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Decomposition of the sensitivity of the symmetry energy observables

He-lei Liu[1,2], Gao-Chan Yong[2,*] and De-Hua Wen[1]
[1] *School of Sciences, South China University of Technology, Guangzhou 510641, P.R. China*
[2] *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*
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To exactly answer which density region that some frequently used symmetry-energy-sensitive observables probe, for the first time, we make a study of decomposition of the sensitivity of some symmetry-energy-sensitive observables. It is found that for the Au+Au reaction at incident beam energies of 200 and 400 MeV/nucleon, frequently used symmetry-energy-sensitive observables mainly probe the density-dependent symmetry energy around $1.25\rho_0$ (for pionic observables) or $1.5\rho_0$ (for nucleonic observables). Effects of the symmetry energy in the low-density region is in general small but observable. The fact that the symmetry-energy-sensitive observables are not sensitive to the symmetry energy in the maximal baryon-density region increases the difficulty of studying nuclear symmetry energy at super-density.

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I. INTRODUCTION

In the last 20 years, great progress has been made in the study of a new branch of nuclear physics, i.e, the isospin nuclear physics [1–4]. Theoretical studies have shown that, within the parabolic approximation, the energy per particle in asymmetric nuclear matter can be approximately expressed as $E(\rho,\delta) = E(\rho,\delta = 0) + E_{sym}(\rho)\delta^2$, where $\delta \equiv (\rho_n - \rho_p)/(\rho_n + \rho_p)$ is the isospin asymmetry parameter and $E_{sym}(\rho)$ is the density-dependent nuclear symmetry energy. The latter has been studied for decades due to its great importance in both nuclear physics and astrophysics [2–10]. Although significant progress has been made, the symmetry energy is still subject to uncertainties especially at high-density region [11, 12]. Nowadays, many sensitive observables have been identified as promising probes of the symmetry energy, such as the π^-/π^+ ratio [13–19], energetic photon as well as η [20–22], the neutron to proton ratio n/p [23–25], $t/^3He$ [26, 27], the isospin fractionation [24, 28–30] and the neutron-proton differential flow [31, 32]. However, one only knows these observables are in general sensitive to the high-density or low-density behaviors of the symmetry energy at certain beam energy whereas none knows the decomposition of sensitivity of the symmetry energy observables in the whole density region. Such knowledge surely affects obtaining information of the density-dependent symmetry energy from comparisons of theoretical simulation and experimental data. In this study, based on the isospin-dependent transport model, we address the above question.

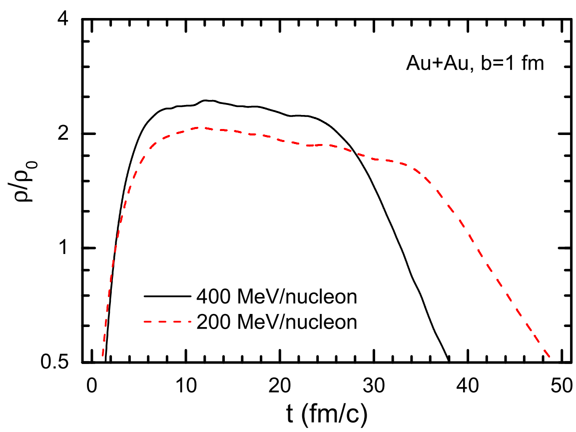

FIG. 1: (Color online) Evolution of the central baryon density in the reaction of $^{197}Au +^{197}Au$ at beam energies of 400 and 200 MeV/nucleon with an impact parameter of b=1 fm. ρ_0 denotes the nuclear saturation density.

II. MODELING NUCLEAR POTENTIAL IN THE IBUU TRANSPORT MODEL

In this study, for simplicity, we use the isospin and density-dependent single particle potential

$$U(\rho,\delta,\tau) = U_0(\rho) + U_{sym}(\rho,\delta,\tau), \quad (1)$$

where the isoscalar potential reads

$$U_0(\rho) = -356\rho/\rho_0 + 303(\rho/\rho_0)^{7/6}. \quad (2)$$

This soft nuclear isoscalar potential (SBKD) with $K_0 = 200$ MeV, was firstly introduced by Bertsch, Kruse and Das Gupta [33]. For the isovector potential $U_{sym}(\rho,\delta,\tau)$, we use the form [34]

$$U_{sym}(\rho,\delta,\tau) = \quad 4\tau\delta(1.27 + 25.4u - 9.31u^2 + 2.17u^3$$

