

Isospin diffusion in heavy-ion collisions and the neutron skin thickness of lead

Andrew W. Steiner^{1,*} and Bao-An Li²

¹Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

²Department of Chemistry and Physics, P.O. Box 419, Arkansas State University, State University, Arkansas, 72467-0419, USA

(Received 18 May 2005; published 12 October 2005)

The correlation between the thickness of the neutron skin in ^{208}Pb and the degree of isospin diffusion in heavy-ion collisions is examined. The same equation of state is used to compute the degree of isospin diffusion in an isospin-dependent transport model and the neutron skin thickness in the Hartree-Fock approximation. We find that skin thicknesses less than 0.15 fm are excluded by the isospin diffusion data.

DOI: [10.1103/PhysRevC.72.041601](https://doi.org/10.1103/PhysRevC.72.041601)

PACS number(s): 25.70.-z, 21.10.Gv, 21.30.Fe, 24.10.Lx

The nuclear symmetry energy and its dependence on density holds a unique place in nuclear physics and astrophysics. It is an essential ingredient in understanding many aspects of nuclear physics, from heavy-ion collisions to nuclear structure, and of astrophysics, from supernovae and neutron stars to r -process nucleosynthesis (for a recent review see Ref. [1]). At the same time, the nuclear symmetry energy is relatively uncertain; it is known to within only about 5 MeV at saturation density (compared with the binding energy, which is known to within 1 MeV). The density dependence of the nuclear symmetry energy at both subsaturation and supersaturation densities is very poorly known.

The symmetry energy is also an important quantity in determining the compressibility of matter. The incompressibility K_0 of symmetric nuclear matter at its saturation density $\rho_0 = 0.16 \text{ fm}^{-3}$ has been determined to be 231 ± 5 MeV from nuclear giant monopole resonances [2], and the equation of state (EOS) at densities of $2\rho_0 < \rho < 5\rho_0$ has been constrained by measurements of collective flows [3–7] in relativistic heavy-ion collisions [8]. However, further progress in determining more precisely both the parameter K_0 and the EOS of symmetric nuclear matter is severely hindered by the uncertainties of the symmetry energy [8,9].

The possibility of determining the EOS of nuclear matter from heavy-ion collisions has been discussed for almost 30 years, and indeed impressive progress has been achieved. A number of heavy-ion collision probes of the symmetry energy have been proposed, including isospin fractionation [10–14], isoscaling [15,16], neutron-proton differential collective flow [17], pion production [18], and the neutron-proton correlation function [19]. Determination of the equation of state from heavy-ion data is typically performed through comparisons with transport model simulations [8,20–23]. A recent analysis of the symmetry energy comes from isospin diffusion data for reactions involving ^{112}Sn and ^{124}Sn from the NSCL/MSU [24,25]. Using an isospin- and momentum-dependent transport model, IBUU04 [26,27], the NSCL/MSU data on isospin diffusion were found to be consistent with a nuclear symmetry energy of $E_{\text{sym}}(\rho) \approx 31.6(\rho/\rho_0)^{1.05}$ at subsaturation densities.

The pressure of neutron-rich matter at densities near two-thirds saturation density (which is closely related to the symmetry energy, see Ref. [1]) is tightly correlated to the neutron skin thickness, δR , in ^{208}Pb [28,29]. The present theoretical uncertainty in the symmetry energy results in a large uncertainty in the theoretical calculations of the skin thickness. Experimental measurements of the skin thickness are also very uncertain, mostly resulting from the difficulty in disentangling the strong interactions between the probe and the neutrons in the nucleus. Values from 0.07 to 0.24 fm have been suggested by the data [30,31]. A determination of the symmetry energy at subsaturation densities would offer a prediction of skin thickness of lead, or vice versa.

