-thickness in \(^{208}\)Pb significantly constrains the neutron skin on a variety of other neutron-rich nuclei. Moreover, the correlation coefficient between the neutron skin and \( \alpha_D \) in \(^{208}\)Pb is very large (of about 0.9). This suggests that a multi-prong approach consisting of combined measurements of both neutron skins and \( \alpha_D \)—ideally on a variety of nuclei—should significantly constrain the isovector sector of the nuclear energy density functional as well as the EOS of neutron-rich matter.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{dipole_strength.png}
\caption{(Color online) Distribution of isovector dipole strength for all neutron-even tin isotopes from \(^{100}\)Sn to \(^{130}\)Sn using the FSUGold parameter set [23]. A detailed description of the RPA formalism required to generate this plot may be found in Ref. [65].}
\end{figure}

Naturally, a more stringent constrain on the isovector sector of the nuclear density functional is expected to emerge along an isotopic chain as the nucleus develops a neutron-rich skin. Concomitant with the development of a neutron skin one expects the emergence of low energy dipole strength—the so-called pygmy dipole resonance [66, 67, 68, 69, 70, 71, 72]. Thus, it has
been suggested that the pygmy dipole resonance (PDR)—speculated to be an excitation of the neutron-rich skin against the isospin symmetric core—may be used as a constraint on the neutron skin of heavy nuclei [65]. In particular, the fraction of the energy weighted sum rule (EWSR) exhausted by the pygmy resonance has been shown to be sensitive to the neutron-skin thickness of heavy nuclei [65, 73, 74, 75, 76]. Recent pioneering experiments on unstable neutron-rich isotopes in Sn, Sb, and Ni seem to support this assertion [75, 77, 78].

To illustrate these ideas we display in Fig. 7 the distribution of isovector dipole strength for all even-even Sn-isotopes from $^{100}$Sn up to $^{130}$Sn. The large collective structure in the $\omega \sim 15-16$ MeV region represents the isovector giant dipole resonance. For medium-to-heavy nuclei this collective vibration represents a coherent oscillation of all protons against all neutrons and is well-developed along the whole isotopic chain [57, 79]. As is characteristic of these collective excitations, a large fraction of the energy-weighted sum rule is exhausted by this one resonance. But certainly not all! The development of low-energy ($\omega \sim 7-9$ MeV) dipole strength with increasing neutron number is clearly discerned. Indeed, the progressive addition of neutrons results in both the emergence of a neutron-rich skin and a well developed, albeit small, low-energy resonance.

![Figure 7](image_url)

**Figure 7.** (Color online) The inverse energy weighted dipole response in $^{68}$Ni computed with the FSU family of effective interactions is shown on the left-hand side of the figure. The inset displays the cumulative sum as defined in Eq. (7). The arrow indicates the (ad-hoc) energy at which the low-energy (pygmy) response is separated from the high-energy (giant) response. On the right-hand side the fractional change in the energy weighted sum and dipole polarizability for $^{68}$Ni are displayed as a function of the neutron-skin thickness of $^{208}$Pb. See Ref. [58] for more details.

But if the fraction of the energy weighted sum rule exhausted by the pygmy resonance has been shown to be sensitive to the neutron skin of heavy nuclei, the fraction of the inverse energy weighted sum rule carried by the PDR appears to be even more sensitive. Again, this is related to the fact that the hardening and quenching of the isovector dipole response is more extreme for models with a soft symmetry energy. The inverse energy weighted response $\omega^{-1} R(\omega)$ is displayed on the left-hand panel of Fig. 8. Given that the $\omega^{-1}$ factor enhances preferentially
the low-energy part of response, the Pygmy resonance accounts for a significant fraction (of about 20-25%) of the $m_{-1}$ moment, which is directly related to the dipole polarizability through Eq. (6). This should be contrasted against the EWSR where the Pygmy resonance exhausts merely 5-8% of the total sum [58]. Moreover, the inverse energy weighting enhances further the response generated from models with a stiff symmetry energy. Pictorially, this behavior is best illustrated in the inset of Fig. 8 which displays the cumulative $m_{-1}(\omega)$ sum:

$$m_{-1}(\omega) = \int_0^\omega \frac{R(\omega')}{\omega'} d\omega'.$$

(7)

