Measuring neutron skin by grazing isobaric collisions

Hao-jie Xu1, Hanlin Li2, Ying Zhou3, Xiaobao Wang1, Jie Zhao4, Lie-Wen Chen5,3 and Fuqiang Wang6,1,4

1School of Science, Huzhou University, Huzhou, Zhejiang 313000, China
2College of Science, Wuhan University of Science and Technology, Wuhan, Hubei 430065, China
3School of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, and Key Laboratory for Particle Astrophysics and Cosmology (MOE), Shanghai Jiao Tong University, Shanghai 200240, China
4Department of Physics and Astronomy, Purdue University, West Lafayette, Indiana 47907, USA

Neutron skin thickness ($\Delta r_{np}$) of nuclei and the inferred nuclear symmetry energy are of critical importance to nuclear physics and astrophysics. It is traditionally measured by nuclear processes with significant theoretical uncertainties. We recently proposed an indirect measurement of the $\Delta r_{np}$ by charged hadron multiplicities in central isobaric collisions at relativistic energies, which are sensitive to nuclear densities. In this Letter, we propose a direct measurement of the $\Delta r_{np}$ by using net-charge multiplicities in ultra-peripheral (grazing) collisions of those isobars, under the assumption that they are simple superimposition of nucleon-nucleon interactions. We illustrate this novel approach by the TRENTO and URQMD models.

Nuclei are bound states of protons and neutrons by the overall attractive nuclear force. The nuclear strong force is isospin symmetric, however, because of Coulomb interactions, heavy nuclei usually need more neutrons than protons to remain stable. The root-mean-square radius of neutron distribution in a heavy nucleus is thus larger than that of the proton distribution. The difference is referred to as the neutron skin thickness, $\Delta r_{np} \equiv r_n - r_p$ [1]. With more neutrons comes the penalty symmetry energy associated with the asymmetry between the proton and neutron numbers. By measuring the $\Delta r_{np}$, one gains valuable information about the nuclear symmetry energy. Of particular interest is the symmetry energy density slope parameters $L$ at the nuclear saturation density $\rho_0$ [2–5] and $L_c$ at the critical density $\rho_c \approx 0.11$ fm$^{-3}$ [6].

The $\Delta r_{np}$ has traditionally been measured by low-energy electron and hadron scatterings off nuclei [3, 4, 7–9]. Because of the inevitable uncertainties in modeling the strong interaction of the scattering processes in quantum chromodynamics (QCD) [10], large uncertainties on the $L$ and $L_c$ persist. Void of the strong interaction uncertainties, parity-violating scattering processes with electrons [11, 12] and neutrons [13], sensitive to the neutral current, have been measured. The latest result from the Lead Radius Experiment (PREX-II) on the $^{208}$Pb, $\Delta r_{np} = 0.283 \pm 0.071$ fm [14, 15], still has a large statistical uncertainty. This leads to $L_c = 71.5 \pm 22.6$ and $L = 105 \pm 37$ MeV[16], compared to $L = 75 \pm 25$ MeV[17] from traditional scattering experiments, where the uncertainty is dominated by statistical one in the former and the systematic one in the latter. Efforts combining the PREX-II and astro-nuclear observations may improve the $L_c$ and $L$ constraints [18].

Recently, we have proposed to use the ratio of charged hadron multiplicities ($N_{ch}$) in most central collisions of isobars ($^{40}$Ru+$^{40}$Ru and $^{96}$Zr+$^{96}$Zr) at the Relativistic Heavy Ion Collider (RHIC) to help constrain the $\Delta r_{np}$ [19]. This exploits the sensitivity of particle production to nucleon density distribution, which differs slightly between Ru and Zr because of their different $\Delta r_{np}$ values. Note that $N_{ch}$ is isospin insensitive; it is essentially the same among $pp$, $pn$, and $nn$ interactions at high energies (see Table I). Our idea in Ref. [19] probes the nucleon density and, in turn, the neutron’s knowing the precisely measured proton’s; it does not directly probe the neutron density.

