Initialization effect in heavy-ion collisions at intermediate energies

Gao-Chan Yong,1 Yuan Gao,2 Wei Zuo,1 and Xun-Chao Zhang1

1Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
2School of Information Engineering, Hangzhou Dianzi University, Hangzhou 310018, China

Based on the isospin-dependent Boltzmann-Uehling-Uhlenbeck transport model plus the Skyrme force parameters, initialization effect is studied in heavy-ion collision at intermediate energies. We find that there are moderate initialization effects in the observables of free neutron to proton ratio (n/p), \( \pi^-/\pi^+ \) ratio, as well as neutron to proton differential flow (\( F_\pi^{n-p} \)). Effects of initialization are larger for charged \( \pi^-/\pi^+ \) ratios than \( n/p \) ratios. And the effects of initialization are more evident in nuclear reactions at lower incident beam energies. We do not see large effects of initialization for light reaction systems or large asymmetric (neutron-richer) reaction systems. We also see relatively large effects of initialization on the neutron to proton differential flow at relatively lower incident beam energies or with large impact parameters. These results may be useful for the delicate studies of Equation of Sate (EoS) of asymmetric nuclear matter.

PACS numbers: 25.70.-z, 24.10.Lx

I. INTRODUCTION

The Equation of State (EoS) of asymmetric nuclear matter becomes one of the hot topics in today’s nuclear physics, simply because its isovector part, i.e., the symmetry energy, is a fundamental and crucial ingredient in the investigations of exotic nuclei, heavy-ion collisions, and astrophysical phenomena [1, 3]. While currently the theoretical predictions on the symmetry energy are quite diverse [4, 23]. Heavy-ion reactions induced by neutron-rich nuclei, especially radioactive beams, provide a unique opportunity to constrain the symmetry energy term in the EOS of isospin asymmetric nuclear matter [24, 31]. Nuclear reaction induced by the proton-rich (\( N < Z \)) nuclei was also studied recently [32]. Of particular interest is to identify experimental observables that are sensitive to the density dependence of nuclear symmetry energy. However, it is very challenging to find such observables since the compression phase is formed only transiently in heavy-ion reactions. Moreover, most hadronic observables are affected by both the isospin symmetric and asymmetric parts of the EOS at all densities throughout the whole dynamical evolution of the reaction. And experimental observables are also affected by nucleon-nucleon (NN) cross sections [33] and momentum dependence of isovector mean-field potential [34]. Thus rather delicate observables have to be selected to probe the density dependence of the nuclear symmetry energy, especially at high densities. The neutron to proton ratio [27, 33–39], the \( \pi^-/\pi^+ \) ratio [2, 41–45], the neutron-proton bremsstrahlung [40], the \( \pi^-/\pi^+ \) ratio [2, 41–45], the neutron-proton differential flow [16, 17] and the \( K^0/K^+ \) ratio [48] were proposed for this purpose. In all the above studies, initialization effect in heavy-ion collisions at intermediate energies was seldom mentioned. In this note, based on the isospin-dependent Boltzmann-Uehling-Uhlenbeck transport model plus the Skyrme force parameters, we studied initialization effect in heavy-ion collisions at intermediate energies. We find that there are moderate initialization effects in some common experimental observables relating to nuclear symmetry energy.

II. THEORETICAL METHODS

The isospin and momentum-dependent mean-field potential used in the present work is [49]

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

where \( \rho_n \) and \( \rho_p \) denote neutron (\( \tau = 1/2 \)) and proton (\( \tau = -1/2 \)) densities, respectively. \( \delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) \) is the isospin asymmetry of nuclear medium. All parameters in the preceding equation can be found in refs. [50]. The variable \( x \) is introduced to mimic 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 \( \rho_0 \). Because the purpose of present studies is just to see how large the effect of nuclear initialization on experimental observables, we just let the variable \( x \) be 0. The main characteristic of the present single particle is the momentum dependence of nuclear symmetry potential, which has evident effect on energetic free \( n/p \) ratio and \( \pi^-/\pi^+ \) ratio in heavy-ion collisions [34, 50]. In the present work, we use the isospin-dependent in-medium reduced NN elastic scattering cross section from the scaling model according to nucleon effective mass [51, 54]. For in-medium NN inelastic scattering cross section, we use the forms in free space since it is quite controversial. For nuclear initializations, we use the Skyrme-Hartree-Fock with Skyrme M* (SM) and Skyrme 1 (S1) force parameters [55].