The structure of nuclei and neutron stars and the properties of heavy-ion collisions are all determined by the same underlying EOS. In particular, both the size of the neutron skin and the degree of isospin diffusion in heavy-ion collisions at intermediate energies are sensitive to the symmetry energy at subsaturation densities. In this article, we study the correlation between the thickness of neutron skin in ^{208}Pb and the strength of isospin diffusion by using the same set of equations of state as for asymmetric nuclear matter. This differs from previous work in that, for the first time, we make a direct connection between observables from nuclear structure and heavy-ion collisions. The transport model IBUU04 was used to predict the isospin diffusion for several equations of state that differ only in the density dependence of the symmetry energy. These equations of state are also used to calculate δR for ^{208}Pb in the Hartree-Fock (HF) approximation. The correlation between the δR and the isospin diffusion provides a more stringent constraint than do their individual values on the EOS of neutron-rich matter. Comparisons with the available data are also discussed.

Isospin diffusion quantitatively measures the net exchange of isospin contents between the projectile and the target nuclei. With symmetric reactions $A + A$ and $B + B$ as references, the degree of isospin diffusion in the asymmetric reaction of $A + B$ can be measured by [32]

$$R_i = \frac{2X^{A+B} - X^{A+A} - X^{B+B}}{X^{A+A} - X^{B+B}}, \quad (1)$$

where X is any isospin-sensitive tracer. In the recent NSCL/MSU experiments with ^{124}Sn on ^{112}Sn at a beam

*Electronic address: asteiner@lanl.gov

energy of 50 MeV/nucleon and an impact parameter of about 6 fm, the isospin asymmetry of the projectilelike residue was used as the isospin tracer [24]. Consistent with the experimental selection, in model analyses the average isospin asymmetry $\langle \delta \rangle$ of the ^{124}Sn -like residue was calculated from nucleons with local densities higher than $\rho_0/20$ and velocities larger than $1/2$ the beam velocity in the c.m. frame. Reactions at intermediate energies are always complicated by preequilibrium particle emission and the production of possibly neutron-rich fragments at mid-rapidity, however, the quantity R_i has the advantage of significantly minimizing these effects [24].

The NSCL/MSU data were recently analyzed by using the IBUU04 version of an isospin and momentum dependent transport model [26,27]. Here, we recall the ingredients of the model that are most relevant for the present study. In this model one can choose to use either the experimental nucleon-nucleon cross sections in free space or reduced in-medium nucleon-nucleon cross sections. Since the later involves several model-dependent assumptions, we have used the free-space cross sections (as in Ref. [25]). The EOS used in this model is based on the Gogny effective interactions. The potential $U(\rho, \delta, \mathbf{p}, \tau)$ for a nucleon with isospin τ ($1/2$ for neutrons and $-1/2$ for protons) and momentum \mathbf{p} in asymmetric nuclear matter at total density ρ is given by [33–36]

$$\begin{aligned}
 U_{\text{MDI}}(\rho, \delta, \mathbf{p}, \tau) = & A_u \frac{\rho_{\tau'}}{\rho_0} + A_l \frac{\rho_{\tau}}{\rho_0} + B \left(\frac{\rho}{\rho_0} \right)^{\sigma} (1 - x\delta^2) \\
 & - 8\tau x \frac{B}{\sigma + 1} \frac{\rho^{\sigma-1}}{\rho_0^{\sigma}} \delta \rho_{\tau'} + \frac{2C_{\tau,\tau}}{\rho_0} \\
 & \times \int d^3\mathbf{p}' \frac{f_{\tau}(\mathbf{r}, \mathbf{p}')}{1 + (\mathbf{p} - \mathbf{p}')^2/\Lambda^2} + \frac{2C_{\tau,\tau'}}{\rho_0} \\
 & \times \int d^3\mathbf{p}' \frac{f_{\tau'}(\mathbf{r}, \mathbf{p}')}{1 + (\mathbf{p} - \mathbf{p}')^2/\Lambda^2}, \quad (2)
 \end{aligned}$$