The nucleon density difference is, of course, also present in peripheral collisions but there, the $N_{ch}$ sensitivity to $\Delta r_{np}$ is weak (see Fig. 4 of Ref. [20] where the isobaric difference is only 2%). However, those ultra-peripheral collisions, where the nuclei are only grazing each other, must have very different mixture of participant protons and neutrons, and therefore likely yield significantly different net-charge numbers ($\Delta Q$). This is obvious especially for the case of full acceptance with exact charge conservation, in which a proton releases one net-charge number, whereas the contribution from neutrons is none. This difference should also manifest in limited-acceptance midrapidity detectors. By measuring $\Delta Q$ in those grazing collisions, one could in principle determine the difference in the numbers of protons and neutrons participating in those collisions, which is directly sensitive to $\Delta r_{np}$.

To make our idea more concrete, we list in Table I the $\Delta Q$ (and $N_{ch}$, as well as the net-proton number $\Delta B_p$) in minimum bias $pp$, $pn$, and $nn$ interactions at $\sqrt{s} = 200$ GeV, simulated by the pythia event generator [21, 22] (version 8.240). We used Monash tune [23] which was based on the LHC data (we will discuss this particular point at end of the paper). The acceptance cuts for $\Delta Q$ are $|\eta| < 1$ and $0.2 < p_T < 2$ GeV/$c$, and we have excluded the (anti-)protons with $p_T < 0.4$ GeV/$c$ (where the protons are strongly contaminated by background in experiments [24]). The $N_{ch}$ is from $|\eta| < 0.5$ and

---

*Corresponding author: haojiexu@zjhu.edu.cn
1Corresponding author: lihl@wust.edu.cn
2Corresponding author: lwchen@sjtu.edu.cn
3Corresponding author: fqwang@purdue.edu
0.2 < p_T < 2 GeV/c (as usually performed in experiment). The ΔQ differs significantly between pp and nn interactions, whereas ΔB_p is almost the same. The charge difference in the initial baryons that have transported to midrapidity is transferred nearly entirely to mesons. This difference will imprint in peripheral nucleus-nucleus (AA) collisions, the magnitude of which depends on Δr_{np}. If a peripheral AA collision is a simple superimposition of nucleon-nucleon (NN) interactions, then one can predict ΔQ in AA by those in NN collisions as

\[ ΔQ_{AA} \propto q_{AA}ΔQ_{pp} + (1 - q_{AA})ΔQ_{nn}, \]

where q_{AA} is the fraction of protons among the participant nucleons. The proportionality (normalization) factor is simply the number of NN collisions. We have taken ΔQ_{pn} = (ΔQ_{pp} + ΔQ_{nn})/2 which is a good assumption as seen in Table I– we have also verified this in the Hijing model [25, 26] and the UrQMD model [27, 28]. One can have a similar equation for ∆B_p, but since ∆B_p’s are almost the same among pp, pn and nn interactions it is of little use for our purpose.

Now consider the isobar collisions of Ru+Ru and Zr+Zr at \( \sqrt{s_{NN}} = 200 \) GeV. The ΔQ ratio in Ru+Ru over Zr+Zr collisions, under the superimposition assumption, is

\[ R_{ΔQ} = \frac{ΔQ_{RuRu}}{ΔQ_{ZrZr}} = \frac{q_{RuRu} + α/(1 - α)}{q_{ZrZr} + α/(1 - α)}, \]

