Probing the Symmetry Energy with the Spectral Pion Ratio

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Many neutron star (NS) properties, such as the proton fraction within a NS, reflect the symmetry energy contributions to the Equation of State that dominate when neutron and proton densities differ strongly. To constrain these contributions at supra-saturation densities, we measure the spectra of charged pions produced by colliding rare isotope tin (Sn) beams with isotopically enriched Sn targets. Using ratios of the charged pion spectra measured at high transverse momenta, we deduce the slope of the symmetry energy to be $2c < L < 117$ MeV. This value is slightly lower but consistent with the $L$ values deduced from a recent measurement of the neutron skin thickness of $^{208}$Pb.

Recent gravitational wave measurements of the neutron star merger event GW170817 provide information about the deformability of neutron stars (NS) [1, 2]. Analyses of the gravitational wave signal reveal that this deformability mainly reflects the nuclear Equation of State (EoS) at densities of about twice the saturation density of nuclear matter, $\rho_0 \approx 2.4 \times 10^{14}$ g cm$^{-3}$ or 0.16 fm$^{-3}$. While the GW170817 observations provide key insights into NS and their mergers, they do not reveal how the NS EoS depends on the abundances of its constituent neutrons, protons, $\alpha$ resonances, and pions [3–12]. To understand what is the prevailing form of matter in the NS outer core, such microscopic information is essential.

Microscopic information about the EoS has only been extracted from laboratory experiments. Measurements of nucleus-nucleus collisions have constrained the EoS for symmetric matter comprised of equal proton, $\rho_p$, and neutron, $\rho_n$, densities for total densities $\rho = \rho_n + \rho_p$ of $\rho_0 \leq \rho \leq 4.5\rho_0$ [13–15]. The main challenge at $\rho > \rho_0$ is to understand the symmetry energy, which describes how the EoS depends upon isovector potentials that have the opposite sign for neutrons as for protons and depend linearly on the difference between neutron and proton densities $(\rho_n - \rho_p)$, or equivalently on the isospin asymmetry $\delta = (\rho_n - \rho_p)/\rho$ [3, 7, 9, 16–18].

The symmetry energy has been constrained at sub-saturation densities using a variety of nuclear structure and reaction observations [16, 17, 19]. To probe higher densities, one must study central collisions between two complex nuclei. At incident energies of about 300 AMeV and above, nuclear matter

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can be compressed to densities approaching $2 \rho_0$ [20]. The isovector mean field potentials cause the flow of neutrons emitted from this dense region to differ from the flow of protons; this difference provides an observable that can constrain the symmetry energy [18, 21].

In these dense regions, nucleon-nucleon inelastic collisions produce $\Delta$ baryons that decay to nucleons by emitting pions. From the $\Delta$ production and decay cross sections, one expects the ratio $M(\pi^-)/M(\pi^+)\equiv M$ of the multiplicity (M) of negatively and positively charged pions per collision to be proportional to $(\rho_n/\rho_p)^2$ [18, 22]. Because the ratio $(\rho_n/\rho_p)$ strongly reflects the isovector mean field potentials within this dense region, both the total pion multiplicity yield ratio $M(\pi^-)/M(\pi^+)$ [18, 23] and the dependence of the pion ratio on pion momentum [23–25], reflect the density dependence of the symmetry energy. Existing studies of $M(\pi^-)/M(\pi^+)$ [26, 27] with stable nuclear beams have not provided a consistent constraint on the symmetry energy at supra-saturation densities, $\rho > \rho_0$. This may result from different assumptions for the $\Delta$ and pion potentials that cause the calculated low energy pion spectra, the $M(\pi^-)/M(\pi^+)$ ratios and the symmetry energy constraints to differ [28].

Powerful new radioactive isotope facilities are being built to investigate how nuclei and the nuclear EoS depend on $\rho$. These facilities, which are not simply satisfied at the two-body level due to the implementation of the conservation of total energy for the system, which is not simply satisfied at the two-body level due to the momentum and isospin asymmetry dependence of interactions. This involves modifying the collision term to allow for energy transfer between scattering particles and the rest of the system, leading to shifts of particle production thresholds [27, 44, 45]. With this correction, consistent constraints for the symmetry energy density dependence were obtained from pion production and elliptic flow [27]. Further details of this model can be found in Refs. [21, 27, 28, 43]. At beam energies of 270 AMeV, high energy pions are primarily produced by exciting $\Delta(1232)$ baryons via two-nucleon $N + N \rightarrow N + \Delta$ inelastic scattering processes. These $\Delta$’s may scatter elastically or inelastically via $N + \Delta \rightarrow N + \Delta'$ or decay via $\Delta \rightarrow N + \pi$ producing pions. Pions, in turn, can be absorbed via $\pi + N \rightarrow \Delta$. Details of the $\Delta$ resonance production parameterization and its modification in nuclear medium

These background contributions are insignificant.