where ρ_{τ} and ρ_{τ}' denote proton or neutron density with $\tau \neq \tau'$ and $\delta \equiv (\rho_n - \rho_p)/\rho$ is the isospin asymmetry. The $f_{\tau}(\mathbf{r}, \mathbf{p})$ denotes the phase-space distribution function at coordinate \mathbf{r} and momentum \mathbf{p} . The corresponding momentum-dependent interaction (MDI) leads to an incompressibility of $K_0 = 211$ MeV for the symmetric nuclear matter at saturation density. On the right-hand side of Eq. (2), the first four terms with $\sigma = 3/4$ and $B = 106.35$ MeV describe the momentum-independent interaction. The terms with parameters $C_{\tau,\tau} = -11.7$ MeV and $C_{\tau,\tau'} = -103.4$ MeV describe the momentum-dependent interaction of a nucleon of isospin τ and momentum \mathbf{p} with like and unlike nucleons in the background fields, respectively. We stress that the momentum dependence in both the isoscalar and the isovector potentials is taken into account in a way consistent with that known empirically from nucleon optical potentials [37]. With the parameter $\Lambda = 1.0p_F^0$, where p_F^0 denotes nucleon Fermi momentum at ρ_0 , the isoscalar potential $[U_n(\rho, p) + U_p(\rho, p)]/2$ coincides with predictions from the variational many-body theory using inputs constrained by nucleon-nucleon scattering data [37,38], and the isovector potential $[U_n(\rho, p) - U_p(\rho, p)]/2$ also agrees with the momentum dependence of the Lane potential

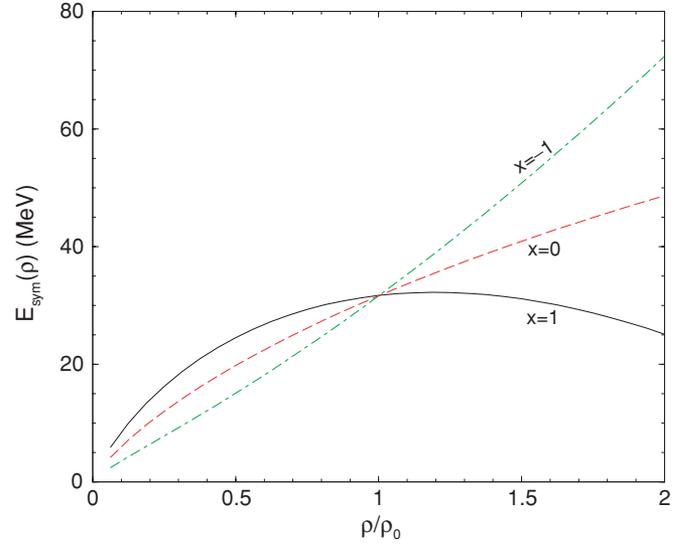


FIG. 1. (Color online) Symmetry energies as a function of baryon number density, ρ , in units of the saturation density, ρ_0 , for three of the equations of state considered in this work.

extracted from nucleon-nucleus scattering experiments up to about 100 MeV [39] and (p,n) charge exchange reactions up to about 45 MeV [37,40].

The parameter x in Eq. (2) is introduced to allow variations in the density dependence of the nuclear symmetry energy $E_{\text{sym}}(\rho)$, which is defined via the parabolic approximation to the nucleon specific energy in isospin asymmetric nuclear matter [20,21], i.e.,

$$E(\rho, \delta) = E(\rho, \delta = 0) + E_{\text{sym}}(\rho)\delta^2 + \mathcal{O}(\delta^4). \quad (3)$$

The symmetry energies for three of the models considered here are displayed in Fig. 1 as a function of density. With $x = 1$, $E_{\text{sym}}(\rho)$ matches what is predicted by a Hartree-Fock calculation using the Gogny effective interaction [36]. The parameters $A_l(x)$ and $A_u(x)$ are $A_l(x) = -120.57 + 2Bx/(\sigma + 1)$ and $A_u(x) = -95.98 - 2Bx/(\sigma + 1)$, respectively. It is important to note that large positive (negative) values of x lead to a higher (lower) symmetry energy at subsaturation densities, but a lower (higher) symmetry energy at supersaturation densities.