where α = ΔQ_{nn}/ΔQ_{pp} is the ΔQ ratio in nn to pp interactions;PYTHIA gives α = −0.352. The overall q_{RuRu} and q_{ZrZr} values for the whole nuclei are 44/96 and 40/96, respectively; they would give \( R_{ΔQ} \approx 1.267 \). Of course, the simple superimposition assumption breaks down in non-peripheral collisions because of nuclear effects. However, the assumption should be good for grazing AA collisions, where one expects Eq. (2) to be valid. The general idea to probe Δr_{np} by \( R_{ΔQ} \) is that a sizable Δr_{np} will make the q_{AA} decrease dramatically with increasing impact parameter (b) in those grazing collisions. Δr_{np} of 96Zr is significantly larger than that of 96Ru, so the \( R_{ΔQ} \) ratio amplifies the Δr_{np} sensitivity. The Δr_{np} of both nuclei are controlled by the \( L_c \) parameter, thus a measurement of \( R_{ΔQ} \) can determine its value.

Following our previous work [19, 29], we examine four sets of 96Ru and 96Zr nuclear densities from energy density functional theory (DFT). One is the standard Skyrme-Hartree-Fock (SHF) model (see, e.g., Ref. [30]) using the well-known interaction set SLy4 [31, 32]. The other is the extended SHF (eSHF) model [33, 34] with three sets of interaction parameters, denoted as Lc47, Lc20 and Lc70, corresponding to \( L_c = 47.3, 20 \) and 70 MeV [35], respectively, all with the symmetry energy \( E_{sym}(\rho_c) = 26.65 \) MeV [6]. The Lc47 set is the best fit to data on the nuclear masses and electric dipole polarizability in 208Pb [6], and the other two are to explore the effects of the symmetry energy (and neutron skin) variations.

With a given nuclear density, one can calculate the q_{AA} parameter in Ru+Ru and Zr+Zr collisions as a function of b (and \( N_{ch} \)). We use the Trento model [36] to do that. In Trento particle production is related to the reduced thickness, \( N_{ch} \propto T_R(p; T_A, T_B) = [(T_A^p + T_B^p)/2]^{1/p} \) [36, 37]. We use the parameter \( p = 0 \) (i.e., \( N_{ch} \propto \sqrt{T_A T_B} \)), a gamma fluctuation parameter \( k = 1.4 \), and a Gaussian nucleon size of 0.6 fm, which were found to well describe the multiplicity data in heavy ion collisions [36, 37]. The q_{RuRu} and q_{ZrZr} from Trento calculations are shown in Fig. 1. They are sensitive to Δr_{np} and thus the \( L_c \) parameter, and decrease with decreasing \( N_{ch} \) in peripheral collisions. Both these features indicate the effect of Δr_{np} on \( R_{ΔQ} \). The sensitivity is larger in Zr+Zr than Ru+Ru collisions because of the larger Δr_{np} of Zr.

![FIG. 1: (Color online). The proton fractions q_{AA} among participant nucleons as function of charged hadron multiplicity N_{ch} calculated by Trento with the 96Ru and 96Zr nuclear densities from eSHF (Lc20, Lc47, Lc70) and SHF (SLy4). The dotted and dashed lines indicate the overall values of 44/96 and 40/96 of the entire Ru and Zr nuclei, respectively.](image-url)
position for those non-peripheral AA collisions, the \( R_{\Delta Q} \) for grazing collisions with small \( N_{ch} \) should be robust and can be used to determine the \( \Delta r_{np} \) and thus the \( L_c \) parameter. We note that the \( \alpha \) value is obtained from minimum bias NN interactions. However, a grazing AA collision with a particular \( N_{ch} \) value selects biased underlying NN interactions, especially when \( N_{ch} \) is small. We have verified that \( \Delta Q_{pp} \) and \( \Delta Q_{nn} \) do indeed depend on \( N_{ch} \) of NN collisions, however, their ratio \( \alpha \) is insensitive to \( N_{ch} \). Using a constant \( \alpha \) in Eq. (2) is, therefore, justified.