Before studying initialization effect in heavy-ion collisions, we first give nuclear density distributions of a
nucleus $^{197}\text{Au}$ with Skyrme $M^\ast$ (SM) and Skyrme 1 (S1) force parameters, respectively. From Fig. 1 we can see that nucleonic distributions are more diffused with the SM force parameters. More clearly, from the inset figure of Fig. 1 we can see that $n/p$ of nucleonic distributions splits with the two set of force parameters in the marginal area of nucleus while the values of $n/p$ are almost the same in the core of nucleus. The SM parameters match small $n/p$ while the S1 parameters give large $n/p$. We also initialized the light nuclei $^{40}\text{Ca}$ and $^{48}\text{Ca}$, their nucleonic distributions show the same features.

III. RESULTS AND DISCUSSIONS

We first see effects of initialization on free $n/p$ since the free $n/p$ is a very common probe of nuclear symmetry energy [27, 35–39]. Fig. 2 shows initialization effect on the free $n/p$. We can see that for all the reaction systems, whether light or heavy, there are almost no initialization effects. Before this, one always think that effects of initialization are large for light reaction system. Our studies show that we can thoroughly neglect effects of initialization on free $n/p$ of preequilibrium emission. From Fig. 2 we can also see that effects of initialization on free $n/p$ are not affected by asymmetry of reaction system.

We next turn to the studies of effects of initialization on $\pi^-/\pi^+$ ratio. $\pi^-/\pi^+$ ratio recently becomes a very hot probe owing to its connection with the high-density behavior of nuclear symmetry energy [2, 41–45]. Fig. 3 shows effects of initialization on charged $\pi^-/\pi^+$ ratio in central reactions of $^{48}\text{Ca}+^{48}\text{Ca}$, $^{40}\text{Ca}+^{40}\text{Ca}$ and $^{197}\text{Au}+^{197}\text{Au}$ at 400 MeV/nucleon. We can first see that effects of initialization are larger on $\pi^-/\pi^+$ ratio than free $n/p$. For heavy system $^{197}\text{Au}+^{197}\text{Au}$, effects of initialization are larger than light systems $^{48}\text{Ca}+^{48}\text{Ca}$ and $^{40}\text{Ca}+^{40}\text{Ca}$. Again we here do not see a large initialization effect for light system. And we also do not see a large initialization effect on $\pi^-/\pi^+$ ratio from the reaction system with larger asymmetry. For S1 force parameters, we see small $\pi^-/\pi^+$ ratio than SM force parameters for the two large N/Z systems $^{197}\text{Au}+^{197}\text{Au}$ and $^{48}\text{Ca}+^{48}\text{Ca}$. This is because the S1 force parameters make the N/Z of nucleus in marginal area large (as shown in Fig. 1). The central area of nucleus, which
goes though a large compression and produces pions, matches small N/Z. While the $\pi^-/\pi^+$ ratio is approximately $(5N^2 + NZ)/(5Z^2 + NZ) \approx (N/Z)^2$ in central heavy-ion reactions with $N$ and $Z$ being the total neutron and proton numbers in the participant region [50]. S1 force parameters thus matches small values of $\pi^-/\pi^+$ ratio. In the calculations, effects of initialization on the central reactions of $^{18}$Ca+$^{48}$Ca, $^{40}$Ca+$^{40}$Ca and $^{197}$Au+$^{197}$Au at 400 MeV/nucleon are 1.6%, 2.9% and 3.5%, respectively. We therefore can almost neglect initialization effect in heavy-ion collisions while using charged pion ratio to probe the density-dependent symmetry energy.

![Image](image_url)

**FIG. 4:** (Color online) Beam energy dependence of initialization effects on charged $\pi^-/\pi^+$ ratio and free $n/p$ ratio in the $^{197}$Au+$^{197}$Au reaction with an impact parameter of 8 fm.

Studies show that charged $\pi^-/\pi^+$ ratio may be more sensitive to nuclear symmetry energy at lower incident beam energies via subthreshold pion production [2]. We thus make a study of beam energy dependence of initialization effects on charged $\pi^-/\pi^+$ ratio as well as free $n/p$ ratio in the $^{197}$Au+$^{197}$Au reaction with an impact parameter of 8 fm. From Fig. 4, we again see that free $n/p$ of preequilibrium emission shows no initialization effects with the increase of beam energy. While for $\pi^-/\pi^+$ ratio, effects of initialization seems larger for lower incident beam energies. Also we can clearly see that the values of $\pi^-/\pi^+$ ratio become larger with the decrease of beam energy. This trend is consistent with recent studies [2]. Comparing with the case of SM, S1 always gives large $\pi^-/\pi^+$ ratio in semi-central collision owing to the large N/Z of compression phase (as shown in Fig. 4). Therefore, it seems necessary to consider initialization effect of nucleus while using $\pi^-/\pi^+$ ratio to study nuclear symmetry energy via subthreshold pion production. One way is that the force parameters used for the initialization of nucleus give rough the “correct” symmetry energy value around saturation density. The other way is making the force parameters give the same symmetry energy, which can be deduced by the mean-field potential used in the model.