An example of the results from the transport calculations, taken from Ref. [25], is given in Fig. 2 for the MDI EOS with $x = -1$. The time evolution of R_i is given for this equation of state. The evolution of the average central density ρ in units of the saturation density ρ_0 is also given. It is clear that the late-time evolution of R_i for the MDI equation of state matches the data obtained from MSU. The central density at these times is quite small, indicating clearly that R_i is sensitive to the symmetry energy at subsaturation densities.

Because the MDI EOS in the form above does not easily avail itself for the calculation of the structure of lead nuclei, we choose to fit the EOS to a Skyrme model and use a Skyrme-Hartree-Fock code to calculate the corresponding lead nucleus. This procedure was used successfully to predict the neutron skin based on the Akmal *et al.* EOS [41] in Ref. [1].

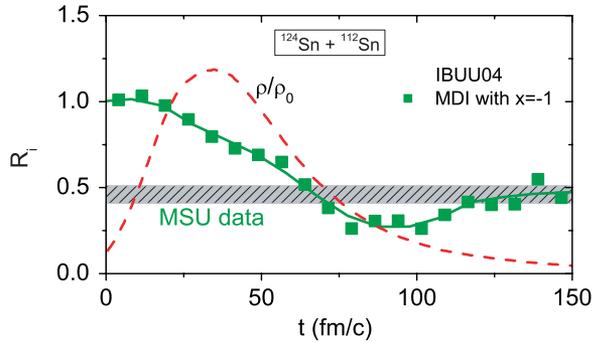


FIG. 2. (Color online) Time evolutions of R_i and average central density for MDI and SBKD interactions with $x = -1$.

The four MDI equations of state with different values of x were fitted to Skyrme models constrained to values for the binding energy (E_b) and the charge radius (R_{ch}) for lead which were within 2% of the experimental values. For the equation of state with $x = -1$, the results of the fit are displayed in Fig. 3. The similar nature of the Skyrme and MDI parametrizations allows for a very close fit. For all four fits employed, the slope, $L \equiv 3\rho_0(dE_{sym}/d\rho)_{\rho=\rho_0}$, and the curvature $K_{sym} \equiv 9\rho_0^2(d^2E_{sym}/d\rho^2)_{\rho=\rho_0}$ of the symmetry energy and the final properties of lead nuclei in the Hartree-Fock approximation are given in Table I. Also given in the table are the experimental values.

The effective mass for the original MDI EOS and the new Skyrme model are not as close; for example, the effective mass at saturation density for the MDI EOS with $x = -1$ is 0.67, while for the Skyrme fit it is 0.77. However, the neutron skin thickness is more sensitive to the bulk energetics than to the effective mass. As a demonstration, a new Skyrme fit to the

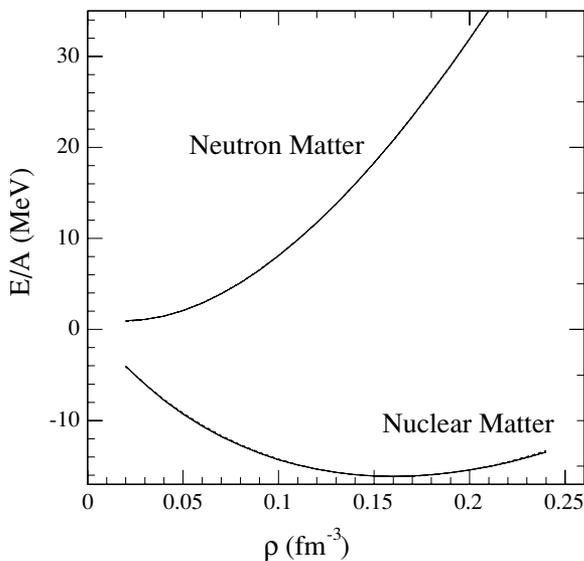


FIG. 3. Results of fitting the MDI EOS for $x = -1$ (solid curves) to a Skyrme EOS (dashed curves). Plotted is the energy per baryon as a function of the baryon density, ρ . The dashed curves are barely visible because of the high quality of the fit.