The DFT densities we used have assumed spherical nuclei without considering the possible deformation in their calculations. Their experimental measurements of the quadrupole deformation parameter are also uncertain, ranging from \( \beta_2 \approx 0.053 \) to 0.158 for Ru and from 0.08 to 0.217 for Zr [38]. To test the sensitivity of our results to nuclear deformation, we follow Ref. [39] using the Woods-Saxon parametrization \( \rho(r, \theta) \propto (1 + \exp [r - R(1 + \beta_2 Y_{20}^2(\theta))/\alpha])^{-1} \) with \( \beta_2 = 0.16 \) fixed and the \( R \) and \( a \) reproducing the first and second radial moments of the DFT-calculated spherical proton and neutron densities of SHF/SLy4. The changes in \( R_{\Delta Q} \) from the spherical case are shown in Fig. 3 for the three combinations of deformed/spherical Ru and Zr nuclei. The effect is only a couple of percent, leading possibly to less than 5 MeV uncertainty in the extracted \( L_c \) parameter. This small effect is not a surprise because the \( R_{\Delta Q} \) is sensitive only to the relative proton/neutron composition on the nuclear surface, which is not sensitive to nuclear deformation.

Next we examine our idea using a dynamical model. We use the urqmd (Ultra relativistic Quantum Molecular Dynamics, v3.4) [27, 28] as it has been widely used to study the conserved charge number and its fluctuations in heavy ion collisions [40, 41]. We simulate events within \( b \in [7, 20] \) fm since we focus only on peripheral collisions. The same acceptance cuts have been applied as performed in pythia simulations. Figure 4 shows \( R_{\Delta Q} \) as a function of \( N_{ch} \). Similar splittings are found at low \( N_{ch} \) as in Fig. 2. urqmd simulations of NN interactions indicate \( \alpha \approx -0.344 \). Using this \( \alpha \) value, the predicted curves by Eq. (2) are superimposed in Fig. 4. The curves can fairly well describe the urqmd data. This indicates that the grazing collisions in urqmd with \( N_{ch} \leq 10 \) are indeed simple superimposition of NN interactions. This is not surprising as only a few nucleons participate in such a grazing AA collision so any nuclear effect would be negligible. At higher \( N_{ch} \) the urqmd data points deviate from the curves, presumably because those collisions are not simple NN superimpositions any more. It may also be viewed as that the effective \( \alpha \) in central AA collisions, because of nuclear effects, is very different from the one calculated using single NN interactions.

The large differences among the nuclear densities are mostly due to the negative value of \( \alpha \) as mentioned before. We note that a larger \( p_T \) cut on (anti)proton makes \( \alpha \) more negative, e.g., \( \alpha = -0.416 \) with \( p_T > 0.8 \text{GeV}/c \) on (anti)proton, which may make the \( R_{\Delta Q} \) more sensitive to \( \Delta r_{np} \). However, excluding any “net-charge” will weaken the correlation between the initial protons from the incoming nuclei and the final-state net-charge observable, which would introduce stronger model dependence. We also note that the finite negative \( \alpha \) value is not merely because we exclude the (anti)proton with \( p_T < 0.4 \text{GeV}/c \); we have checked that without any \( p_T \) cut, the \( \alpha \) value is \(-0.370 \) at mid-rapidity (|\( \eta \)| < 1.0). In our urqmd...
simulations, the hyperon decays are not included. The hyperon decays can introduce net-charge because of the combined effect of the finite acceptance (which does not always cover both daughter particles from the decay) and the asymmetry of those decay. We have calculated the effect of $\Lambda$ decays for the Lc47 case and found that the effect is negligible (see the open red squares in Fig.4).

