Influence of the nuclear symmetry energy on the collective flows of charged pions

Yuan Gao,[1,*] Gao-Chan Yong,[2,3] Lei Zhang,[1] and Wei Zuo[2,3]
[1]*School of Information Engineering, Hangzhou Dianzi University, Hangzhou 310018, China*
[2]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*
[3]*School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China*

(Received 15 August 2017; revised manuscript received 20 November 2017; published 22 January 2018)

Based on the isospin-dependent Boltzmann-Uehling-Uhlenbeck (IBUU) transport model, we studied charged pion transverse and elliptic flows in semicentral ^{197}Au + ^{197}Au collisions at 600 MeV/nucleon. It is found that $\pi^+ - \pi^-$ differential transverse flow and the difference of π^+ and π^- transverse flows almost show no effects of the symmetry energy. Their corresponding elliptic flows are largely affected by the symmetry energy, especially at high transverse momenta. The isospin-dependent pion elliptic flow at high transverse momenta thus provides a promising way to probe the high-density behavior of the symmetry energy in heavy-ion collisions at the Facility for Antiproton and Ion Research (FAIR) at GSI, Darmstadt or at the Cooling Storage Ring (CSR) at HIRFL, Lanzhou.

DOI: 10.1103/PhysRevC.97.014609

I. INTRODUCTION

One of the main goals of heavy ion collisions (HIC) at intermediate energies is to study the properties of isospin-asymmetric nuclear matter, especially to determine the density dependence of the symmetry energy at low and high densities [1,2]. The equation of state (EoS) of nuclear matter at density ρ and isospin asymmetry δ [$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$] is usually expressed as

$$E(\rho,\delta) = E(\rho,0) + E_{\text{sym}}(\rho)\delta^2 + O(\delta^4). \quad (1)$$

Here $E_{\text{sym}}(\rho)$ is the symmetry energy (SE), which can be considered as the difference between the energy per nucleon of neutron matter and that of symmetric matter. The symmetry energy plays essential roles in understanding a number of physical phenomena and processes [3], such as the structure of radioactive and exotic nuclei, the reaction dynamics induced by rare isotopes, the structure and evolution of compact astrophysical objects such as neutron stars (NS), supernovae, and binary mergers, and so on [4,5]. Nevertheless, a direct connection between the phenomenology and the EoS is not straightforward, thus usually theoretical assumptions are necessary for the interpretation of the observable data [6]. Therefore, the related symmetry energy topic has attracted a lot of attention in the past few decades [6–11].

In principle the density-dependent symmetry energy can be calculated theoretically [12–15]. However, calculations with different theories present us with a variety of density-dependent symmetry energies, and some of them are in conflict with each other, except at the saturation point. This confusion may result for several reasons. Phenomenological forces are well constrained near or just below saturation density, but lead to largely diverging results with increasing density [16,17]. In most microscopic many-body calculations the three-body forces and short-range correlations are in fact not well considered [18–20]. Chiral effective field theories have no free parameters for three-body forces and bring in large uncertainties at high densities [21–23]. Owing to complexity of the nuclear force, modeling the density-dependent symmetry energy by a power-law fit at lower density and higher density may require different exponents [24]. The symmetry energy at high densities is thus still very controversial [25,26].

Heavy-ion collisions (HIC) provide the only method in present-day laboratory experiments to compress nuclear matter and study the symmetry energy at densities exceeding saturation, at which the theoretical predictions diverge. Unfortunately, the density-dependent symmetry energy generally cannot be measured directly in experiments; it can only be determined by comparisons among experimental data and theoretical observables which are related to the symmetry energy. During the last decade, great efforts have been devoted to finding observables sensitive enough to the symmetry energy, and a lot of sensitive probes were suggested, such as the free neutron/proton ratio [27], isospin fractionation [28,29], the neutron-proton correlation function [30], $t/^3$He [31], isospin diffusion [32], neutron-proton transverse differential flow [33], collective flows of nucleons [34,35], the π^-/π^+ ratio [36–40], etc. Among them, probes related to pions may offer an advantage in exploring the symmetry energy as well as the reaction dynamics [41]. However, in Ref. [42], it is argued that below 400 MeV/nucleon incident beam energies, for light or medium nucleus-nucleus reaction systems, the π^-/π^+ ratio mainly probes the symmetry energy around saturation density. To probe the high-density symmetry energy by the π^-/π^+ ratio, a heavy reaction system at relatively high beam energies is preferable.