The inset provides a clear indication that both the total $m_{-1}$ moment as well as the fraction contained in the Pygmy resonance are highly sensitive to the neutron-skin thickness of $^{208}$Pb. To heighten this sensitivity we display on the right-hand panel of Fig. 8 the fractional change in both the total and Pygmy contributions to the $m_1$ moment and to the dipole polarizability $\alpha_D$ as a function of the neutron skin of $^{208}$Pb (we denote these fractional changes with a “tilde” in the figure). These results illustrate the strong correlation between the neutron skin and $\alpha_D$ and establish how a combined measurement of these laboratory observables will be of vital importance in constraining the isovector sector of the nuclear density functional.

6. Conclusions

Measurements of neutron radii provide important constraints on the isovector sector of nuclear density functionals and offer vital guidance in areas as diverse as atomic parity violation, heavy-ion collisions, and neutron-star structure. In this contribution we examined the possibility of using the quintessential nuclear mode—the isovector dipole resonance—as a promising complementary observable. For this mode of excitation in which protons oscillate coherently against neutrons, the symmetry energy acts as its restoring force. Thus, models with a soft symmetry energy predict large values for the symmetry energy at the densities of relevance to the excitation of this mode. As a consequence, softer models generates a dipole response that is both hardened and quenched relative to the stiffer models. However, being protected by the TRK sum rule, the energy weighted sum rule is largely insensitive to this behavior. In contrast, for the inverse energy-weighted sum—which is directly proportional to the electric dipole polarizability $\alpha_D$—the quenching and hardening act in tandem. Thus, models with a soft symmetry energy predict smaller values of $\alpha_D$ than their stiffer counterparts. This results in a powerful “data-to-data” relation: the smaller $\alpha_D$ the thinner the neutron skin.

A particular intriguing question concerns the role of the pygmy dipole resonance in constraining the density dependence of the symmetry energy. Regarded as an oscillation of the neutron-rich skin of a heavy nucleus against its isospin-symmetric core, the PDR was suggested to be strongly correlated to the neutron skin. In the particular case of the Tin isotopes, a clear emergence of low-energy dipole strength is observed as the nucleus develops a neutron-rich skin. Moreover, it appears that although the total EWSR is fairly insensitive to the density dependence of the symmetry energy, the fraction of the EWSR exhausted by the pygmy displays some sensitivity. However, in the case of the dipole polarizability the conclusion that the PDR is highly sensitive to the density dependence of symmetry energy appears inescapable. Indeed, in the particular case of $^{68}$Ni the PDR accounts for 20-25% of the total dipole polarizability and displays a strong sensitivity to the neutron skin. Yet, many open questions remain. First and foremost, the strong correlation between the PDR and the neutron skin found here appears to be model dependent. While we support the notion of a strong correlation between these two observables, Reinhard and Nazarewicz conclude that the neutron-skin thickness of $^{208}$Pb is very weakly correlated to the low-energy dipole strength [62]. Moreover, even the nature of the low-energy mode is unclear. Is it indeed a collective mode? Is it a skin oscillation? Can it be cleanly decoupled from the low-energy tail of the giant resonance? Although most of these
issues were not addressed in this contribution, attempts to answer some of these question may be found in two recent reviews [80, 81]. Regardless of the nature of the mode, the emergence of low-energy dipole strength as nuclei develop a neutron-rich skin is an incontrovertible fact. As such, it should play a pivotal role in constraining the EOS of neutron-rich matter.

In summary, motivated by two seminal experiments [42, 60], we examined possible correlations between the electric dipole polarizability and the neutron skin of neutron-rich nuclei. The neutron-skin thickness of a heavy nucleus is a quantity of critical importance for our understanding of a variety of nuclear and astrophysical phenomena. In particular, the neutron-skin thickness of $^{208}$Pb can provide stringent constrains on the density dependence of the symmetry energy which, in turn, has a strong impact on the structure, dynamics, and composition of neutron stars. We conclude that precise measurements of neutron skins and $\alpha_D$—ideally on a variety of nuclei—should significantly constrain the isovector sector of the nuclear energy density functional and will provide critical insights into the nature of neutron-rich matter.

Acknowledgments

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