We have simulated $\sim 4.5 \times 10^8$ $\text{uROMD}$ events for each isobar system in Fig. 4. They give a statistical uncertainty on $L_c$ of roughly 9 MeV using data points at $N_{ch}$ $\leq$ 10. It should be noted that our proposal requires measurements of ultra-peripheral collisions which are often difficult because of trigger inefficiencies in experiment, increasing in severity with decreasing $N_{ch}$. Over $2 \times 10^9$ minimum bias events have been collected at the RHIC for each isobar system; they would likely give similar statistics to our simulated $\text{uROMD}$ sample, given the typical experimental trigger inefficiency. Thus, the statistical uncertainty on the extracted $L_c$ using isobar data is expected to be $\sim$10 MeV. Since our $R_{\Delta Q}$ observable is a ratio of two isobar systems, many experimental systematic effects cancel and would unlikely contribute a significant part to the overall experimental uncertainty. We note that the electromagnetic interactions could affect the proposed method. However, in experiment, one can avoid electromagnetic interactions by triggering on minimum bias hadronic interactions only.

Our idea relies on the state of the art DFT calculation and the assumption of simple NN superimposition for grazing isobar collisions. The theoretical uncertainty from the former may be gauged by the two parameter sets of SLy4 and Lc47 shown in Fig. 2, corresponding to similar $L_c$ values. Their difference would give an uncertainty of $\sim$6 MeV. This is rather modest compared to the substantial uncertainties from QCD modeling of traditional scattering observables. Another theoretical uncertainty on density distributions comes from nuclear deformation; this is insignificant as indicated by Fig. 3.

The assumption of simple NN superimposition should be rather robust for grazing heavy ion collisions over a wide range of relativistic energies. We have focused on $\sqrt{s_{NN}} = 200$ GeV in this Letter because the isobar collision data recently taken at RHIC were at this energy [42]. We note that isospin-sensitive observables, such as the $\pi^+ / \pi^-$ ratio, have been proposed long ago to probe high-density symmetry energy in low energy nuclear collisions (not particularly in grazing collisions) [43]. In our study of grazing AA collisions, the NN information imprint in $\Delta Q$ is carried over by the $\alpha$ parameter. The $\alpha$ value we used in this Letter comes from a particular tune of $\text{PYTHIA}$ and $\text{uROMD}$. It is used only to illustrate our proposed method; its value should be taken with caution. For example, $\text{PYTHIA}6$ (version 6.416) tuned to the RHIC data [44] would give $\alpha = -0.315$, the result of which with the Lc47 density is shown by the dashed curve in Fig. 2. Hijing gives $\alpha = -0.389$ which is shown by the dashed-dot curve in Fig. 2 for Lc47. This would result in an uncertainty on $L_c$ comparable to the range of the parameter sets in Fig. 2 (which was constrained from traditional scattering measurements). The determination of the $\alpha$ parameter is therefore essential. The $\Delta Q$ data in $pp$ interactions are abundant, that in $nn$ is experimentally not available. Although $nn$ interactions are hard to perform, their information may be indirectly accessed by proton-deuteron and/or deuteron-deuteron collisions, yet to be conducted. In addition, one may gain valuable information on the $\alpha$ parameter from existing $p$-Au and $d$-Au data at RHIC. Provided that the $\alpha$ parameter can be determined relatively precisely, our proposal will likely result in a $L_c$ value with an overall uncertainty of 10-15 MeV. This would be a substantial complement to traditional methods with the present overall $\sim$20 MeV uncertainty [16].

To summarize, we demonstrate that the net-charge ratio $R_{\Delta Q}$ in isobar $^{96}\text{Ru} + ^{96}\text{Ru}$ over $^{96}\text{Zr} + ^{96}\text{Zr}$ collisions can be predicted from those in $pp$ and $nn$ interactions under the assumption that nucleus-nucleus AA collisions are a simple superimposition of NN interactions. We show using the $\text{uROMD}$ model that this assumption is valid for ultra-peripheral (grazing) collisions with $N_{ch} \leq 10$ within the midrapidity range of $|\eta| < 0.5$. The predicted $R_{\Delta Q}$ depends on the proton and neutron densities, particularly on the neutron skin thickness $\Delta r_{np}$. The $R_{\Delta Q}$ measurement in grazing isobar collisions, together with DFT calculations of nuclear densities can, therefore, determine the $\Delta r_{np}$ and, in turn, the symmetry energy density slope parameter $\tilde{\gamma}_{\text{sym}}$.