The TPC pion acceptance in the current experiment allows energy of pions to be accurately measured down to 0 MeV in the center-of-mass of the total system (CM). We focus on pions measured to polar angles of $\theta_{CM} < 90^\circ$ with respect to the beam where pion acceptance is complete. This angular cut is also applied to the theoretical calculations discussed later. We calculate the efficiency by embedding Monte-Carlo pion tracks into real events and determining the fraction of these tracks that are accurately reconstructed. We used a calibration beam composed of hydrogen isotopes at well known momenta to check the momentum determination of the TPC. The momentum values obtained by using the TPC design geometry and SAMURAI dipole magnetic field agreed to within 1% of the known values [41]. The estimated systematic uncertainties are 4% for the individual pion spectra and 2% for the single and double ratios of charged pion spectra. These uncertainties are incorporated into the discussion below.

The total $\pi^-$ and $\pi^+$ multiplicities and their ratios for central ($b \approx 3$ fm) $^{132}$Sn + $^{124}$Sn, $^{112}$Sn + $^{124}$Sn, $^{108}$Sn + $^{112}$Sn collisions are published in Ref. [42]. Comparisons of the total pion ratios predicted by seven different theoretical calculations exhibit differences among them that exceed their sensitivity to the symmetry energy. Different assumptions regarding the mean field potentials for $\Delta$ baryons and pions can strongly influence the production of low energy pions and thus the total charged pion multiplicities and their ratios [28]. To reduce this sensitivity, we focus on pion spectra at higher momenta where sensitivity to the isospin dependence of the nucleonic mean fields dominates [28]. Using the pion spectral ratios at high transverse momenta, we obtain a correlated constraint at supra-saturation densities on the symmetry energy and the momentum dependence of the isovector nucleonic mean field potentials.

For our investigations, we use the dcQMD semi-classical Quantum Molecular Dynamics (QMD) model of Ref. [28]. This model has provided constraints on the symmetry energy from neutron and proton elliptic flow measurements [21] and from pion production [27, 43]. It also provides reasonable predictions of the pion multiplicities and ratios for the current experiment [42]. A unique aspect of the dcQMD model is the implementation of the conservation of total energy for the system, which is not simply satisfied at the two-body level due to the momentum dependence of the isospin asymmetry dependence of interactions. This involves modifying the collision term to allow for energy transfer between scattering particles and the rest of the system, leading to shifts of particle production thresholds [27, 44, 45]. With this correction, consistent constraints for the symmetry energy density dependence were obtained from pion production and elliptic flow [27]. Further details of this model can be found in Refs. [21, 27, 28, 43].
can be found in Refs. [46, 47]. The present calculations require realistic binding energies per nucleon, charged radii and neutron skins for projectile and target nuclei and a good quantitative description of the experimental stopping, directed flow and elliptic flow observables [48, 49]. These prior analyses are consistent with the isoscalar effective mass $m^*/m = 0.7$, compressibility modulus $K_0 = 245$ MeV [28] and in-medium elastic nucleon-nucleon cross-sections [50] used here.

The Gaussian wave functions for nucleons and pions in deQMD have widths that reflect the experimental ratio of pion-to-proton charge radii [43]. Pions move under the influence of the Coulomb interaction and $S$ and $P$ wave pion optical potentials calculated with the “Batty-1” parameters of Ref. [43, 51]. We find that the usual Ansatz of setting the $\Delta$ potential in nuclear matter equal to that of nucleons leads to incorrect $\pi^-$ and $\pi^+$ production thresholds and total multiplicities [28, 42]. Therefore, we adjust the potential depths at saturation per nucleon and is given by [52]:

$$
\frac{E}{N}(\rho, \delta) = KE(\rho, \delta) + A_0 \rho (1 - \delta^2) + A_1 \rho (1 + \delta^2) + \frac{B}{\sigma + 1} \rho^{\sigma} (1 - \chi \delta^2) + \frac{D}{3} \rho^2 (1 - \gamma \delta^2)
$$

$$
+ \frac{1}{\rho_0} \sum_{\tau, \tau'} C_{\tau\tau'} \int d^3\mathbf{p}_d d^3\mathbf{p}_f \frac{f_s(\mathbf{p}_d, \mathbf{p}_f) f_t(\mathbf{p}_s, \mathbf{p}_t)}{1 + (\mathbf{p} - \mathbf{p}')^2/A^2}.
$$