TABLE I. Properties of lead nuclei for the Skyrme equations of state and their experimental values. L and K_{sym} are the slope and curvature of the corresponding symmetry energy at ρ_0 .

x	E_b (MeV)	R_{ch} (fm)	δR (fm)	L (MeV)	K_{sym} (MeV)
-2	7.8598	5.517	0.38	153.0	276.3
-1	7.8702	5.520	0.28	107.4	94.1
0	7.8584	5.547	0.22	62.1	-88.6
1	7.8719	5.522	0.16	16.4	-270.4
Exp.	7.8675	5.503	0.07-0.24		

MDI EOS with $x = -1$ with a lower effective mass of 0.65 only lowers the skin thickness by 0.01 fm.

Now we turn to the correlation between the degree of isospin diffusion and the size of the neutron skin in ^{208}Pb . Do we expect a correlation between these two seemingly different observables? As has been discussed in detail in Refs. [42,43], the size of neutron skins in heavy nuclei is determined by the difference in pressures on neutrons and protons δP . The latter is proportional to L , which measures the stiffness of the symmetry energy at saturation density. As shown in Table I, the symmetry energy becomes stiffer (for densities larger than the saturation density) as x decreases from 1 to -2, and the size of the neutron skin in ^{208}Pb increases. Alternatively, one can understand this effect by noting that the symmetry energy is lower (e.g., with $x = -2$) at subsaturation densities; the cost of creating a difference between the neutron and proton densities is small, and the skin thickness is large. As the symmetry energy increases with larger values of x , the neutron skin thickness decreases accordingly.

It is also well known that the degree of isospin diffusion in heavy-ion collisions depends sensitively on the stiffness of the symmetry energy [22,24,25,44,45]. A correlation between the degree of isospin diffusion in heavy-ion collisions and the size of neutron skins in heavy nuclei using the same EOS is thus expected. Of course, it is understood that this correlation is not universal, as both the isospin diffusion and size of neutron skins are system dependent. However, an examination of this correlation for any system and simultaneous comparisons with the corresponding data may provide a more stringent constraint on the underlying EOS. Shown in Fig. 4 is our analysis of this correlation for the isospin diffusion in $^{124}\text{Sn}+^{112}\text{Sn}$ and the neutron skin in ^{208}Pb . The available data on both quantities are also included in the graph. There are some remaining systematic uncertainties that are difficult to estimate, which are not addressed here (see Ref. [26] for more details).

From Eq. (1), we can see that $R_i = 1$ implies that the projectilelike residue has the same isospin asymmetry as the projectile ^{124}Sn without any net exchange of isospin asymmetry with the target ^{112}Sn . This is also often referred to as the complete isospin transparency. A value of zero for R_i implies a complete mixing between the projectile and target, indicating the establishment of an isospin equilibrium during the reaction.

The NSCL/MSU data indicate that the mixing is about 50%. Unlike the relation between x and the neutron skin thickness, the relation between R_i and the parameter x is nonmonotonic.