*Electronic address: yonggaochan@impcas.ac.cn

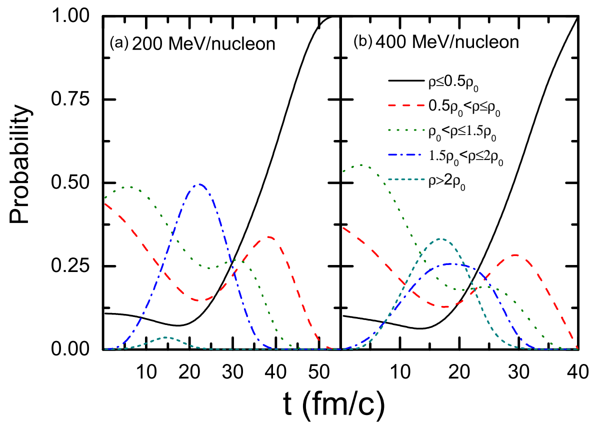

FIG. 2: (Color online) Evolution of the distribution percentage of baryon number in different density regions in the central reaction of $^{197}Au+^{197}Au$ at beam energies of 400 and 200 MeV/nucleon, respectively.

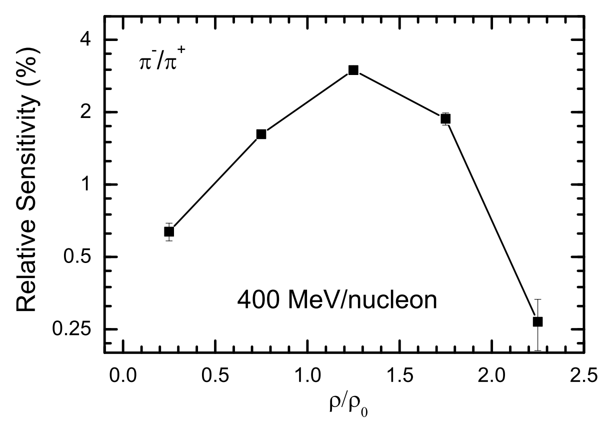

FIG. 3: Relative Sensitivity (RS) of the symmetry-energy-sensitive observable π^-/π^+ as a function of density.

$$-0.21u^4) - \delta^2(1.27 + 9.31u^2 - 4.33u^3 +0.63u^4), \quad (3)$$

where $u = \rho/\rho_0$ is the reduced bayron density and $\tau = 1/2$ (-1/2) for neutrons (protons). This symmetry potential roughly stands for one of the frequently used symmetry potential in nuclear transport models.

III. METHODS AND RESULTS

To probe the density-dependent symmetry energy, it is instructive to know the time evolution of central maximal baryon density reached in heavy-ion collisions. Figure 1 shows the evolution of the central maximal baryon density reached in $^{197}Au+^{197}Au$ reaction at beam energies of 400 and 200 MeV/nucleon with an impact parameter of b=1 fm. One can see that the central maximal baryon density reached is about $2.5\rho_0$ for the incident beam energy of 400 MeV/nucleon and about $2.0\rho_0$ for 200 MeV/nucleon case. And one can also see that the supra-density nuclear matter exists longer for 200 MeV/nucleon case than that for 400 MeV/nucleon case.

In order to better understand our target of studying the sensitivity of symmetry-energy-sensitive observables in different density regions, as shown in Figure 2, we plot the evolution of the distribution percentage of baryon number in different density regions. We can see that the distribution percentage of baryon number in different density regions changes with reaction time. More baryons lie in the density region around $1\sim1.5\rho_0$ in the whole reaction process. At the beginning of the reaction (t $\geq$ 1 fm/c) nucleons in the two colliding nuclei are slightly compressed, thus more nucleons lie in the density region $\rho > \rho_0$. Immediately after this, the central density of the reaction increases rapidly due to compression as shown in Figure 1.