In this paper, we studied the effects of the symmetry energy on pionic transverse and elliptic flows in mid-central reactions of ^{197}Au + ^{197}Au at 600 MeV/nucleon. The beam energy is

*gaoyuan@impcas.ac.cn

in the range of the ASY-EOS experiments at the Facility for Antiproton and Ion Research (FAIR) at GSI in Germany [43], and also in the energy range of the Cooling Storage Ring of the Heavy Ion Research Facility at IMP (HIRFL-CSR) in China [44]. It is found that, contrary to pionic transverse flow, pionic elliptic flow, especially at high transverse momenta, is very sensitive to the symmetry energy, thus can be used to probe the high-density behavior of the symmetry energy.

II. THE THEORETICAL MODEL

In studying isospin physics in heavy-ion collisions at intermediate energies, the isospin-dependent Boltzmann-Uehling-Uhlenbeck (IBUU) transport model is well known to describe the dynamical evolution of nucleons in phase space. In this model the mean-field potential (MDI) is given by [45]

$$U(\rho,\delta,\mathbf{p},\tau) = A_u(x)\frac{\rho_{\tau'}}{\rho_0} + A_l(x)\frac{\rho_\tau}{\rho_0} + B\left(\frac{\rho}{\rho_0}\right)^\sigma(1-x\delta^2) - 8x\tau\frac{B}{\sigma+1}\frac{\rho^{\sigma-1}}{\rho_0^\sigma}\delta\rho_{\tau'} + \sum_{t=\tau,\tau'}\frac{2C_{\tau,t}}{\rho_0}\int d^3\mathbf{p}'\frac{f_t(\mathbf{r},\mathbf{p}')}{1+(\mathbf{p}-\mathbf{p}')^2/\Lambda^2}, \quad (2)$$

where ρ_n and ρ_p denote neutron ($\tau = 1/2$) and proton ($\tau = -1/2$) densities, respectively. $f_t(\mathbf{r},\mathbf{p})$ represents the phase space distribution function, which is solved by following a test particle evolution on a lattice. $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$ is the isospin asymmetry of nuclear medium. The parameters $A_u(x), A_l(x)$ are x dependent and expressed as

$$A_u(x) = -95.98 - \frac{2B}{\sigma+1}x, \quad (3)$$

$$A_l(x) = -120.57 + \frac{2B}{\sigma+1}x, \quad (4)$$

with $B = 106.35$ MeV, $\sigma = 4/3$. $\Lambda = p_F^0$ is the nucleon Fermi momentum in symmetric nuclear matter, $C_{\tau,\tau'} = -103.4$ MeV, and $C_{\tau,\tau} = -11.7$ MeV. The $C_{\tau,\tau'}$ and $C_{\tau,\tau}$ terms are the momentum-dependent interactions of a nucleon with unlike and like nucleons in the surrounding nuclear matter. It should be noted that this potential includes an isovector part (symmetry potential) and an isoscalar part. Because of the nonlocality of strong interactions and the Pauli exchange effects in many-fermion systems, both of the two parts are momentum dependent, which is very important in understanding not only dynamics in intermediate-energy heavy-ion collisions, but also thermodynamical properties of nuclear matter [46–51]. With this potential one can get binding energy −16 MeV and incompressibility 211 MeV for symmetric nuclear matter and the symmetry energy 31.5 MeV at saturation density.

Another important ingredient in heavy-ion collisions is the nucleon-nucleon (NN) cross sections. Medium effects on the NN elastic cross sections have not been well determined so far. In our calculations, the reduction scale according to nucleon effective masses is adopted [52]. This modification is isospin and momentum dependent, and is similar to the Brueckner–Hartree–Fock (BHF) with three-body force or Dirac Brueckner–Hartree–Fock (DBHF) approach calculations only if nucleonic momentum is not too large [53,54]. The total and differential cross sections for all other particles are taken either from experimental data or obtained by using the detailed balance formula. By varying the variable x in Eq. (2), one can get different forms of the symmetry energy predicted by various many-body theories without changing any property of symmetric nuclear matter and the value of symmetry energy at normal density ρ_0. The corresponding density-dependent symmetry energies with different x values are plotted in Fig. 1. It is seen that these density-dependent symmetry energies cover the current uncertainty of the symmetry energy as shown in Ref. [26]. For pion production and more details of the transport model, we refer the reader to Refs. [36,39].