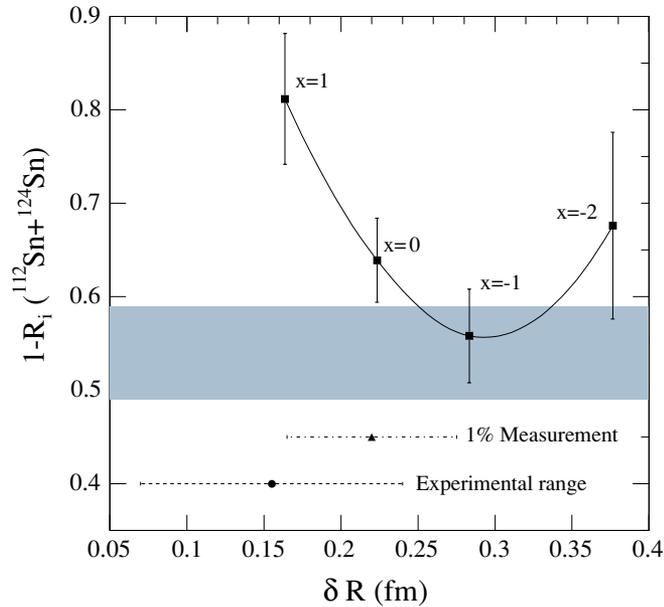


FIG. 4. (Color online) Skin thickness in lead, δR , versus the isospin diffusion parameter $1 - R_i$ for the four equations of state in this work. A sample measurement with an uncertainty corresponding to a 1% measurement of the neutron radius is included, as well as the present acceptable experimental range.

This is because R_i is directly related to the symmetry potential, which depends on both the density and the momentum as discussed in detail in Ref. [25]. Transport model calculations with $x = -1$ are closest to the experimental data, although $x = 0$ and $x = -2$ are not necessarily excluded within the current uncertainties of both the experimental data and the model calculations.

On comparison with previous estimates for δR , the connection with the moderate amount of isospin diffusion displayed in heavy-ion reactions suggests that δR is in the upper range of the present experimental uncertainty. Only skin thicknesses larger than about 0.2 fm are consistent with the transport model calculations. Skin thicknesses lower than 0.15 fm appear to be excluded. However, the isospin dependence of the in-medium nucleon-nucleon cross sections may affect the isospin diffusion. It was shown analytically that the degree of isospin diffusion depends on both the symmetry energy and the neutron-proton scattering cross section [44]. Because of the momentum dependence of the single nucleon potential of Eq. (2), not only are the values of the n - n and p - p cross

sections reduced and different from each other compared to their free-space values, the ratio $2\sigma_{np}/(\sigma_{pp} + \sigma_{nn})$ is also modified from its free-space value. While the reduction of in-medium n - n and p - p scattering cross sections is expected to have little effect on the value of R_i , the reduced in-medium n - p scattering cross sections leads to smaller isospin diffusion. To reproduce the NSCL/MSU data, a larger symmetry energy at subsaturation densities is then needed. The use of in-medium cross sections will, in effect, decrease the preferred neutron skin thicknesses for the isospin diffusion data. An investigation of this effect is currently underway, and the results will be reported elsewhere.

Although isospin diffusion in heavy-ion collisions constrains primarily the symmetry energy at subsaturation densities, it is useful to check to ensure that the information from heavy-ion collisions is not inconsistent with neutron star observations. Neutron star radii are sensitive probes of the symmetry energy at higher density [46]. We solve the Tolman-Oppenheimer-Volkov equations for the MDI EOS with $x = 0, -1$, and -2 . The maximum masses (in order of decreasing x) are 1.92, 2.08, and 2.13 M_\odot , and the radii of the maximum mass stars are 10.1, 11.2, and 11.8 km. In addition to being consistent with the compactness constraint given by the measurement of the redshift of EXO0748-676 in Ref. [47], this equation of state is also consistent with the recent neutron star radius measurement in Ref. [48].

Recently, Todd-Rutel *et al.* [49] also explored the effect of the symmetry energy on the neutron skin thickness in lead. Using an relativistic mean-field model, they construct an equation of state that faithfully describes the giant monopole and dipole resonances in nuclei. Their model suggests a neutron skin thickness of 0.21 fm in Pb^{208} , which is consistent with our constraints from isospin diffusion in heavy-ion collisions.

In summary, we examined the correlation of the degree of isospin diffusion in heavy-ion collisions and the size of neutron skin in ^{208}Pb , by using the same EOS within the IBUU04 transport model and the HF approach. We found that neutron skin thicknesses less than 0.15 are disfavored by the isospin diffusion data. Reduction of the experimental and theoretical uncertainties will likely lead to an important constraint on the symmetry energy at subsaturation density.

