The influence of reconstruction criteria on the sensitive probes of the symmetry potential

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Different criteria of constructing clusters and tracing back $\Delta$ resonances from the intermediate-energy neutron-rich HICs are discussed by employing the updated UrQMD transport model. It is found that both the phase-space and the coordinate-density criteria affect the single and the double neutron/proton ratios of free nucleons at small transverse momenta, but the influence becomes invisible at large transverse momenta. The effect of different methods of reconstructing freeze-out $\Delta$s on the $\Delta^0/\Delta^{++}$ ratio is strong in a large kinetic energy region.

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I. INTRODUCTION

The equation of state (EoS) of nuclear matter is one of the most important topics in the field of low and intermediate energy heavy ion collisions (HICs). In recent years, more and more work have been focusing on the isospin asymmetry of the HICs, which introduces more uncertainties into the EoS. Without considering the momentum dependence of the EoS, the isospin dependent EoS for asymmetric nuclear matter can be simply expressed as $e(u, \delta) = e_0(u) + e_{\text{sym}} \delta^2$ where $u = \rho/\rho_0$ is the reduced nuclear density and $\delta = (\rho_n - \rho_p)/\rho$ is the isospin asymmetry in terms of neutron and proton densities. $e_0$ and $e_{\text{sym}}$ are the isospin independent term (which includes the Skyrme and the Yukawa potentials) and the symmetry energy (which can be expressed as $e_{\text{sym}} = S_0 F(u)$ where $S_0$ is the symmetry energy coefficient and $F(u)$ the density dependence), respectively (see, e.g., Refs. \textsuperscript{[1, 2]}). Since the symmetry energy term plays also an important role in nuclear structure and astrophysics, it indeed deserves more attention. With the many efforts from both theoretical and experimental sides, the uncertainties in EoS have been largely constrained although arguments remain in this field. For example, (1) the isospin-independent EoS has been constrained into a soft compress modulus ($K \simeq 190 - 270$ MeV, see, for example, \textsuperscript{[3, 4, 5, 6]}). (2) The symmetry energy coefficient has been constrained into the region $S_0 \simeq 30 - 36$ MeV \textsuperscript{[4, 7, 8]}. And, (3) the strength factor ($\gamma$) of the density dependence of the symmetry potential is also shown not to be stiff at subnormal densities \textsuperscript{[9, 10]}, i.e., $\gamma = 0.69$ or $1.05$ when the form $F(u) = u^\gamma$ is employed, which depends on the treatments of nucleon-nucleon collisions in the BUU transport model.

While the density dependence of the symmetry potential at supranormal densities is still quite uncertain. So far several (probably) sensitive probes especially on this issue have been brought out by theoretical groups, which are hoped to be observed from experiments such as the planned FRIB(USA), the upcoming GSI new facility FAIR (Germany), and the cooling storage ring CSR being tested at Lanzhou (China), etc. For example, the $\pi^-$ to $\pi^+$ multiplicity ratio and the neutron-proton collective transverse flow were firstly pointed out in Ref. \textsuperscript{[11]}. While the threshold production of pions and kaons and the difference between neutron and proton elliptic flows were stressed in Refs. \textsuperscript{[12, 13]}. In our previous investigations, we found that the $\Sigma^-/\Sigma^+$ ratio \textsuperscript{[14]} at threshold, the $\pi^+ - \pi^-$ elliptic flow difference at moderate transverse momentum \textsuperscript{[13]}, and the $\Delta^-/\Delta^{++}$ ratios at large transverse momenta \textsuperscript{[16]} are sensitive to the density dependence of the symmetry potential at high densities. Despite of the difficulties of detecting and analyzing $\Delta$ resonances, the advantage of taking $\Delta$ as a probe for symmetry potential at high densities is also obvious: firstly, it is known that most of $\Delta$s can be produced from the high density region. Secondly, the $\Delta \to N\pi$ loop sustains the $\Delta$ matter for a relatively long time, hence the evolution of $\Delta$s should be heavily influenced by the mean field. Finally, since some of nucleon- and the pion-related quantities are predicted to be sensitive to the symmetry potential, it is believed that the corresponding $\Delta$-related quantities will show strong effect on symmetry potential as well. Thus we are interested in checking one crucial question: can the transverse momentum distribution of the $\Delta^-/\Delta^+$ ratio, or more realistically, the kinetic energy distribution of the $\Delta^0/\Delta^+$ ratio (since it is not easy to reconstruct $\Delta^-$ and its momentum components through its neutron and $\pi^-$ daughters), be experimentally taken as a sensitive candidate for detecting the symmetry potential at supranormal densities? Besides, we found that the transverse momentum dependence of the neutron/proton ($n/p$) ratio of free nucleons is also sensitive to symmetry