Since baryons lie in different density regions, it is thus necessary to study in which density region the symmetry-energy-sensitive observables show maximal sensitivity. In order to know in which density region the frequently used symmetry energy sensitive observables show maximal sensitivity to the symmetry energy, similar with the study in Ref. [35], in the whole density region ($0 < \rho < 2.5\rho_0$) we use the U_{sym} as the standard calculation, which gives a value of one observable R_0, i.e.,

$$U_{sym}^{0<\rho<2.5\rho_0} \rightarrow R_0. \quad (4)$$

To see the relative sensitivity of this observable in different density regions (i.e., $\rho_1 \leq 0.5\rho_0,\ 0.5\rho_0 < \rho_2 \leq \rho_0,\ \rho_0 < \rho_3 \leq 1.5\rho_0,\ 1.5\rho_0 < \rho_4 \leq 2\rho_0,\ \rho_5 > 2\rho_0$), we turn off the symmetry energy in one density region but keep the symmetry energy in the residual density region. We thus get the other value of this observable R_i, i.e.,

$$U_{sym}^{0<\rho<2.5\rho_0} - U_{sym}^{\rho_i} \rightarrow R_i (i = 1, 2, 3, 4, 5). \quad (5)$$

Through comparing these new computational results with the standard calculation R_0, one can obtain the relative sensitivity in a certain density region, which reads

$$RS = \frac{|R_0 - R_i|}{R_0} \times 100. \quad (6)$$

In the following, we demonstrate decomposition of the sensitivity of the frequently mentioned observables in the literature.

The π^-/π^+ ratio was first proposed as a probe of nuclear symmetry energy in 2002 by *Li* [13]. It is generally considered to be sensitive to the high-density behavior of the symmetry energy. Shown in Figure 3 is the decomposition of the sensitivity of the symmetry energy

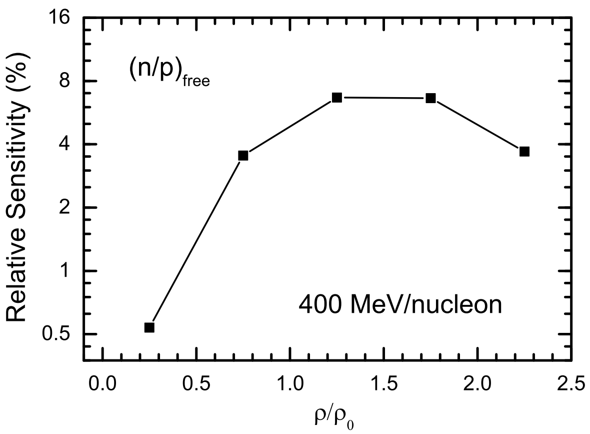

FIG. 4: Relative Sensitivity (RS) of the symmetry-energy-sensitive observable pre-equilibrium free n/p as a function of density.

observable π^-/π^+ in different density regions. From Figure 3 we can clearly see that the maximal sensitivity of π^-/π^+ to the density-dependent symmetry energy lies in the density region around $1.25\rho_0$. Above $1.5\rho_0$, sensitivity of π^-/π^+ to the symmetry energy is roughly equal to that below ρ_0. With increase of density, collision effect becomes larger. Thus one can see that the maximal sensitivity does not lie in the maximal density region reached. Due to rescatterings of pion meson in the low-density region, charged pion ratio π^-/π^+ is also affected by the low-density behavior of the symmetry energy in some degree. In general, the sensitivity of charged pion ratio π^-/π^+ to the nuclear symmetry energy is larger in the high density region $\rho > \rho_0$ than that in low density region $\rho < \rho_0$.

Shown in Figure 4 is decomposition of the sensitivity of the symmetry energy observable pre-equilibrium free neutron to proton ratio n/p in different density regions. From Figure 4, we can clearly see that the maximal sensitivity of the free neutron to proton ratio n/p at the incident beam energy of 400 MeV/nucleon lies in the density region around $1.5\rho_0$. Because nucleon emission at pre-equilibrium of the reaction does not suffer scatterings from the low-density matter, the symmetry energy in the low density region thus has minor effect.

It is of interest to make similar study at incident beam energy below 400 MeV/nucleon since such experiments of probing the symmetry energy and related are being planned or performed at RIKEN in Japan [36]. Shown in Figure 5 is decomposition of the sensitivity of the symmetry energy observable π^-/π^+ in different density regions in Au+Au reactions at the beam energy of 200 MeV/nucleon. We can see that the maximal sensitivity of π^-/π^+ to the density-dependent symmetry energy lies also in the density region around $1.25\rho_0$. And it is