(1)

Here, $KE(\rho, \delta)$ is the kinetic energy density, followed by four local potential energy terms that depend on density $\rho$ and asymmetry $\delta$. The final non-local term models Pauli exchange terms and the finite range of nucleon-nucleon interactions. Parameter $D$ controls the compressibility $K_0 = 245$ MeV and skewness $Q_0 = -350$ MeV of symmetric matter, and $x$ and $y$ controls slope $L$ and curvature $K_{sym}$ parameters of the symmetry energy $S(\rho)$. We correlate $L$ and $K_{sym}$ via $K_{sym} = -488 + 6.728 \times L$ (MeV) and also set $S(\rho = 0.1 \text{ fm}^{-3}) = 25.5$ MeV, consistent with nuclear mass and radius measurements [53, 54].

The left and right panels of Fig. 1 show the CM transverse momentum spectra $dM/dp_T$ at $\theta_{CM} < 90^\circ$ for the very neutron rich $^{132}\text{Sn} + ^{124}\text{Sn}$ and the nearly symmetric $^{108}\text{Sn} + ^{112}\text{Sn}$ systems, respectively. The difference in the $p_T$ values for the maxima of the $\pi^-$ and $\pi^+$ spectra reflects the influence of the Coulomb interaction. The calculations with $L = 80$ MeV, shown in the figure have been fitted to the total multiplicities by optimizing the $\Delta$ potentials and effective masses. Here, the scaled difference between neutron and proton effective masses, $\Delta m_{np}/\delta = [m_n^* - m_p^*]/(m\delta)$ is set to zero. The red curves show the resulting calculations including pion optical potentials while the blue curves show calculations where pion potentials are removed. Simulations without the pion optical potential result in a significant underprediction of the pion spectra at low $p_T$ and that extends over a larger range of momenta in the case of the $\pi^+$ spectra in both reactions. However, the shapes of the spectra at higher transverse momentum $p_T > 200$ MeV $c^{-1}$ are largely unchanged by the choice of $\Delta$ and pion optical potentials, and remain sensitive to the nucleonic mean field potentials and to the symmetry energy [28]. Such sensitivities to the details in pion and $\Delta$ potentials for the low energy pions could account for the differences in transport code predictions for the total pion yields reported in Ref. [42].

Next, we focus on the isovector mean field potentials that contribute to the symmetry energy and are opposite in sign for neutrons vs. protons and $\pi^-$ vs. $\pi^+$. We highlight these isovector potentials by constructing the single ratio $SR(\pi^-/\pi^+) = [dM(\pi^-)/dp_T]/[dM(\pi^+)/dp_T]$. In Fig. 2, $SR(\pi^-/\pi^+)$ for the neutron rich $^{132}\text{Sn} + ^{124}\text{Sn}$ system is shown in the top panel and $SR(\pi^-/\pi^+)$ for the nearly symmetric $^{108}\text{Sn} + ^{112}\text{Sn}$ systems in the bottom panel. The steep rise in the single ratios at low $p_T$ originates from the opposite Coulomb forces experienced by $\pi^-$ and $\pi^+$. We construct the pion single spectral ratios using deQMD with 12 sets of calculations with values for $L$ of (15, 60, 106 and 151 MeV) and $\Delta m_{np}/\delta$ of (-0.33, 0 and 0.33). For clarity, we show only four calculations with ($L$, $\Delta m_{np}/\delta$) = (60, -0.33), (60, 0.33), (151, -0.33) and (151, 0.33) represented by blue solid, blue dashed, red solid and red dashed curves respectively. All calculations under-predict the data at $p_T < 50$ MeV $c^{-1}$ and over-predict the data at $p_T \approx 150$ MeV $c^{-1}$ for both systems. As expected, the neutron rich system of $^{132}\text{Sn} + ^{124}\text{Sn}$ displays much more sensitivity at high $p_T$ to the slope of