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potential \(^{17}\). However, since the effect of symmetry energy term is secondary when comparing it with the isospin-independent term, one should pay attention to the late stage of HICs in any transport-model related calculations. In this work, we also intend to test the influence of different criteria of constructing clusters on the \(n/p\) ratio of free nucleons.

The paper is arranged as follows: in section 2, the UrQMD model is introduced briefly and the projectile-target combinations to be investigated are chosen. Section 3 explains different criteria of constructing free nucleons/fragments and tracing back \(\Delta\) resonances at freeze-out. The effect of the reconstruction criteria on the multiplicities of nucleons and \(\Delta\) is discussed. In section 4, the influence of different reconstruction criteria on the transverse momentum dependence of the \(n/p\) ratio and the kinetic energy dependence of the \(\Delta^0/\Delta^{++}\) ratio is illustrated and discussed. The conclusions are given in section 5.

II. SYSTEM DETERMINATION

The UrQMD transport model \(^{18, 19}\) has been updated for the investigations of intermediate energy HICs. For details of the updated version of the UrQMD model, the reader is referred to Ref. \(^{20}\) and references therein. In this work, the soft EoS with a momentum dependent term (SM-EoS) is adopted. Two types of density dependent symmetry potential energy are selected: (1) \(F(u) = u^\gamma\), where \(\gamma\) factor varies from 0.5 (dubbed as “g05”, soft), 1.0 (“g1”, moderate) to 1.5 (“g15”, hard). (2) the so-called “DDHρs” (very soft) symmetry potential energy from the relativistic mean-field calculation \(^{21}\). Furthermore, The “Dirac”-type medium modification of nucleon-nucleon elastic cross sections discussed in \(^{22}\) is also considered here.

The choice of the reaction system should be with great care as well. For \(\Delta\)-related probes, first of all, in order to excite enough \(\Delta(1232)\) resonances but not to excite too many other higher-lying resonances, the HICs at moderate beam energies such as 400 \(\sim\) 1000A MeV should be chosen. At the same time, considering of the large background spectrum of non-correlated \((p, \pi)\) pairs which is induced especially by heavy system collision \(^{23}\), a midsize and neutron-rich projectile-target system is necessary in order also to obtain an initially large isospin asymmetry \(\delta\) value. Further, inspired by the experiments with 2 or 4 sets of projectile-target systems of different asymmetry \(^{24, 25}\) and the model-based investigations \(^{20, 26}\) in order to cancel other potential effects which are not (obviously) related to isospin, we select the central \((b = 0 – 2 \text{ fm})\) \(^{132}\)Sn\(^{+}\)\(^{132}\)Sn and \(^{112}\)Sn\(^{+}\)\(^{112}\)Sn reactions at \(E_b = 800\)A MeV as examples. While for nucleon-related probes, the HICs (besides the reactions with respect to Sn-isotopes we select the Pb+Pb system as well) at a lower beam energy such as 400A MeV are preferred and adopted in this work.