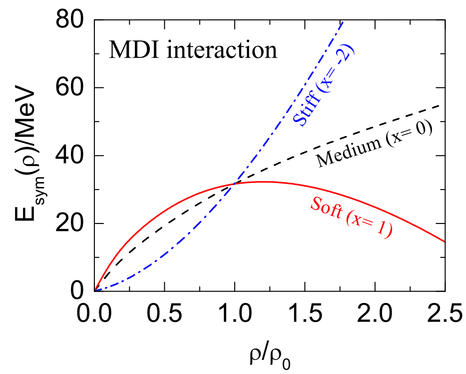

FIG. 1. Density dependence of nuclear symmetry energy from the MDI interaction with $x = -2$ (stiff), 0 (medium), and 1 (soft).

III. RESULTS AND DISCUSSIONS

Before discussing the influence of the symmetry energy on the pion collectivity flows, we first investigate the rapidity distributions of π^- and π^+ as well as the ratio π^-/π^+ with different symmetry energies, although they have been studied extensively in the literature. Plotted in Fig. 2 are the rapidity distributions of π^- and π^+. It is seen that, compared with π^-, π^+ distribution is almost independent of the symmetry energy. The softer symmetry energy ($x = 1$) causes a high value of π^-, especially at mid-rapidity. From Fig. 2, it is also seen that both π^- and π^+ show maximum distribution at mid-rapidity.

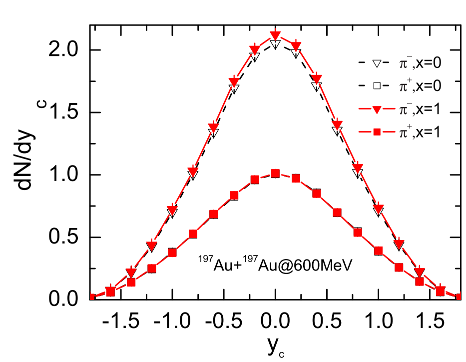

FIG. 2. Effects of nuclear symmetry energy on the rapidity distributions of π^- and π^+ in the reaction of ^{197}Au + ^{197}Au at a beam energy of 600 MeV/nucleon with an impact parameter of 7 fm.

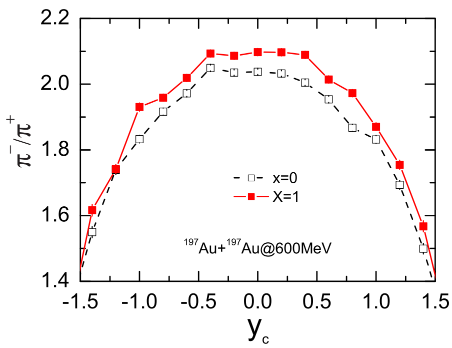

FIG. 3. Effects of nuclear symmetry energy on the rapidity distribution of the π^-/π^+ ratio in the reaction of ^{197}Au + ^{197}Au at an incident beam energy of 600 MeV/nucleon with an impact parameter of 7 fm.

Shown in Fig. 3 is the corresponding π^-/π^+ ratio as a function of rapidity. It is clearly seen that the π^-/π^+ ratio is sensitive to the symmetry energy, and the effect seems somewhat more clear at mid-rapidity. It is noted that the rapidity distributions of π^- and π^+ and their ratio all qualitatively agree with that in Ref. [41].

