Nuclear symmetry energy probed by neutron skin thickness of nuclei

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We describe a relation between the symmetry energy coefficients $c_{\text{sym}}(\rho)$ of nuclear matter and $a_{\text{sym}}(A)$ of finite nuclei that accommodates other correlations of nuclear properties with the low-density behavior of $c_{\text{sym}}(\rho)$. Here we take advantage of this relation to explore the prospects for constraining $c_{\text{sym}}(\rho)$ of systematic measurements of neutron skin sizes across the mass table, using as example present data from antiprotonic atoms. The found constraints from neutron skins are in harmony with the recent determinations from reactions and giant resonances.

A wealth of measured data on densities, masses and collective excitations of nuclei has allowed to resolve basic features of the equation of state (EOS) of nuclear matter, like the density $\rho_0 \approx 0.16$ fm\textsuperscript{-3}, energy per particle $a_n \approx -16$ MeV, and incompressibility $K_n \approx 230$ MeV\textsuperscript{1} at saturation. However, the symmetry properties of the EOS due to differing neutron and proton numbers remain more elusive to date. The quintessential paradigm is the density dependence of the symmetry energy\textsuperscript{1,2,3,4,6,7,8,10}. The accurate characterization of this property entails profound consequences in studying the neutron distribution in stable and exotic nuclei and neutron-rich matter\textsuperscript{2,3,4}. It impacts on heavy ion reactions\textsuperscript{5,6,7,8,9}, nuclear astrophysics\textsuperscript{3,4,10}, and on diverse areas such as tests of the Standard Model via atomic parity violation\textsuperscript{11}.

The general expression $e(\rho, \delta) = e(\rho, 0) + c_{\text{sym}}(\rho)\delta^2 + O(\delta^4)$ for the energy per particle of nuclear matter of density $\rho = \rho_n + \rho_p$ and asymmetry $\delta = (\rho_n - \rho_p)/\rho$ defines the symmetry energy coefficient $c_{\text{sym}}(\rho)$ of a nuclear EOS. It is customary and insightful to characterize the behavior of an EOS around the saturation density $\rho_0$ in terms of a few bulk parameters, like $e(\rho, 0) \approx a_v + c_{\text{sym}}(\rho)\rho^2/2$ and $c_{\text{sym}}(\rho) \approx J - Lc + K_{\text{sym}}c^2$ where $c = (\rho_0 - \rho)/3\rho_0$\textsuperscript{3,6,7,12}. The value of $J = c_{\text{sym}}(\rho_0)$ is acknowledged to be about 32 MeV. The values of $L = 3\rho\partial c_{\text{sym}}(\rho)/\partial\rho|_{\rho_0}$ and $K_{\text{sym}} = 9\rho^2\partial^2 c_{\text{sym}}(\rho)/\partial\rho^2|_{\rho_0}$ govern the density dependence of $c_{\text{sym}}$ around $\rho_0$. They are less certain and the predictions vary largely among nuclear theories, see e.g. Ref.\textsuperscript{7} for a review.