We have previously proposed [19] an indirect observable, the $N_{ch}$ ratio in central isobar collisions, to probe the $\Delta r_{np}$. This observable is isospin insensitive and is based on the fact that particle production in relativistic heavy ion collisions depends
on the total nuclear (proton+neutron) density which has some sensitivity to the $\Delta r_{np}$. The $R_{QQ}$ observable proposed here is isospin sensitive, directly related to the $\Delta r_{np}$. It is based on the simple superimposition of NN interactions for those grazing AA collisions, and depends on the difference (proton – neutron) density which is highly sensitive to the $\Delta r_{np}$. Combining these two observables will yield stringent constrains on the $\Delta r_{np}$ and, thus, the $L_c$ parameter.

Acknowledgments

HX thanks Dr. Qiang Zhao and Dr. Wenbin Zhao for useful discussions. FW thanks Dr. Torbjörn Sjöstrand and Dr. Christian Bierlich for helpful information on Pythia. This work is supported in part by the National Natural Science Foundation of China (Grant Nos. 11905059, 11947410, 12035006, 12047568, 12075085, 11625521, U1732138, 11605054, 11505056), the Ministry of Science and Technology of China (Grant No. 2020YFE0202001), National SKA Program of China (Grant No. DE-SC0012910), and the U.S. Department of Energy (Grant No. DE-SC00102910).