The collective flow observables are commonly used in studying the EoS and properties of dense matter formed in heavy-ion collisions at both intermediate and ultrarelativistic energies. The neutron-proton differential flow was first introduced by Li to be a potential probe of the symmetry energy [55], since it minimizes the influence of the isoscalar potential but maximizes the effects of the symmetry potential [56]. Similar to the neutron-proton differential transverse flow, the $\pi^+ - \pi^-$ differential transverse flow can be written as

$$\Delta' F_\pi^x = \frac{N_{\pi^+}(y)}{N(y)}\langle p_{\pi^+}^x(y)\rangle - \frac{N_{\pi^-}(y)}{N(y)}\langle p_{\pi^-}^x(y)\rangle, \tag{5}$$

where $\langle\cdots\rangle$ denotes the average of a physical quantity and $N(y) = N_{\pi^+}(y) + N_{\pi^+}(y)$. $N_{\pi^+}(y)$ and $N_{\pi^-}(y)$ are, respectively, numbers of free π^+ and π^-, at rapidity y. The rapidity distribution of the differential transverse flow $\Delta' F_\pi^x$ is shown in the lower panel of Fig. 4. It is seen that $\pi^+ - \pi^-$ differential transverse flow is weakly dependent on the stiffness of the symmetry energy. Compared with the upper panel of Fig. 4, $\Delta F_\pi^x = \langle p_{\pi^+}^x(y)\rangle - \langle p_{\pi^-}^x(y)\rangle$, i.e., the difference of π^+ and π^- transverse flows, one can see that the two kinds of transverse flow have almost the same sensitivity to the symmetry energy. It is interesting to see that both the two kinds of transverse flow are antiflow. This is because π^+ transverse flow is affected by spectators through re-scatterings and reabsorptions, and larger shadowing effect reverses π^+ transverse flow. Also π^- transverse flow is always much smaller. So $\Delta' F_\pi^x$ and ΔF_π^x as a function of rapidity appear to be antiflow [41,57,58]. Due to the shadowing effect, final pion momenta cannot directly reflect the EoS of compressed matter, thus pion transverse flow shows no effects of the symmetry energy.

It is well known that the particle directed and elliptic flows in heavy-ion collisions are useful to probe the nuclear EoS [43,59,60]. They can be derived from the Fourier expansion of the azimuthal distribution [59,61], i.e.,

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{i=1}^{n} v_n \cos(n\phi). \tag{6}$$

For charged pions, the directed flow can be expressed as

$$v_1^{\pi^\pm} = \langle\cos(\phi)\rangle = \left\langle\frac{p_x}{p_t}\right\rangle. \tag{7}$$

The $\pi^+ - \pi^-$ differential directed flow is defined as

$$\Delta' v_1^\pi = \frac{N_{\pi^+}(y)}{N(y)} v_1^{\pi^+} - \frac{N_{\pi^-}(y)}{N(y)} v_1^{\pi^-}, \tag{8}$$

and the difference of π^+ and π^- directed flow is

$$\Delta v_1^\pi = v_1^{\pi^+} - v_1^{\pi^-}. \tag{9}$$

The pion elliptic flow v_2 can be obtained from

$$v_2^{\pi^\pm} = \langle\cos(2\phi)\rangle = \left\langle\frac{p_x^2 - p_y^2}{p_t^2}\right\rangle, \tag{10}$$

and the $\pi^+ - \pi^-$ differential elliptic flow is defined as

$$\Delta' v_2^\pi = \frac{N_{\pi^+}(y)}{N(y)} v_2^{\pi^+} - \frac{N_{\pi^-}(y)}{N(y)} v_2^{\pi^-}. \tag{11}$$

Figure 5 shows pion directed flows $\Delta' v_1^\pi$ and Δv_1^π which are almost the same as $\Delta' F_\pi^x$ and ΔF_π^x as shown in Fig. 4. Both show almost no effects of the symmetry energy owing to the shadowing effects.