In experiment, recent research in intermediate-energy heavy ion collisions (HIC) is consistent with a dependence $c_{\text{sym}}(\rho) = c_{\text{sym}}(\rho_0)(\rho/\rho_0)^7$ at $\rho < \rho_0$\textsuperscript{3,4,5,6,7}. Isoscalar diffusion predicts $\gamma = 0.7-1.05$ ($L = 88 \pm 25$ MeV)\textsuperscript{5,7}, isoscaling favors $\gamma = 0.69$ ($L \sim 65$ MeV)\textsuperscript{8}, and a value closer to 0.55 ($L \sim 55$ MeV) is inferred from nucleon emission ratios\textsuperscript{6}. Nuclear resonances are another hopeful tool to calibrate $c_{\text{sym}}(\rho)$ below $\rho_0$\textsuperscript{6,7,8,12,13,10}. Indeed, the giant dipole resonance (GDR) of $^{208}$Pb analyzed with Skyrme forces suggests a constraint $c_{\text{sym}}(0.1 \text{ fm}^{-3}) = 23.3-24.9$ MeV\textsuperscript{14}, implying $\gamma \sim 0.5-0.65$. Note that the Thomas-Fermi model fitted very precisely to binding energies of 1654 nuclei\textsuperscript{17} predicts an EOS that yields $\gamma = 0.51$. With the caveat that the connection of experiments to the EOS often is not at all trivial it is important to seek further clues from the above and other isospin-sensitive signals, such as the neutron skin thickness $S = R_n - R_p$ of nuclei (difference of neutron and proton rms radii). Because $S$ of heavy nuclei correlates linearly with the slope $L$ of $c_{\text{sym}}$ in mean field theories of nuclear structure\textsuperscript{2,3,4,5,6,7,12,13,19}, these studies have far-reaching implications for nuclear theory.

In this work we show that $c_{\text{sym}}(\rho)$ of the EOS equals at $\rho \approx 0.1$ fm\textsuperscript{-3} the value of the symmetry energy coefficient $a_{\text{sym}}(A)$ of heavy finite nuclei, universally in mean field theories. The observed correlations of $S$\textsuperscript{2,3,4,5,6,7} and of the excitation energy of the GDR\textsuperscript{14} with the density dependence of $c_{\text{sym}}$ can be deduced naturally from this relation. We resort to the nuclear droplet model (DM)\textsuperscript{12} to work out the analytical formulas. The result derived for $S$ is applied to investigate limits to the slope and curvature of $c_{\text{sym}}$ from neutron skins measured for 26 stable nuclei, from $^{40}$Ca to $^{238}$U, in antiprotonic atoms\textsuperscript{20}. A main point is ascertaining how far uniformly measured neutron skins over the periodic table may help constrain the density dependence of $c_{\text{sym}}$. We provide first evidence that the constraints from skins are in consonance with the recent observations from reactions and giant resonances, though the probed densities and energies are not necessarily the same.

The symmetry energy coefficient $a_{\text{sym}}(A)$ of finite nuclei is smaller than the bulk value $J$. Given a nuclear force, the DM allows one to extract $a_{\text{sym}}(A)$ as\textsuperscript{12,21}

$$a_{\text{sym}}(A) = \frac{J}{1 + x_A}, \quad \text{with} \quad x_A = \frac{9J}{4Q}A^{-1/3}. \quad (1)$$

The so-called surface stiffness $Q$ measures the resistance of the nucleus against separation of neutrons from protons to form a neutron skin. One can obtain $Q$ of nu-
clear forces by asymmetric semi-infinite nuclear matter (ASINM) calculations [12, 21, 22]. The contribution of $a_{sym}(A)$ to the nuclear energy is $a_{sym}(A) (I + x_A I_C)^2 A$, where $I = (N - Z)/A$ and $I_C = e^2 Z/(20 A R)$ is due to Coulomb. One has $R = r_0 A^{1/3}$. A small correction to $a_{sym}(A)$ from surface compression [12] is neglected here. Let us mention that (1) may be derived also from the notion of surface symmetry energy [4, 19].

The neutron skin thickness of nuclei is obtained as

$$S = \sqrt{3/5} \left[ t - e^2 Z/(70 J) \right] + S_{sw}$$

in the DM [12, 23]. The quantity $t$ gives the distance between the neutron and proton mean surface locations:

$$t = \frac{3 r_0}{2} \left( \frac{J}{Q} (I - I_C) \right)$$

$$= \frac{2 r_0}{3 J} \left( J - a_{sym}(A) \right) A^{1/3} (I - I_C),$$

where in the second line we have introduced the surface symmetry term $a_{sw}(A) = [J - a_{sym}(A)] A^{1/3}$ using Eq. (1). The second term in Eq. (2) is due to Coulomb repulsion, and $S_{sw} = \sqrt{3/5} [5 b_n^2 - b_p^2]/(2 R)$ is a correction caused by an eventual difference in the surface widths $b_n$ and $b_p$ of the neutron and proton density profiles.