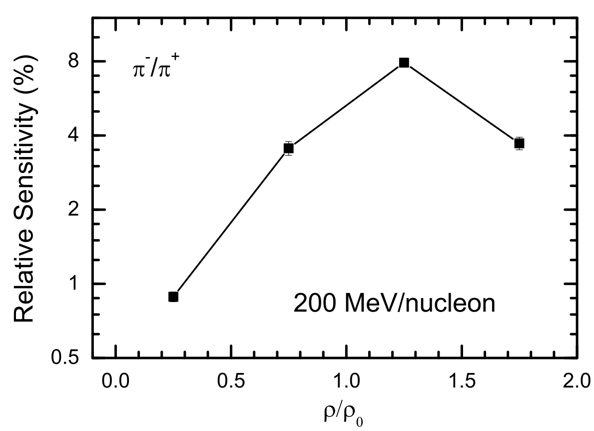

FIG. 5: Same as Figure 3, but at the beam energy of 200 MeV/nucleon.

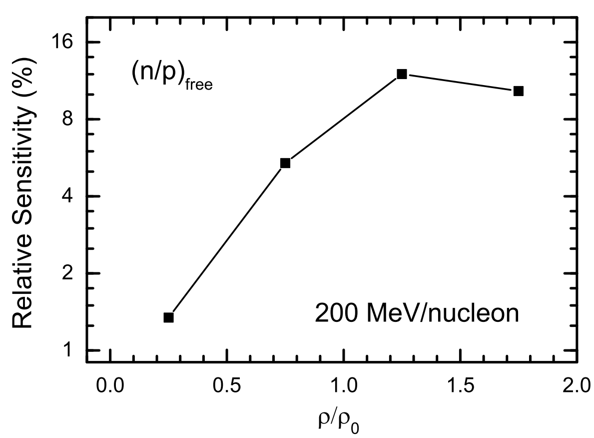

FIG. 6: Same as Figure 4, but at the beam energy of 200 MeV/nucleon.

in general still sensitive to the high density ($\rho > \rho_0$) behavior of the symmetry energy. More interestingly, we can see that the sensitivity of charged pion ratio π^-/π^+ to the symmetry energy is about two times larger than that at 400 MeV/nucleon beam energy. Therefore, one uses charged pion ratio π^-/π^+ to probe the high-density behavior of the symmetry energy, it is better to do experiments at relatively lower incident beam energy [37]. As for the observable pre-equilibrium free neutron to proton ratio at incident beam energy of 200 MeV/nucleon, it is shown in Figure 6. The maximal sensitivity of the pre-equilibrium free neutron to proton ratio n/p at the incident beam energy of 200 MeV/nucleon also lies in the density region around $1.5\rho_0$. In general, the symmetry energy in the low density region has minor effect.

As shown in Figure 2, because only a small percentage of baryon lies in the maximum density region reached and also in the maximum density there are larger collision effects, symmetry-energy-sensitive observables are not sensitive to the symmetry energy in the maximal baryon-density region. To probe the symmetry energy at higher densities, one thus needs heavy-ion collisions at even higher beam energy. However, the larger collision effects at higher beam energy increase the difficulty of studying nuclear symmetry energy.

IV. CONCLUSIONS

In summary, within the isospin dependent IBUU transport model, we studied the Au+Au reaction at incident beam energies of 200 and 400 MeV/nucleon. It is found that the symmetry-energy-sensitive observables including charged pion ratio π^-/π^+, pre-equilibrium free neutron-proton ratio n/p mainly probe the density-dependent symmetry energy around $1.25\rho_0$ (for pion emission) or $1.5\rho_0$ (for pre-equilibrium nucleon emission). Effects of the symmetry energy in the low-density region is in general small but observable. Since the symmetry-energy-sensitive observables are not sensitive to the symmetry energy in the maximal baryon-density region, it is therefore a challenge to probe the symmetry energy at higher densities.