Figure 6 shows $\pi^+ - \pi^-$ differential elliptic flow $\Delta' v_2$ as a function of transverse momentum p_t in different rapidity ranges. We also analyzed the difference of π^+ and π^- elliptic

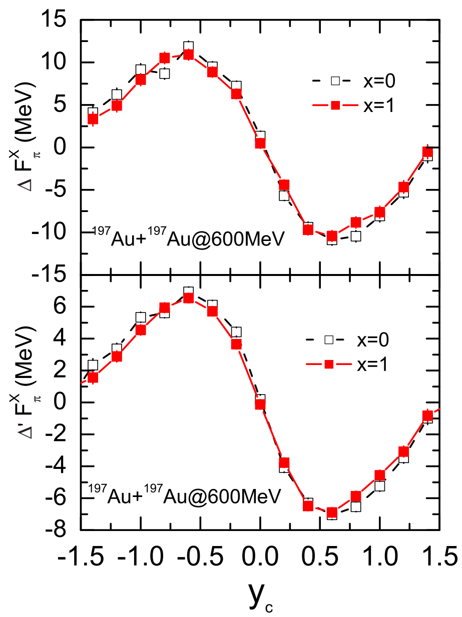

FIG. 4. Effects of nuclear symmetry energy on the charged pion transverse flows $\Delta' F_\pi^x$ (lower panel) and ΔF_π^x (upper panel) as a function of rapidity in the reaction of ^{197}Au + ^{197}Au at a beam energy of 600 MeV/nucleon and an impact parameter of 7 fm.

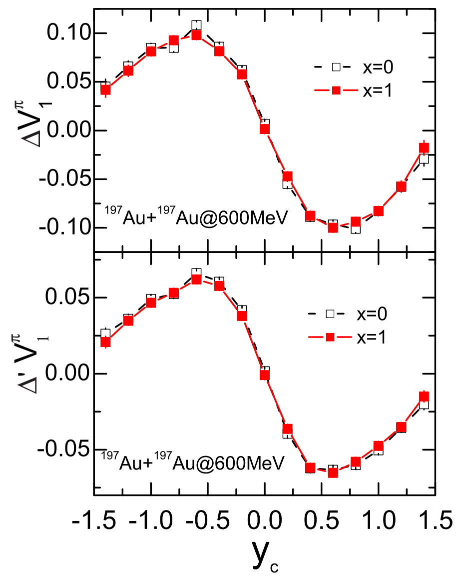

FIG. 5. Effects of nuclear symmetry energy on the charged pion directed flow $\Delta' v_1^\pi$ and Δv_1^π as a function of rapidity in the reaction of ^{197}Au + ^{197}Au at a beam energy of 600 MeV/nucleon and an impact parameter of 7 fm.

flows, i.e.,

$$\Delta v_2^\pi = v_2^{\pi^+} - v_2^{\pi^-}, \tag{12}$$

which is illustrated in Fig. 7. To probe the high-density behavior of nuclear symmetry energy more delicately, we present pion elliptic flows, shown in Figs. 6 and 7 with $x = -2$ (stiff), 0 (medium), and 1 (soft). It is seen that both the differential elliptic flow $\Delta' v_2^\pi$ and the difference of elliptic flows of charged pions Δv_2^π show almost the same behavior to the symmetry energy. From Figs. 6 and 7 it is seen that the effects of the symmetry energy on the pion elliptic flow are larger than that of the pion transverse flow [41], especially when $p_t \geqslant 0.3$ GeV/c. This is because in the semicentral reaction of ^{197}Au + ^{197}Au at a beam energy of 600 MeV/nucleon, at higher transverse momenta, numbers of π^+ and π^- are almost the same, as shown in Fig. 8, thus the differential elliptic flow $\Delta' v_2$ is reduced to the difference of π^+ and π^- elliptic flows Δv_2^π. At higher transverse momenta, π^+ and π^- come directly from the high-density region, thus they carry substantial information on the high-density behavior of the symmetry energy. The effects of the symmetry energy at high p_t values shown in Figs. 6 and 7 are measurable experimentally at FAIR-GSI [43] or CSR-Lanzhou [44]. From Fig. 8, one can also see that the π^-/π^+ ratio is in fact less sensitive to the symmetry energy in semicentral reactions at incident beam energies of 600 MeV/nucleon.