We first illustrate the aforesaid correlation of $S$ of heavy nuclei with $L$ in Fig. 1(a). It depicts the quantal self-consistent value of $S$ in 208Pb against $L$ for multiple Skyrme, Gogny, and covariant models of different nature [2, 3, 4, 5, 6, 7, 18, 21, 22]. In Fig. 1(b) we show that a similar correlation exists with the ratio $L/J$, which is proportional to $\gamma$ if a scaling $(\rho_a/\rho_0)^\gamma$ holds for $c_{sym}(\rho)$. And in Fig. 1(c) we show that the close dependence of $S$ on $J - a_{sym}(A)$ predicted by the DM is borne out in the quantal $S$ value, using forces where we have computed $Q$ in ASINM. It reassures one that the DM expression incorporates the proper elements for the study. Many of the given nuclear interactions are accurately fitted to experimental binding energies, single-particle data, and charge radii of a variety of nuclei. However, their isospin structure is not sufficiently firmed up as seen e.g. in the differing predictions for $S^{(208Pb)}$. There is thus a need to deepen our knowledge of isospin-sensitive observables like $S$ and of their constraints on $c_{sym}(\rho)$.

We bring into notice a genuine relation between the symmetry energy coefficients of the EOS and of nuclei: $c_{sym}(\rho)$ equals $a_{sym}(A)$ of a heavy nucleus like 208Pb at a density $\rho \approx 0.1$ fm$^{-3}$. Indeed, the relation holds similarly down to medium mass numbers, at lower $\rho$ values and a little more spread. Table I exemplifies this fact with several nuclear models, where we show the density fulfilling $c_{sym}(\rho) = a_{sym}(A)$ for $A = 208$, 116, and 40. We find that this density can be parametrized as

$$\rho_A = \rho_0 - \rho_0/(1 + c A^{1/3})$$

with $c$ fixed by $\rho_{208} = 0.1$ fm$^{-3}$ (which gives $\rho_{116} \approx 0.093$ fm$^{-3}$ and $\rho_{40} \approx 0.08$ fm$^{-3}$ for the models of Table I). The relation “$c_{sym}(\rho) = a_{sym}(A)$” can be very helpful to elucidate other correlations of isospin observables with $c_{sym}(\rho)$ and to gain deeper insights into them. For example, it allows one to replace $a_{sym}(A)$ in Eq. (3) for a heavy nucleus by $c_{sym}(\rho) \approx J - L \epsilon + \frac{1}{2} K_{sym} \epsilon^2$ with $\epsilon$ computed at $\rho \approx 0.1$ fm$^{-3}$ [22]:

$$t = \frac{2 r_0}{3 J} L \left( 1 - \frac{K_{sym}}{2 L} \right) \epsilon A^{1/3}(I - I_C).$$

The imprint of the density content of the symmetry energy on the neutron skin appears now explicitly. The leading proportionality of $\Delta$ with $L$ explains the observed linearity of $S$ of a heavy nucleus with $L$ in nuclear models [2, 4, 5]. The correction with $K_{sym}$ does not alter the situation as $\epsilon \sim 1/9$ is small. One can use Eq. (5) in

![FIG. 1: (Color online) Correlation of the quantal selfconsistent $S$ value in 208Pb with the slope of the symmetry energy $L (a)$, the ratio $L/J (b)$, and with $J - a_{sym}(A) (c)$, for various nuclear models (DD and PC stand for density dependent and point coupling models). From left to right, the correlation factors are $r = 0.961, 0.945$ and 0.970.](image-url)
other mass regions by calculating $\epsilon$ from $\rho_A$ of Eq. [4].
We have checked numerically in multiple forces that the results closely agree with Eq. [3] for the $40 \leq A \leq 238$
stable nuclei given in Fig. 2.