We thank Lie-Wen Chen and Madappa Prakash for helpful discussions. This work was supported in part by the Department of Energy under grant DOE/W-7405-ENG-36 (for A. W. Steiner), by the National Science Foundation under grant PHY-0243571, PHY-0354572, and by the NASA-Arkansas Space Grant Consortium Award ASU15154 (for B.-A. Li)

- [1] A. W. Steiner, M. Prakash, J. M. Lattimer, and P. J. Ellis, *Phys. Rep.* **411**, 325 (2005).
- [2] D. H. Youngblood, H. L. Clark, and Y.-W. Lui, *Phys. Rev. Lett.* **82**, 691 (1999).
- [3] H. H. Gutbrod, A. M. Poskanzer, and H. G. Ritter, *Rep. Prog. Phys.* **52**, 267 (1989).
- [4] P. Danielewicz and G. Odyniec, *Phys. Lett.* **B157**, 146 (1985).
- [5] H. A. Gustafsson, H. H. Gutbrod, B. Kolb, H. Löhner,

- B. Ludewigt, A. M. Poskanzer, T. Renner, H. Riedesel, H. G. Ritter, A. Warwick *et al.*, *Phys. Rev. Lett.* **52**, 1590 (1984).
- [6] G. M. Welke, M. Prakash, T. T. S. Kuo, S. Das Gupta, and C. Gale, *Phys. Rev. C* **38**, 2101 (1988).
- [7] P. J. Siemens and J. O. Rasmussen, *Phys. Rev. Lett.* **42**, 880 (1979).
- [8] P. Danielewicz, R. Lacey, and W. G. Lynch, *Science* **298**, 1592 (2002).