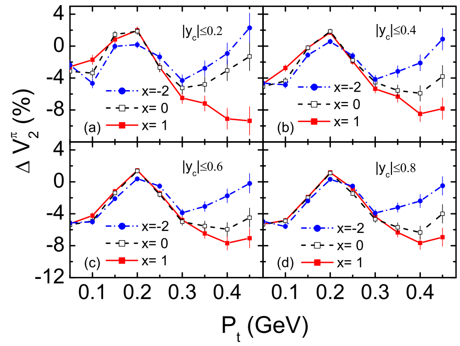

FIG. 7. Effects of nuclear symmetry energy on the difference of π^+ and π^- elliptic flows Δv_2^π as a function of transverse momentum in different rapidity regions in the reaction of ^{197}Au + ^{197}Au at a beam energy of 600 MeV/nucleon and an impact parameter of 7 fm.

The neutron-proton effective mass splitting associated with the momentum-dependent isovector potential may affect the value of the π^-/π^+ ratio. The neutron-proton effective mass splitting affects the isospin dependence of in-medium nucleon-nucleon cross sections [52], the neutron to proton ratio of emitted free nucleons, and thus the asymmetry of dense matter formed in heavy-ion collisions [62]. Therefore the neutron-proton effective mass splitting may affect the productions of π^- and π^+ in heavy-ion collisions at intermediate energies. Owing to our poor knowledge of the isospin dependence of in-medium nuclear effective interactions, predictions based on various many-body theories are rather diverse. Analysis of limited heavy-ion reaction data available using various

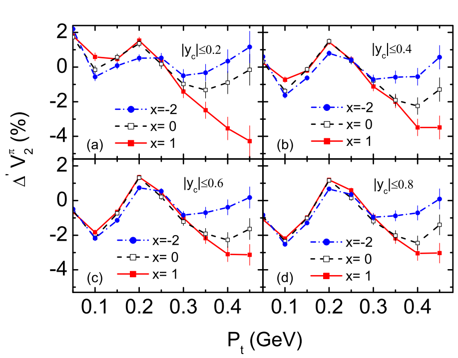

FIG. 6. Effects of nuclear symmetry energy on the $\pi^+ - \pi^-$ differential elliptic flow $\Delta' v_2^\pi$ as a function of transverse momentum in different rapidity regions in the ^{197}Au + ^{197}Au reaction at a beam energy of 600 MeV/nucleon and an impact parameter of 7 fm.

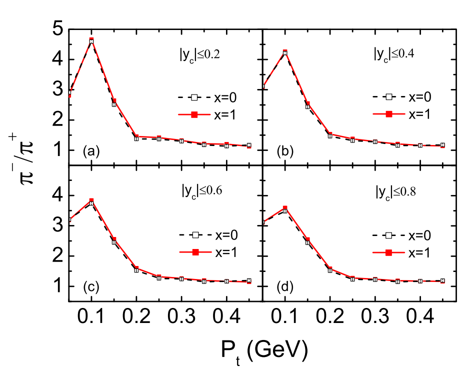

FIG. 8. Effects of nuclear symmetry energy on the π^-/π^+ ratio as a function of transverse momentum in different rapidity regions in the reaction of ^{197}Au + ^{197}Au at a beam energy of 600 MeV/nucleon and an impact parameter of 7 fm.

transport models has not reached a consensus. But recently significant progress in constraining the neutron-proton effective mass splitting at saturation density has been made by conducting a rather extensive analysis of huge sets of nucleon-nucleus scattering data [62]. As the neutron-proton effective mass splitting and the density-dependent symmetry energy are closely related to each other [63], constraints of the neutron-proton effective mass splitting would also help us pin down the density dependence of the symmetry energy.

IV. CONCLUSION

In the framework of the IBUU transport model, the differential transverse flow, the differential elliptic flow, and the elliptic flow difference of charged pions, as well as their dependences on the nuclear symmetry energy, are investigated in semicentral reactions of ^{197}Au + ^{197}Au at a beam energy of 600 MeV/nucleon. It is found that isospin-dependent pion transverse flow shows almost no effects of the symmetry energy, while the isospin-dependent pion elliptic flow, especially at high transverse momenta, exhibits significant sensitivity to the symmetry energy. The isospin-dependent pion elliptic flow at high p_t values may be a promising probe to constrain the high density behavior of the nuclear symmetry energy at facilities that offer radioactive beams, such as FAIR-GSI or CSR-Lanzhou.