[1] B. A. Brown, Phys. Rev. Lett. 85, 5296 (2000).
[2] L.-W. Chen, C. M. Ko, and B.-A. Li, Phys. Rev. C72, 064309 (2005), nucl-th/0509009.
[3] X. Roca-Maza, M. Centelles, X. Vinas, and M. Warda, Phys. Rev. Lett. 106, 252501 (2011), 1103.1762.
[4] M. B. Tsang et al., Phys. Rev. C86, 015803 (2012), 1204.0466.
[5] C. J. Horowitz, E. F. Brown, Y. Kim, W. G. Lynch, R. Michaels, A. Ono, J. Piekarewicz, M. B. Tsang, and H. H. Wolter, J. Phys. G41, 093001 (2014), 1401.5839.
[6] Z. Zhang and L.-W. Chen, Phys. Lett. B726, 234 (2013), 1302.5327.
[7] B. Frois and C. N. Papanicolas, Ann. Rev. Nucl. Part. Sci. 37, 133 (1987).
[8] L. Lapikas, Nucl. Phys. A553, 297c (1993).
[9] C. M. Tarbert et al., Phys. Rev. Lett. 112, 242502 (2014), 1311.0168.
[10] L. Ray, G. W. Hoffmann, and W. R. Coker, Phys. Rept. 212, 223 (1992).
[11] T. W. Donnelly, J. Dubach, and I. Sick, Nucl. Phys. A503, 589 (1989).
[12] C. J. Horowitz, S. J. Pollock, P. A. Souder, and R. Michaels, Phys. Rev. C63, 025501 (2001), nucl-th/9912038.
[13] D. Akimov et al. (COHERENT), Science 357, 1123 (2017), 1708.01294.
[14] S. Abrahamyan et al., Phys. Rev. Lett. 108, 112502 (2012), 1201.2568.
[15] D. Adhikari et al. (PREX), Phys. Rev. Lett. 126, 172502 (2021), 2102.10767.
[16] B. T. Reed, F. J. Fattoyev, C. J. Horowitz, and J. Piekarewicz, Phys. Rev. Lett. 126, 172503 (2021), 2101.03193.
[17] M. Centelles, X. Roca-Maza, X. Vinas, and M. Warda, Phys. Rev. Lett. 102, 122502 (2009), 0806.2886.
[18] T.-G. Yue, L.-W. Chen, Z. Zhang, and Y. Zhou (2021), 2102.05267.
[19] H. Li, H.-j. Xu, Y. Zhou, X. Wang, J. Zhao, L.-W. Chen, and F. Wang, Phys. Rev. Lett. 125, 222301 (2020), 1910.06170.
[20] H. Li, H.-j. Xu, J. Zhao, Z.-W. Lin, H. Zhang, X. Wang, C. Shen, and F. Wang, Phys. Rev. C98, 054907 (2018), 1808.06711.
[21] T. Sjostrand, S. Mrenna, and P. Z. Skands, JHEP 05, 026 (2006), hep-ph/0603175.
[22] T. Sjostrand, S. Mrenna, and P. Z. Skands, Comput. Phys. Commun. 178, 852 (2008), 0710.3820.
[23] P. Skands, S. Carrazza, and J. Rojo, Eur. Phys. J. C 74, 3024 (2014), 1404.5630.
[24] B. I. Abelev et al. (STAR), Phys. Rev. C79, 034909 (2009), 0808.2041.
[25] X.-N. Wang and M. Gyulassy, Phys. Rev. D44, 3501 (1991).
[26] X.-N. Wang, Phys. Rept. 280, 287 (1997), hep-ph/9605214.
[27] S. A. Bass et al., Prog. Part. Nucl. Phys. 41, 255 (1998), nucl-th/9803035.
[28] M. Bleicher et al., J. Phys. G25, 1859 (1999), hep-ph/9909407.
[29] H.-J. Xu, X. Wang, H. Li, J. Zhao, Z.-W. Lin, C. Shen, and F. Wang, Phys. Rev. Lett. 121, 022301 (2018), 1710.03086.
[30] E. Chabanat, J. Meyer, P. Bonche, R. Schaeffer, and P. Haensel, Nucl. Phys. A627, 710 (1997).
[31] E. Chabanat, P. Bonche, P. Haensel, J. Meyer, and R. Schaeffer, Nucl. Phys. A635, 231 (1998), [Erratum: Nucl. Phys. A643,441(1999)].
[32] X. B. Wang, J. L. Friar, and A. C. Hayes, Phys. Rev. C94, 034314 (2016), 1607.02149.
[33] N. Chapel, S. Goriely, and J. M. Pearson, Phys. Rev. C80, 065804 (2009), 0911.3346.
[34] Z. Zhang and L.-W. Chen, Phys. Rev. C94, 064326 (2016), 1510.06459.
[35] Z. Zhang and L.-W. Chen, Phys. Rev. C90, 064317 (2014), 1407.8054.
[36] J. S. Moreland, J. E. Bernhard, and S. A. Bass, Phys. Rev. C92, 011901 (2015), 1412.4708.
[37] J. E. Bernhard, J. S. Moreland, S. A. Bass, J. Lii, and U. Heinz, Phys. Rev. C94, 024907 (2016), 1605.03954.
[38] W.-T. Deng, X.-G. Huang, G.-L. Ma, and G. Wang, Phys. Rev. C94, 044901 (2016), 1607.04697.
[39] H.-j. Xu, H. Li, X. Wang, C. Shen, and F. Wang, Phys. Lett. B819, 136453 (2021), 2103.05595.
[40] L. Adamczyk et al. (STAR), Phys. Rev. Lett. 112, 032302 (2014), 1309.5681.
[41] J. Xu, S. Yu, F. Lii, and X. Luo, Phys. Rev. C94, 024901 (2016), 1606.03900.
[42] V. Koch, S. Schlichting, V. Skokov, P. Sorensen, J. Thomas, S. Voloshin, G. Wang, and H.-U. Yee, Chin. Phys. C41, 072001 (2017), 1608.00982.
[43] B.-A. Li, Phys. Rev. Lett. 88, 192701 (2002), nucl-th/0205002.
[44] S. Zhang, L. Zhou, Y. Zhang, M. Zhang, C. Li, M. Shao, Y. Sun, and Z. Tang, Nucl. Sci. Tech. 29, 136 (2018), 1803.05767.