FIG. 1. Measured and calculated pion spectra. The red lines are the calculated pion spectra after adjusting the $\Delta$ potential to reproduce the pion multiplicities. The blue lines differ from the red lines in that the the pion optical potential has been removed. The nucleon potentials in these simulations correspond to $L = 80$ MeV and $\Delta m_{np} = 0$. The left and right panels of Fig. 1 show the CM transverse momentum spectra $dM/dp_T$ at $\theta_{CM} < 90^\circ$ for the very neutron rich $^{132}\text{Sn} + ^{124}\text{Sn}$ and the nearly symmetric $^{108}\text{Sn} + ^{112}\text{Sn}$ systems, respectively. The difference in the $p_T$ values for the maxima of the $\pi^-$ and $\pi^+$ spectra reflects the influence of the Coulomb interaction. The calculations with $L = 80$ MeV, shown in the figure have been fitted to the total multiplicities by optimizing the $\Delta$ potentials and effective masses. Here, the scaled difference between neutron and proton effective masses, $\Delta m_{np}/\delta = [m_n^* - m_p^*]/(m\delta)$ is set to zero. The red curves show the resulting calculations including pion optical potentials while the blue curves show calculations where pion potentials are removed. Simulations without the pion optical potential result in a significant underprediction of the pion spectra at low $p_T$ and that extends over a larger range of momenta in the case of the $\pi^+$ spectra in both reactions. However, the shapes of the spectra at higher transverse momentum $p_T > 200$ MeV $c^{-1}$ are largely unchanged by the choice of $\Delta$ and pion optical potentials, and remain sensitive to the nucleonic mean field potentials and to the symmetry energy [28]. Such sensitivities to the details in pion and $\Delta$ potentials for the low energy pions could account for the differences in transport code predictions for the total pion yields reported in Ref. [42].

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the symmetry energy, $L$, than does the nearly symmetric $^{108}$Sn + $^{112}$Sn system. The disagreement with data observed at
low $p_T$ for both systems suggests some inaccuracy in the
theory that does not depend strongly on the asymmetry $\delta$. Such
effects could originate from inaccuracies in the treatment of
Coulomb interactions or of the pion optical potentials above
saturation density, for example. Non-resonant pion emission
or absorption, neglected in the current calculations, could also
contribute to the incorrect shape of the single spectral ra-
tios at low $p_T$ in Fig. 2 and its influence should be inves-
tigated. These effects should be much less important above
200 MeV $c^{-1}$ where the trends of the data and the calculations
become more comparable.

Interpolating the dcQMD calculations, we fit the single ra-
tios at $p_T > 200$ MeV $c^{-1}$ and extract correlated constraints
on $L$ and $\Delta m^*_{np}$ shown in Fig. 3. The correlated nature of
this constraint means that larger values for $\Delta m^*_{np}$ would imply
larger values for $L$. Absent any constraint on $\Delta m^*_{np}$, the best

fit value is $L = 79.9 \pm 37.6$ MeV with $S_0 = 35.3 \pm 2.8$ MeV,
with statistical uncertainty making the largest contribution to
the total uncertainty. This value is consistent with constraints
extracted from proton and neutron elliptic flows in Ref. [21]
using the same transport model.

Since both reactions have the same total charge, approxi-
mately the same isoscalar fields and differ principally by their asymmetry $\delta$, the double ratio,
$\text{DR}(\pi^-/\pi^+) = \text{SR}(\pi^-/\pi^+)_{132+124}/\text{SR}(\pi^-/\pi^+)_{108+112}$, should
primarily reflect the isovector mean fields that determine the
symmetry energy. Experimentally, the double ratio cancels

![FIG. 2. Single pion spectral ratios for $^{132}$Sn+$^{124}$Sn (top panel) and $^{108}$Sn+$^{112}$Sn (bottom panel) reactions. The curves are dcQMD predictions from different $L$ and $\Delta m^*_{np}$ values listed in the top panel.](image1)

![FIG. 3. Correlation contours between $L$ and $\Delta m^*_{np}/\delta$ extracted from the single pion spectral ratio of the neutron-rich $^{132}$Sn+$^{124}$Sn and near symmetric $^{108}$Sn+$^{112}$Sn reactions. The green shaded region lies within the 68% confidence level for data with $p_T > 200$ MeV/c. The dotted blue lines denote contours corresponding to the 95% confidence level.](image2)

![FIG. 4. Transverse momentum spectra of the double pion ratio. The shaded region covers dcQMD predictions within 1$\sigma$ of the most probable values of $L$ and $\Delta m^*_{np}$ values.](image3)
out most of the systematic errors but the statistical errors propagate. The current uncertainties in the double ratios shown in Fig. 4 are large and thus offer less precise constraints than single ratios. Nonetheless, the data are statistically consistent with the predictions indicated by the shaded area allowed by the 1-$\sigma$ range of the $L$ values (49-105 MeV) assuming the most probably value of $\Delta m_{\pi p}/\delta = 0.004$.