- [9] G. Colò, N. V. Giai, J. Meyer, K. Bennaceur, and P. Bonche, *Phys. Rev. C* **70**, 024307 (2004).
- [10] H. Müller and B. D. Serot, *Phys. Rev. C* **52**, 2072 (1995).
- [11] B. A. Li and C. M. Ko, *Nucl. Phys.* **A618**, 498 (1997).
- [12] V. Baran, M. Colonna, M. Di Toro, and A. B. Larionov, *Nucl. Phys.* **A632**, 287 (1998).
- [13] H. S. Xu, M. B. Tsang, T. X. Liu, X. D. Liu, W. G. Lynch, W. P. Tan, A. Vander Molen, G. Verde, A. Wagner, H. F. Xi *et al.*, *Phys. Rev. Lett.* **85**, 716 (2000).
- [14] W. P. Tan, B.-A. Li, R. Donangelo, C. K. Gelbke, M. J. van Goethem, X. D. Liu, W. G. Lynch, S. Souza, M. B. Tsang, G. Verde *et al.*, *Phys. Rev. C* **64**, 051901(R) (2001).
- [15] M. B. Tsang, W. A. Friedman, C. K. Gelbke, W. G. Lynch, G. Verde, and H. S. Xu, *Phys. Rev. Lett.* **86**, 5023 (2001).
- [16] A. Ono, P. Danielewicz, W. A. Friedman, W. G. Lynch, and M. B. Tsang, *Phys. Rev. C* **68**, 051601(R) (2003).
- [17] B.-A. Li, *Phys. Rev. Lett.* **85**, 4221 (2000).
- [18] B.-A. Li, *Phys. Rev. Lett.* **88**, 192701 (2002).
- [19] L.-W. Chen, V. Greco, C. M. Ko, and B.-A. Li, *Phys. Rev. Lett.* **90**, 162701 (2003).
- [20] B.-A. Li, C. M. Ko, and W. Bauer, *Int. J. Mod. Phys. E* **7**, 147 (1998).
- [21] B.-A. Li and W. U. Schröder, eds., *Isospin Physics in Heavy-Ion Collisions at Intermediate Energies* (Nova Science Publishers, Inc., New York, 2001).
- [22] V. Baran, M. Colonna, V. Greco, and M. Di Toro, *Phys. Rep.* **410**, 335 (2005).
- [23] B.-A. Li, G. C. Yong, and W. Zuo, *Phys. Rev. C* **71**, 014608 (2005).
- [24] M. B. Tsang, T. X. Liu, L. Shi, P. Danielewicz, C. K. Gelbke, X. D. Liu, W. G. Lynch, W. P. Tan, G. Verde, A. Wagner *et al.*, *Phys. Rev. Lett.* **92**, 062701 (2004).
- [25] L.-W. Chen, C. M. Ko, and B.-A. Li, *Phys. Rev. Lett.* **94**, 032701 (2005).
- [26] B.-A. Li, C. B. Das, S. Das Gupta, and C. Gale, *Phys. Rev. C* **69**, 011603(R) (2004).
- [27] B.-A. Li, C. B. Das, S. Das Gupta, and C. Gale, *Nucl. Phys.* **A735**, 563 (2004).
- [28] B. A. Brown, *Phys. Rev. Lett.* **85**, 5296 (2000).
- [29] S. Typel and B. A. Brown, *Phys. Rev. C* **64**, 027302 (2001).
- [30] V. E. Starodubsky and N. M. Hintz, *Phys. Rev. C* **49**, 2118 (1994).
- [31] B. C. Clark, L. J. Kerr, and S. Hama, *Phys. Rev. C* **67**, 054605 (2003).
- [32] F. Rami, Y. Leifels, B. de Schauenburg, A. Gobbi, B. Hong, J. P. Alard, A. Andronic, R. Averbeck, V. Barret, Z. Basrak *et al.*, *Phys. Rev. Lett.* **84**, 1120 (2000).
- [33] M. Prakash, T. T. S. Kuo, and S. Das Gupta, *Phys. Rev. C* **37**, 2253 (1988).
- [34] M. Prakash, I. Bombaci, M. Prakash, P. J. Ellis, and J. M. Lattimer, *Phys. Rep.* **280**, 1 (1997).
- [35] I. Bombaci, in Ref. [21], p. 35.
- [36] C. B. Das, S. Das Gupta, C. Gale, and B.-A. Li, *Phys. Rev. C* **67**, 034611 (2003).
- [37] B.-A. Li, L.-W. Chen, C. B. Das, S. Das Gupta, C. Gale, G. C. Yong, and W. Zuo, *nucl-th/0504069* (2005).
- [38] R. B. Wiringa, *Phys. Rev. C* **38**, 2967 (1988).
- [39] P. E. Hodgson, *The Nucleon Optical Model* (World Scientific, Singapore, 1994).
- [40] G. Hoffmann, *Phys. Rev. Lett.* **29**, 227 (1972).
- [41] A. Akmal, V. R. Pandharipande, and D. G. Ravenhall, *Phys. Rev. C* **58**, 1804 (1998).
- [42] C. J. Horowitz and J. Piekarewicz, *Phys. Rev. Lett.* **86**, 5647 (2001).
- [43] C. J. Horowitz and J. Piekarewicz, *Phys. Rev. C* **66**, 055803 (2002).
- [44] L. Shi and P. Danielewicz, *Phys. Rev. C* **68**, 064604 (2003).
- [45] B.-A. Li, *Phys. Rev. C* **69**, 034614 (2004).
- [46] J. M. Lattimer and M. Prakash, *Astrophys. J.* **550**, 426 (2001).
- [47] J. Cottam, F. Paerels, and M. Mendez, *Nature (London)* **420**, 51 (2002).
- [48] B. Gendre, D. Barret, and N. Webb, *Astron. Astrophys.* **403**, L11 (2003).
- [49] B. G. Todd-Rutel and J. Piekarewicz, *Phys. Rev. Lett.* **95**, 122501 (2005).