With the help of Eq. [3] for $t$ (using $\rho_A$ to compute $\epsilon$), we next analyze constraints on the density dependence of
the symmetry energy by optimization of Eq. [2] to experimental $S$ data. We employ $c_{\text{sym}}(\rho) = 31.6(\rho/\rho_0)^2$ MeV
and take as experimental baseline the neutron skins measured in 26 antiprotonic atoms [20] (see Fig. 2).

These data constitute the largest set of uniformly measured neutron skins over the mass table till date. With
allowance for the error bars, they are fitted linearly by $S = (0.9 \pm 0.15) I + (-0.03 \pm 0.02)$ fm [20]. This systematic
renders comparisons of skin data with DM formulas, which by construction average the microscopic shell effect, more meaningful [26]. We first set $b_n = b_p$ (i.e., $S_{sw} = 0$) as done in the DM [12, 23, 26] and in the analysis of data in Ref. [13]. Following the above, we find $L = 75 \pm 25$ MeV (\(\gamma = 0.79 \pm 0.25\)). The range $\Delta L = 25$ MeV stems from the window of the linear averages of experiment. The $L$ value and its uncertainty obtained from neutron skins with $S_{sw} = 0$ is thus quite compatible with the quoted constraints from isospin diffusion and isoscaling observables in HIC [6, 7, 8]. On the other hand, the symmetry term of the incompressibility of the nuclear EOS around equilibrium ($K = K_\sigma + K_\delta \delta^2$) can be estimated using information of the symmetry energy as $K_\delta \approx K_{\text{sym}} - 6L [2, 6, 12]$. The constraint $K_\delta = -500 \pm 50$ MeV is found from isospin diffusion [2, 6, 12], whereas our study of neutron skins leads to $K_\delta = -500^{+125}_{-100}$ MeV. A value $K_\delta = -550 \pm 100$ MeV seems to be favored by the giant monopole resonance (GMR) measured in Sn isotopes as is described in [26]. Even if the present analyses may not be called definitive, significant consistency arises among the values extracted for $L$ and $K_\delta$ from seemingly unrelated sets of data from reactions, ground-states of nuclei, and collective excitations.

To assess the influence of the correction $S_{sw}$ in Eq. [2], we compute the surface widths $b_n$ and $b_p$ in ASINM [22]. This yields the $b_n(p)$ values of a finite nucleus if we relate the asymmetry \(\delta_0\) in the bulk of ASINM to $I$ by $\delta_0(1 + x_A) = I + x_A I C$ [21, 22, 23]. In doing so, we find that Eq. [2] reproduces trustingly $S$ (and its change with $I$) of self-consistent Thomas-Fermi calculations of finite nuclei made with the same nuclear force. Also, $S_{sw}$ is very well fitted by $S_{sw} = \sigma_{sw} I$. All slopes $\sigma_{sw}$ of the forces of Fig. 1(c) lie between $\sigma_{\text{sw}}^{\text{min}} = 0.15$ fm (SGH) and $\sigma_{\text{sw}}^{\text{max}} = 0.31$ fm (NL3). We then reanalyze the experimental neutron skins including $S_{\text{sw}}^{\text{min}}$ and $S_{\text{sw}}^{\text{max}}$ in Eq. [2] to simulate the two conceivable extremes of $S_{sw}$ according to mean field models. The results are shown in Fig. 3. Our above estimates of $L$ and $K_\delta$ could be shifted by up to $-25$ and $+125$ MeV, respectively, by nonzero $S_{sw}$. This is on the soft side of the HIC [6, 7, 8] and GMR [13] analyses of the symmetry energy, but closer to the alluded predictions from nucleon emission ratios [9], the GDR [14], and nuclear binding systematics [17]. One should mention that the properties of $c_{\text{sym}}(\rho)$ derived from terrestrial nuclei have intimate connections to astrophysics [3, 4, 10]. As an example, we can estimate the transition density $\rho_t$ between the crust and the core of a neutron star [3, 10] as $\rho_t/\rho_0 \sim 2/3 + (2/3)^2 K_{\text{sym}}/2K_\delta$, following the model of Sect. 5.1 of Ref. [10]. The constraints from neutron skins hereby yield $\rho_t/\rho_0 \sim 0.095 \pm 0.01$ fm$^{-3}$. This value would not support the direct URCA process of cooling of a neutron star that requires a higher $\rho_t/\rho_0$ [3, 10]. The result is in accord with $\rho_t/\rho_0 \sim 0.096$ fm$^{-3}$ of the microscopic EOS of Friedman and Pandharipande [27], as well as with $\rho_t \sim 0.09$ fm$^{-3}$ predicted by a recent analysis of pynyg dipole resonances in nuclei [15].