Additional measurements would reduce the uncertainties of this constraint. These include pion measurements at higher and lower incident energies to constrain non-resonant pion emission and the interactions of $\Delta$ baryons with nuclear matter. Precise measurements of the ratios of neutron and proton energy spectra should constrain $\Delta m_{\pi p}$ more accurately removing an important contribution to the present uncertainty. Complementary measurements of proton and neutron elliptic flow are also desirable. Finally, ongoing efforts in transport theory by the Transport Model Evaluation Project (TMEP) collaboration (e.g. Ref. [55]) would allow a more comprehensive exploration of the equation of state of dense neutron-rich matter via heavy ion collisions.

In conclusion, we present precise spectra of charged pions produced in intermediate energy collisions involving rare isotope Sn beams on isotopic Sn targets and use them to constrain the symmetry energy at supra-saturation densities. To avoid complications resulting from poorly constrained $\Delta$ baryon potentials and non-resonant pion emission that are currently difficult to model, we focus our analyses on energetic pions with the symmetry energy at supra-saturation densities. To avoid complications resulting from poorly constrained $\Delta$ baryon potentials and non-resonant pion emission that are currently difficult to model, we focus our analyses on energetic pions with the symmetry energy at supra-saturation densities. To avoid complications resulting from poorly constrained $\Delta$ baryon potentials and non-resonant pion emission that are currently difficult to model, we focus our analyses on energetic pions with the symmetry energy at supra-saturation densities.

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1. B. P. Abbott et al. (LIGO Scientific, Virgo), GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral, Phys. Rev. Lett. 119, 161101 (2017).
2. B. P. Abbott et al. (The LIGO Scientific Collaboration and the Virgo Collaboration), Gw170817: Measurements of neutron star radii and equation of state, Phys. Rev. Lett. 121, 161101 (2018).
3. M. Tsang, W. Lynch, P. Danielewicz, and C. Tsang, Symmetry energy constraints from GW170817 and laboratory experiments, Phys. Lett. B 795, 533 (2019).
4. C. Tsang, M. Tsang, P. Danielewicz, W. Lynch, and F. Fattoyev, Insights on Skyrme parameters from GW170817, Phys. Lett. B 796, 1 (2019).
5. Y. Lim and J. W. Holt, Neutron star tidal deformabilities constrained by nuclear theory and experiment, Phys. Rev. Lett. 121, 062701 (2018).
6. I. Tews, J. Margueron, and S. Reddy, Critical examination of constraints on the equation of state of dense matter obtained from GW170817, Phys. Rev. C 98, 045804 (2018).
7. J. Lattimer and M. Prakash, Neutron star structure and the equation of state, Astrophys. J. 550, 426 (2001).
8. A. Drago, A. Lavagno, G. Pagliara, and D. Pigato, Early appearance of $\Delta$ isobars in neutron stars, Phys. Rev. C 90, 065809 (2014).
9. C. Ducoin, J. Margueron, C. Providência, and I. Vidaña, Core-crust transition in neutron stars: Predictivity of density developments, Phys. Rev. C 83, 045810 (2011).
10. J. M. Lattimer and M. Prakash, The Equation of State of Hot, Dense Matter and Neutron Stars, Phys. Rept. 621, 127 (2016).
11. J. J. Li and A. Sedrakian, Implications from GW170817 for $\Delta$-isobar Admixed Hypernuclear Compact Stars, Astrophys. J. Lett. 874, L22 (2019).
12. B. Fore and S. Reddy, Pions in hot dense matter and their astrophysical implications, Phys. Rev. C 101, 035809 (2020).
13. P. Danielewicz, R. Lacey, and W. G. Lynch, Determination of the equation of state of dense matter, Science 298, 1592 (2002).
14. W. Lynch, M. Tsang, Y. Zhang, P. Danielewicz, M. Famiano, Z. Li, and A. Steiner, Probing the Symmetry Energy with Heavy Ions, Prog. Part. Nucl. Phys. 62, 427 (2009).
15. A. Le Fèvre, Y. Leifels, W. Reisdorf, J. Aichelin, and C. Hartnack, Constraining the nuclear matter equation of state around twice saturation density, Nucl. Phys. A 945, 112 (2016).
16. C. Horowitz, E. Brown, Y. Kim, W. Lynch, R. Michaels, A. Ono, J. Piekarewicz, M. Tsang, and H. Wolter, A way forward in the study of the symmetry energy: experiment, theory, and observation, J. Phys. G 41, 093001 (2014).
17. M. B. Tsang, J. R. Stone, F. Camera, P. Danielewicz, S. Gandolfi, K. Hebeler, C. J. Horowitz, J. Lee, W. G. Lynch, Z. Kohley, R. Lemmon, P. Möller, T. Murakami, S. Riordan, X. Roca-Maza, F. Sammarruca, A. W. Steiner, I. Vidaña, and S. J. Yennello, Constraints on the symmetry energy and neutron skins from experiments and theory, Phys. Rev. C 86, 015803 (2012).
M. D. Cozma, Feasibility of constraining the curvature parameter of the symmetry energy using elliptic flow data, Eur. Phys. J. A 54, 40 (2018).