V. ACKNOWLEDGMENTS

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[1] B.A. Li, W. Udo Schröder(Eds), Isospin Physics in Heavy-Ion Collisions at Intermediate Energies, Nova Science, New York, 2001.
[2] A.W. Steiner, M. Prakash, J.M. Lattimer, et al., Phys. Rep. **411**, 325 (2005).
[3] V. Baran, M. Colonna, V. Greco, M. Di Toro, Phys. Rep. **410**, 335 (2005).
[4] B.A. Li, L.W. Chen, and C.M. Ko, Phys. Rep. **464**, 113 (2008).
[5] K. Sumiyoshi, H. Toki, Astrophys. J. **422**, 700 (1994).
[6] P. Danielewicz, R. Lacey, and W.G. Lynch, Science **298**, 1592 (2002).
[7] J.M. Lattimer and M. Prakash, Science **304**, 536 (2004); Phys. Rep. **442**, 109 (2007).
[8] M.B. Tsang, Yingxun Zhang, P. Danielewicz, M. Famiano, Zhuxia Li, W.G. Lynch, A.W. Steiner, Phys. Rev. Lett. **102**, 122701 (2009).
[9] M.B. Tsang, Z. Chajecki, D. Coupland, P. Danielewicz, F. Famiano, R. Hodges, M.Kilburn, F. Lu, W.G. Lynch, J. Winkelbauer, M. Youngs, YingXun Zhang, Prog. Part. Nucl. Phys. **66**, 400 (2011).
[10] M. B. Tsang, J. R. Stone, F. Camera, P. Danielewicz, S. Gandolfi, K. Hebeler, C. J. Horowitz, Jenny Lee, W. G. Lynch, Z. Kohley, R. Lemmon, P. Moller, T. Murakami, S. Riordan, X. Roca-Maza, F. Sammarruca, A. W. Steiner, I. Vidaña, S. J. Yennello, Phys. Rev. C **86**, 015803 (2012).
[11] W.M. Guo, G.C. Yong, Y.J. Wang, Q. Li, H.F. Zhang, W. Zuo, Phys. Lett. B **726**, 211 (2013).
[12] W.M. Guo, G.C. Yong, Y.J. Wang, Q. Li, H.F. Zhang, W. Zuo, Phys. Lett. B **738**, 397 (2014).
[13] B.A. Li, Phys. Rev. Lett **88**, 192701 (2002).
[14] T. Gaitanos, M.Di Toro, S. Typei, V. Baran, C. Fuchs, V. Greco, and H.H. Wolter, Nucl. Phys. **A732**, 24 (2004).
[15] Q.F. Li et al., Phys. Rev. C **72**, 034613 (2005).
[16] F. Gulminelli and P. Chomaz, Phys. Rev. C **71**, 054607 (2005).
[17] G.C. Yong, B.A. Li, L.W. Chen, W. Zuo, Phys. Rev. C **73**, 051601 (2006).
[18] Z.G. Xiao et al, Nucl. Part. Phys **36**, 064040 (2009).
[19] Y. Gao, L. Zhang, W. Zuo, J.Q. Li, Phys. Rev. C **86**, 034611 (2012).
[20] G.C. Yong, B.A. Li, Phys. Lett. B **723**, 388 (2013).
[21] Z.G. Xiao, G.C. Yong, L.W. Chen, B.A. Li, M. Zhang, G.Q. Xiao, N. Xu, Eur. Phys. J. **A50**,37 (2014).
[22] G.C. Yong, B.A. Li, L.W. Chen, Phys. Lett. B **661**, 82 (2008).
[23] B.A. Li, Phys. Rev. Lett **78**, 1644 (1997).
[24] W.P. Tan et al., Phys. Rev. C **64**, 051901 (2001).
[25] V. Baran et al., Nucl. Phys. **A703**, 603 (2002).
[26] L.W. Chen, C.M. Ko, and B.A. Li, Phys, Rev. C **68**, 017601 (2003); Nucl. Phys. **A729**, 809 (2003).
[27] Y. Zhang and Z. Li, Phys. Rev. C **71**, 024604 (2005).
[28] H. Muller and B. Serot, Phys. Rev. C **52**, 2072 (1995).
[29] B.A. Li and C.M. Ko, Nucl. Phys. A **618**, 498 (1997).
[30] H.S. Xu et al., Phys. Rev. Lett. **85**, 716 (2000).
[31] B.A. Li, Phys. Rev. Lett **85**, 4221 (2000).
[32] V. Greco et al., Phys. Rev. C **67**, 015203 (2003).
[33] G.F. Bertsch et al., Phys. Rev. C **29**, 673 (1984).
[34] B.A. Li et al., Phys. Rev. C **69**, 011603 (2004).
[35] H.L. Liu, G.C. Yong, D.H. Wen, Phys. Rev. C **91**, 024604 (2015).
[36] http://dx.doi.org/10.1016/j.nima.2015.01.026.
[37] F. Zhang, Y. Liu, G.C. Yong, W. Zuo, Chin. Phys. Lett. **29**, 052502 (2012).