It is instructive to make a study of impact parameter dependence of charged pion ratio in heavy-ion collisions at intermediate energies. Fig. 5 shows impact parameter dependence of initialization effects on charged $\pi^-/\pi^+$ ratio and free $n/p$ ratio in the $^{197}$Au+$^{197}$Au reaction at 400 MeV/nucleon. We can first see that the values of $\pi^-/\pi^+$ ratio increase with the impact parameter owing to the large N/Z of compression phase. Initialization effect, however, does not keep stable. Comparing with the case of SM, S1 gives small $\pi^-/\pi^+$ ratio in central collision and shows large $\pi^-/\pi^+$ ratio in semi-central collision and for marginal collision S1 again provides small $\pi^-/\pi^+$ ratio. We also see that free n/p of preequilibrium emission shows no initialization effects with the increase of impact parameter. We thus conclude that impact parameter dependence of initialization effects on charged $\pi^-/\pi^+$ ratio can be neglected in heavy-ion collisions at intermediate energies.

At last we turn to the studies of neutron-proton differential flow [60] [13]. The neutron-proton differential transverse flow was defined as [17]

$$F_{n-p}^x(y) = \frac{1}{N(y)} \sum_{i=1}^{N(y)} \mathbf{p}_i^x(y) w_i$$

$$= \frac{N_n(y) (\langle p_n^x(y) \rangle) - N_p(y) (\langle p_p^x(y) \rangle)}{N(y)} \quad (2)$$

where $N(y)$, $N_n(y)$ and $N_p(y)$ are the number of free nucleons, neutrons and protons, respectively, at rapidity.
FIG. 6: (Color online) Effects of initialization of neutron-proton differential flow (as a function of reduced rapidity in C.M.) in $^{197}$Au+$^{197}$Au reaction at beam energies of 200, 400 and 800 MeV/nucleon, respectively.

FIG. 7: (Color online) Beam energy dependence of the effects of initialization of neutron-proton differential flow parameter (slope of $F_{n-p}$ at mid-rapidities) in $^{197}$Au+$^{197}$Au reaction with an impact parameter of 8 fm.

that effects of initialization on neutron-proton differential flow are large at lower incident beam energies. Initialization effect disappears at relatively large incident beam energies. Fig. 7 clearly show that we should consider the effects of nucleus initialization at relatively lower incident beam energies. We can also see that flow parameter is large with the SM force parameters (which makes the nucleonic distributions more diffused as shown in Fig. 1).

FIG. 8: (Color online) Impact parameter dependence of the effects of initialization of neutron-proton differential flow parameter in $^{197}$Au+$^{197}$Au reaction at beam energy of 400 MeV/nucleon.

FIG. 8 shows impact parameter dependence of the effects of initialization on neutron-proton differential flow parameter. It is clearly shown that effects of initialization on neutron-proton differential flow parameter are large with the increase of impact parameter owing to large difference of nucleonic flow of emitting nucleons.

IV. CONCLUSIONS

In conclusion, based on a transport model IBUU plus the Skyrme force parameters, we studied the effects of initialization on several probes in heavy-ion collisions at intermediate energies. We find that for particle emission, reactions at lower incident beam energies show relatively large initialization effects. And we do not see large initialization effects for lighter reaction systems. We also see large initialization effects on neutron-proton differential flow at lower incident beam energies or with large impact parameters. These results may be useful for the transport model simulations. And they may be also useful for the delicate studies of Equation of State of asymmetric nuclear matter.
Acknowledgments

The author G.C. Yong thanks Prof. Bao-An Li and Prof. Lie-Wen Chen for useful discussions. The work is supported by the National Natural Science Foundation of China (10875151, 1074020550), the Knowledge Innovation Project (KJCX2-EW-N01) of Chinese Academy of Sciences, the Major State Basic Research Developing Program of China under No. 2007CB815004, the CAS/SAFEA International Partnership Program for Creative Research Teams (CXTD-J2005-1) and the Zhejiang Provincial Natural Science Foundation of China (Grant No. Y6110644).
[54] D. Persram and C. Gale, Phys. Rev. C65, 064611 (2002).
[55] J. Friedrich and P.G. Reinhard, Phys. Rev. C33, 335 (1986).
[56] R. Stock, Phys. Rep. 135, 259 (1986).