We would like to close with a brief comment regarding the GDR. As mentioned, Ref. [14] very interestingly constrains $c_{\text{sym}}(0.1)$ from the GDR of $^{208}$Pb. The anal-

![Figure 2: (Color online) Comparison of the fit described in the text of Eq. (2) with the experimental neutron skins from antiprotonic measurements and their linear average $S = (0.9 \pm 0.15) I + (-0.03 \pm 0.02)$ fm [20]. Results of the modern Skyrme SLy4 and relativistic FSUGold forces are also shown.](image)

![Figure 3: (Color online) Constraints on $L$ and $K_\delta$ from neutron skins and their dependence on the $S_{sw}$ correction of Eq. (2). The crosses express the $L$ and $K_\delta$ ranges compatible with the uncertainties in the skin data. The shaded regions depict the constraints on $L$ and $K_\delta$ from isospin diffusion [2, 6, 12] and on $K_\delta$ as determined in [13] from the GMR of Sn isotopes.](image)
analysis notes that the mean excitation energy of the GDR depends on $g(A) = J / \{ 1 + \frac{2}{3} a_{\text{sym}}(A) A^{-1/3} / J \}$ and shows numerically that the values of $g(208)$ and $c_{\text{sym}}(0.1)$ are correlated in Skyrme forces. Inserting the data of [20], the size of the final uncertainties in $g_{\text{sym}}$ depends on $c_{\text{sym}}(0.1)$, gives it analytically, and validates it for any type of mean field model [28]. One could extend it to other $A$ values through Eq. (3). In conclusion, the discussed relation of $c_{\text{sym}}(\rho)$ with $a_{\text{sym}}(A)$ can be much valuable to link different problems depending upon $a_{\text{sym}}(A)$ of nuclei to the symmetry properties of the EOS.

Summarizing, we have described a generic relation between the symmetry energy in finite nuclei and in nuclear matter at subsaturation. It plausibly encompasses other prime correlations of nuclear observables with the density content of the symmetry energy. We take advantage of this relation to explore constraints on $c_{\text{sym}}(\rho)$ from neutron skins measured in antiprotonic atoms [20]. We discuss the $L$ and $K_F$ values that skins favor vis-à-vis most recent observations from reactions and giant resonances. The difficult experimental extraction of neutron skins limits their potential to constrain $c_{\text{sym}}(\rho)$. Interestingly, we learn that in spite of present error bars in the data of [20], the size of the final uncertainties in $L$ or $K_F$ is comparable to the other analyses. This highlights the value of having skin data consistently measured across the mass table, and calls for pursuing extended measurements of neutron radii and skins with “conventional” hadronic probes. Combined with a precision extraction of $R_n$ of $^{208}$Pb through electroweak probes [29], they would contribute to cast uniquely tight constraints on $c_{\text{sym}}(\rho)$.