Z. Xiao, B.-A. Li, G.-C. Yong, and M. Zhang, Circumstantial Evidence for a Soft Nuclear Symmetry Energy at Suprasaturation Densities, Phys. Rev. Lett. 102, 062502 (2009).

M. D. Cozma, The impact of energy conservation in transport models on the $π^-/π^+$ multiplicity ratio in heavy-ion collisions and the symmetry energy, Phys. Lett. B 753, 166 (2016).

M. D. Cozma and M. B. Tsang, In-medium $\delta(1232)$ potential, pion production in heavy-ion collisions and the symmetry energy (2021), arXiv:2101.08679 [nucl-th].

Y. Blumenfeld, T. Nilsson, and P. Van Duppen, Facilities and methods for radioactive ion beam production, Phys. Scripta T 152, 014023 (2013).

H. Otsu, S. Koyama, N. Chiga, T. Iseobe, T. Kobayashi, Y. Kondo, M. Kurokawa, W. Lynch, T. Motobayashi, T. Murakami, T. Nakamura, M. Kurata-Nishimura, V. Panin, H. Sato, Y. Shimizu, H. Sakurai, M. Tsang, K. Yoneda, and H. Wang, SAMURAI in its operation phase for RIBF users, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 376, 175 (2016), proceedings of the XVIII International Conference on Electromagnetic Isotope Separators and Related Topics (EMIS2015), Grand Rapids, MI, U.S.A., 11-15 May 2015.

R. Shane, A. McIntosh, T. Iseobe, W. Lynch, H. Baba, J. Barney, Z. Chajecki, M. Chartier, J. Estee, M. Famiano, B. Hong, K. Ieki, G. Jiang, R. Lemmon, F. Lu, T. Murakami, N. Nakatsuka, M. Nishimura, R. Olsen, W. Powell, H. Sakurai, A. Taketani, S. Tangwancharoen, M. Tsang, T. Usukura, R. Wang, S. Yennello, and J. Yurkon, SrRIT: A time-projection chamber for symmetry-energy studies, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 784, 513 (2015), symposium on Radiation Measurements and Applications 2014 (SORMA XV).