ACKNOWLEDGMENTS

This work is supported in part by the National Natural Science Foundation of China under Grants No. 11775275, No. 11435014, No. 11375239, and No. 11475050, by the 973 Program of China (2007CB815004), and by a Zhejiang Province Science and Technology Plan project (2015C33035). The work is also supported by the National Supercomputer Center in Tianjin, and the calculations were performed on the TianHe-1A supercomputer.

[1] B. A. Li, L. W. Chen, and C. M. Ko, Phys. Rep. **464**, 113 (2008).
[2] V. Baran, M. Colonna, V. Greco, and M. Di Toro, Phys. Rep. **410**, 335 (2005).
[3] *Topical Issue on Nuclear Symmetry Energy*, edited by B. A. Li, À. Ramos, G. Verde, and I. Vidaña, Eur. Phys. J. A **50**, 2 (2014).
[4] S. N. Wei, W. Z. Jiang, R. Y. Yang *et al.*, Phys. Lett. B **763**, 145 (2016).
[5] J. A. Lopez and S. T. Porras, Nucl. Phys. A **957**, 312 (2017).
[6] M. Baldo and G. F. Burgio, Prog. Part. Nucl. Phys. **91**, 203 (2016).
[7] Y. Gao, L. Zhang, W. Zuo, and J. Q. Li, Phys. Rev. C **86**, 034611 (2012).
[8] Y. Gao, G. C. Yong, Y. J. Wang, Q. F. Li, and W. Zuo, Phys. Rev. C **88**, 057601 (2013).
[9] Y. J. Wang, C. C. Guo, Q. F. Li, and H. F. Zhang, Eur. Phys. J. A **51**, 37 (2015).
[10] H. Zheng, S. Burrello, M. Colonna, and V. Baran, Phys. Lett. B **769**, 424 (2017).
[11] Y. Wang, C. Guo, Q. Li, Z. Li, J. Su, and H. Zhang, Phys. Rev. C **94**, 024608 (2016).
[12] I. Bombaci and U. Lombardo, Phys. Rev. C **44**, 1892 (1991).
[13] A. E. L. Dieperink, Y. Dewulf, D. Van Neck, M. Waroquier, and V. Rodin, Phys. Rev. C **68**, 064307 (2003).
[14] Z. H. Li, U. Lombardo, H. J. Schulze, W. Zuo, L. W. Chen, and H. R. Ma, Phys. Rev. C **74**, 047304 (2006).
[15] L. W. Chen, C. M. Ko, and B. A. Li, Phys. Rev. C **76**, 054316 (2007).
[16] C. Fuchs and H. H. Wolter, Eur. Phys. J. A **30**, 5 (2006).
[17] B. A. Brown, Phys. Rev. Lett. **85**, 5296 (2000).
[18] R. Subedi *et al.*, Science **320**, 1476 (2008).
[19] C. Xu and B. A. Li, Phys. Rev. C **81**, 064612 (2010).
[20] A. W. Steiner and S. Gandolfi, Phys. Rev. Lett. **108**, 081102 (2012).
[21] K. Hebeler and A. Schwenk, Phys. Rev. C **82**, 014314 (2010).
[22] P. Russotto, M. D. Cozma, A. Le Fèvre *et al.*, Eur. Phys. J. A **50**, 38 (2014).
[23] W. Trautmann and H. H. Wolter, Int. J. Mod. Phys. E **21**, 1230003 (2012).
[24] W. Zuo, A. Lejeune, U. Lombardo, and J. F. Mathiot, Eur. Phys. J. A **14**, 469 (2002).
[25] W. M. Guo *et al.*, Phys. Lett. B **726**, 211 (2013).
[26] W. M. Guo *et al.*, Phys. Lett. B **738**, 397 (2014).
[27] B. A. Li, Phys. Rev. C **69**, 034614 (2004).
[28] H. Muller and B. D. Serot, Phys. Rev. C **52**, 2072 (1995).
[29] V. Baran *et al.*, Nucl. Phys. A **703**, 603 (2002).
[30] L. W. Chen, V. Greco, C. M. Ko, and B. A. Li, Phys. Rev. Lett. **90**, 162701 (2003).
[31] L. W. Chen, C. M. Ko, and B. A. Li, Phys. Rev. C **68**, 017601 (2003).
[32] L. Shi and P. Danielewicz, Phys. Rev. C **68**, 064604 (2003).
[33] L. Scalone, M. Colonna, and M. Di. Toro, Phys. Lett. B **461**, 9 (1999).
[34] Q. Li, C. Shen, C. Guo, Y. Wang, Z. Li, J. Lukasik, and W. Trautmann, Phys. Rev. C **83**, 044617 (2011).
[35] M. D. Cozma, Phys. Lett. B **700**, 139 (2011).
[36] B. A. Li, Phys. Rev. Lett. **88**, 192701 (2002).
[37] T. Gaitanos, M. Di Toro, S. Typel, V. Baran, C. Fuchs, V. Greco, and H. H. Wolter, Nucl. Phys. A **732**, 24 (2004).
[38] B. A. Li, G. C. Yong, and W. Zuo, Phys. Rev. C **71**, 014608 (2005).
[39] G. C. Yong, B. A. Li, L. W. Chen, and W. Zuo, Phys. Rev. C **73**, 034603 (2006).
[40] M. D. Cozma, Phys. Rev. C **95**, 014601 (2017).
[41] Q. F. Li, Z. X. Li, S. Soff *et al.*, J. Phys. G **32**, 151 (2006).
[42] G.-C. Yong, Y. Gao, G.-F. Wei, and W. Zuo, arXiv:1704.05166 (2017).
[43] P. Russotto, S. Gannon, S. Kupny *et al.*, Phys. Rev. C **94**, 034608 (2016).
[44] L. M. Lü *et al.*, Sci. China Phys. Mech. Astron. **60**, 012021 (2017).
[45] C. B. Das, S. Das Gupta, C. Gale, and B. A. Li, Phys. Rev. C **67**, 034611 (2003).
[46] C. Gale, G. Bertsch, and S. Das Gupta, Phys. Rev. C **35**, 1666 (1987).
[47] G. M. Welke, M. Prakash, T. T. S. Kuo, S. Das Gupta, and C. Gale, Phys. Rev. C **38**, 2101 (1988).