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[1] J. Piekarewicz, Phys. Rev. C76, 031301(R) (2007), and references therein.
[2] B. A. Brown, Phys. Rev. Lett. 85, 5296 (2000); S. Typel and B. A. Brown, Phys. Rev. C64, 027302 (2001).
[3] C. J. Horowitz and J. Piekarewicz, Phys. Rev. Lett. 86, 5647 (2001); B. G. Todd-Rutel and J. Piekarewicz, Phys. Rev. Lett. 95, 122501 (2005).
[4] A. W. Steiner et al, Phys. Rep. 411, 325 (2005).
[5] V. Baran, M. Colonna, V. Greco, and M. Di Toro, Phys. Rep. 410, 335 (2005).
[6] L. W. Chen, C. M. Ko, and B. A. Li, Phys. Rev. Lett. 94, 032701 (2005); Phys. Rev. C72, 064309 (2005).
[7] B. A. Li, L. W. Chen, and C. M. Ko, Phys. Rep. 464, 113 (2008).
[8] D. V. Shetty, S. J. Yennello, and G. A. Souliotis, Phys. Rev. C76, 024606 (2007).
[9] M. A. Famiński et al, Phys. Rev. Lett. 97, 052701 (2006).
[10] J. M. Lattimer, M. Prakash, Phys. Rep. 442, 109 (2007).
[11] T. Sil, M. Centelles, X. Viñas, and J. Piekarewicz, Phys. Rev. C71, 045502 (2005).
[12] W. D. Myers and W. J. Świątecki, Ann. Phys. 55, 395 (1969); Ann. Phys. 84, 186 (1974); W. D. Myers, Droplet Model of Atomic Nuclei (Plenum, New York, 1977).
[13] T. Li et al, Phys. Rev. Lett. 99, 162503 (2007).
[14] L. Trippa, G. Colò, and E. Vigezzi, Phys. Rev. C77, 061304(R) (2008). We thank an unknown referee for bringing this paper to our attention.
[15] A. Klimkiewicz et al, Phys. Rev. C76, 051603(R) (2007).
[16] H. Liang, N. Van Giai, and J. Meng, Phys. Rev. Lett. 101, 122502 (2008).
[17] W. D. Myers and W. J. Świątecki, Nucl. Phys. A601, 141 (1996); Phys. Rev. C57, 3020 (1998).
[18] R. J. Furnstahl, Nucl. Phys. A706, 85 (2002).
[19] P. Danielewicz, Nucl. Phys. A727, 233 (2003).
[20] A. Tätzki et al, Phys. Rev. Lett. 87, 082501 (2001); J. Jastrzebski et al, Int. J. Mod. Phys. E13, 343 (2004).
[21] M. Brack, C. Guet, and H.-B. Häkansson, Phys. Rep. 123, 275(1985).
[22] M. Centelles, M. Del Estal, and X. Viñas, Nucl. Phys. A635, 193 (1998).
[23] W. D. Myers and W. J. Świątecki, Nucl. Phys. A336, 267 (1980).
[24] J. P. Blaizot et al, Nucl. Phys. A591, 435 (1995).
[25] The expression $J - L\epsilon + \frac{2}{3} K_{\text{sym}} \epsilon^2$ differs from the exact value of $c_{\text{sym}}(\rho)$ by less than 1% at $\rho = 0.1$ fm$^{-3}$ in all forces tested, thus being of sufficient accuracy.
[26] W. J. Świątecki, A. Trzcińska, and J. Jastrzębski, Phys. Rev. C71, 047301 (2005).
[27] C. P. Lorenz, D. G. Ravenhall, C.J. Pethick, Phys. Rev. Lett. 70, 379 (1993).
[28] In practice this dependence becomes almost linear: using the same forces of Fig. 1(c) as well as the TF model of [17], we find that $g(208)$ has a correlation factor 0.991 with $a_{\text{sym}}(208)$ and 0.983 with $c_{\text{sym}}(0.1)$.
[29] R. Michaels, P. A. Souder, and G. M. Urciolli, spokespersons, http://hallaweb.jlab.org/parity/prex.