S. Tangwancharoen, W. G. Lynch, J. Barney, J. Estee, R. Shane, M. B. Tsang, Y. Zhang, T. Iseobe, M. Kurata-Nishimura, T. Murakami, Z. Xiao, Y. F. Zhang, and the SrRIT collaboration, A gating grid driver for time-projection chambers, Nucl. Inst. Meth. A 853, 44 (2017).
A. Larionov and U. Mosel, The N N
G. Ferini, T. Gaitanos, M. Colonna, M. Di Toro, and H. H.
W. Reisdorf
T. Song and C. M. Ko, Modifications of the pion-production
C. J. Batty, S. F. Biagi, E. Friedman, S. D. Hoath, J. D. Davies,
W. Reisdorf
M. D. Cozma, Constraining the density dependence of the sym-
Q. Li, C. Shen, C. Guo, Y. Wang, Z. Li, I. Lukasik, and W. Traut-
mann, Nonequilibrium dynamics in heavy-ion collisions at low
energies available at the GSI Schwerionen Synchrotron, Phys.
Rev. C86, 1 (2012).
[50] Q. Li, C. Shen, C. Guo, Y. Wang, Z. Li, I. Lukasik, and W. Traut-
mann, Nonequilibrium dynamics in heavy-ion collisions at low
energies available at the GSI Schwerionen Synchrotron, Phys.
Rev. C86, 1 (2012).
[51] C. J. Batty, S. F. Biagi, E. Friedman, S. D. Hoath, J. D. Davies,
G. J. Pyle, and G. T. A. Squier, Shifts and Widths of 2p Levels
in Pionic Atoms, Phys. Rev. Lett. 93, 044617 (2011).
[52] C. B. Das, S. DasGupta, C. Gale, and B.-A. Li, Momentum
dependence of symmetry potential in asymmetric nuclear matter
for transport model calculations, Phys. Rev. C67, 034611 (2003).
[53] B. A. Brown, Constraints on the Skyrme Equations of State
from Properties of Doubly Magic Nuclei, Phys. Rev. Lett. 111,
232502 (2013).
[54] Z. Zhang and L.-W. Chen, Constraining the symmetry energy at
subsaturation densities using isotope binding energy difference
and neutron skin thickness, Phys. Lett. B726, 234 (2013).
[55] A. Ono, J. Xu, M. Colonna, P. Danielewicz, C. M. Ko, M. B.
Tsang, Y.-J. Wang, H. Wolter, Y.-X. Zhang, L.-W. Chen,
D. Cozma, H. Elfner, Z.-Q. Feng, N. Ikeno, B.-A. Li, S. Malik,
Y. Nara, T. Ogawa, A. Ohnishi, D. Oliynichenko, J. Su, T. Song,
F.-S. Zhang, and Z. Zhang, Comparison of heavy-ion transport
simulations: Collision integral with pions and Δ resonances in a
box, Phys. Rev. C100, 044617 (2019).
[56] B. T. Reed, F. J. Fattoyev, C. J. Horowitz, and J. Piekarewicz,
Implications of PREX-II on the equation of state of neutron-rich
matter (2021), arXiv:2101.03193 [nucl-th].
[57] D. Adhikari, H. Albataineh, D. Andrioct, K. Aniol, D. S. Arm-
strong, T. Averett, S. Barcus, V. Bellini, R. S. Beminiwatha,
J. F. Benesch, H. Bhatt, D. B. Pathak, D. Bhetuwal, B. Blakie,
Q. Campagna, A. Cansonne, Y. Chen, C. Clarke, J. C. Cornejo,
S. C. Dusa, P. Datta, A. Deshpande, D. Dutta, C. Feldman,
E. Fuchey, C. Gal, D. Gaskell, T. Gatum, C. A. Gayoso,
M. Gericke, C. Ghosh, I. Halilovic, J. O. Hansen, F. Hauenstein,
W. Henry, C. J. Horowitz, C. Jantzi, S. Jian, S. Johnston, D. C.
Jones, B. Karki, S. Katagamoda, C. Keppel, P. M. King, D. E.
King, M. Knauss, K. S. Kumar, T. Kutn, N. Lashley-Collhirst,
G. Leverick, H. Liu, N. Liyange, S. Malace, R. Mammela,
J. Mammel, M. McLaughan, D. McNulty, D. Meekins, C. Metts,
R. Michaels, M. M. Mondal, J. Napolitano, A. Narayan, D. Niko-
laev, M. N. H. Rashad, V. Owen, C. Palatchi, J. Pan, B. Pandey,
P. Park, K. D. Paschke, M. Petrusky, M. L. Pitt, S. Premfilakate,
A. J. R. Puckett, B. Quinn, R. Radloff, S. Rahman, A. Rath-
nayake, B. T. Reed, P. E. Reimer, R. Richards, S. Riordan,
Y. Roblin, S. Seeds, A. Shahiyana, P. Souder, L. Tang, . M. Thiel,
Y. Tian, G. M. Urciuoli, E. W. Wertz, B. Wojtsekhowski, B. Yale,
T. Ye, A. Yoon, A. Zec, W. Zhang, J. Zhang, and X. Zheng,
An Accurate Determination of the Neutron Skin Thickness of
208 Pb through Parity-Violation in Electron Scattering (2021),
arXiv:2102.10767 [nucl-ex].