[48] J. Xu, L. W. Chen, B. A. Li, and H. R. Ma, Phys. Lett. B **650**, 348 (2007).
[49] J. Xu, L. W. Chen, B. A. Li, and H. R. Ma, Phys. Rev. C **77**, 014302 (2008).
[50] Y. Gao, L. Zhang, H. F. Zhang, X. M. Chen, and G. C. Yong, Phys. Rev. C **83**, 047602 (2011).
[51] L. Zhang, Y. Gao, Y. Du, G. H. Zuo, and G. C. Yong, Eur. Phys. J. A **48**, 30 (2012).
[52] B. A. Li and L. W. Chen, Phys. Rev. C **72**, 064611 (2005).
[53] G. Q. Li and R. Machleidt, Phys. Rev. C **48**, 1702 (1993).
[54] C. Fuchs, A. Faessler, and M. El-Shabshiry, Phys. Rev. C **64**, 024003 (2001).
[55] B. A. Li, Phys. Rev. Lett. **85**, 4221 (2000).
[56] G. C. Yong, B. A. Li, and L. W. Chen, Phys. Rev. C **74**, 064617 (2006).
[57] S. A. Bass, C. Hartnack, H. Stöcker, and W. Greiner, Phys. Rev. C **51**, 3343 (1995).
[58] B. A. Li and C. M. Ko, Phys. Rev. C **53**, R22 (1996).
[59] S. Voloshin and Y. Zhang, Z. Phys. C **70**, 665 (1996).
[60] P. Danielewicz, Roy A. Lacey, P. B. Gossiaux, C. Pinkenburg, P. Chung, J. M. Alexander, and R. L. McGrath, Phys. Rev. Lett. **81**, 2438 (1998).
[61] G. H. Liu, Y. G. Ma, X. Z. Cai *et al.*, Phys. Lett. B **312**, 145 (2008).
[62] B. A. Li and L. W. Chen, Mod. Phys. Lett. A **30**, 1530010 (2015).
[63] C. Xu, B. A. Li, and L. W. Chen, Phys. Rev. C **82**, 054607 (2010).