III. DIFFERENT CRITERIA OF CONSTRUCTING CLUSTERS AND TRACING BACK \(\Delta\) RESONANCES

Generally speaking, two methods for constructing clusters exist in the transport model calculations. The one is called as the coalescence model, which is normally used in the QMD-like analysis. In the coalescence model nucleons with relative distances \(|\Delta r| < R_0\) and relative momenta \(|\Delta p| < P_0\) are considered to belong to one cluster (depicted in the left plot of Fig. 1 titled as “T-I”), otherwise, the nucleons are free. The other one adopts a coordinate density cut \(\rho_c\). (depicted in the right plot of Fig. 1 titled as “T-II”) to separate “free” nucleons from other fragments. This method is often used in the BUU-like model analysis, in which the density of each real particle is obtained with respect to all of its test particles. While in QMD-like transport models, each particle is represent by a Gaussian wave packet in the phase space, the density of each particle in coordinate space can be expressed as

\[
\rho_i = \int \rho(r_i) \rho(\mathbf{r}) d\mathbf{r} = \int \rho(r_i) \sum_j \rho(r_j) d\mathbf{r} = \frac{1}{\sqrt{(4\pi)^3 |\Delta r|^2}} \sum_j e^{-\frac{(r_i - r_j)^2}{4|\Delta r|^2}}. \]

In this work, we examine the freeze-out condition \(\rho_i < \rho_c = \rho_0 / 10\) (dubbed as “\(\text{Rc}\)”) to “find” free nucleons. Fig. 2 shows the time evolution of the fraction of nucleons to be free from Pb+Pb central collisions at \(E_b = 0.4\)A GeV (by averaging 100 events). The SM-EoS with a linear symmetry potential (“g1”) is adopted as an example. In the “T-I” mode, the free nucleons are found out with two sets of \(R_0\) and \(P_0\) parameters: (1) “\(\text{RP-I}\)”: \(R_0 = 2.8\) fm and \(P_0 = 0.2\) GeV/c, (2) “\(\text{RP-II}\)”: \(R_0 = 3.5\) fm and \(P_0 = 0.3\) GeV/c. In the “T-II” mode, the “\(\text{Rc}\)” parameter set is used. It is easy to understand that with the increase of \(R_0\) and \(P_0\) values, the number of free nucleons becomes less and less. Meanwhile, it is seen that the number of free nucleons with “\(\text{RP-I}\)” mode is almost same as that with “\(\text{Rc}\)” mode after \(t \sim \delta \text{ fm/c}\) and not sensitive to the time evolution any more. Before this time, much more nucleons in “\(\text{RP-I}\)” mode than in “\(\text{Rc}\)” mode are taken as free due to the large momentum difference but the relatively small distance difference between nucleons. Therefore, the choice of the cut-time \(t_c\) to stop the transport program will affect the final freeze-out of nucleons if a too short time is selected. From now on, the \(t_c = 100\) fm/c is selected for further investigations.

In order to track the resonances at freeze-out, one needs to look through the detailed history of the time evolution
FIG. 1: Two methods for constructing clusters. Left plot: the relative distance of two particles $|\Delta r| < R_0$ and the relative momentum of two particles $|\Delta p| < P_0$ ("T-I"), $R_0$ and $P_0$ are free parameters in units of fm and GeV/c. Right plot: coordinate density cut for the particle $i$ in fragments: $\rho_i > \rho_c = \rho_0/c$ ("T-II").

FIG. 2: Time evolution of the fraction of “free” nucleons from Pb+Pb central collisions at $E_b = 0.4A$ GeV. The SM-EoS with a linear symmetry potential is adopted in calculations. No other physical cuts are selected. Results of “finding” free nucleons from different criteria ("RP-I", "RP-II", and "Rc") are compared (see context).
FIG. 3: Two methods for reconstructing \( \Delta \) resonance at freeze-out. Left plot: the pion produced from a \( \Delta \) decay is found and the pion does not rescatter any more. It is not concerned if the other nucleon daughter collides further with other particles or not (marked with a shadowed box). This mode is called as “M-I”. Right plot: only the \( \Delta \)s whose decay daughters do not rescatter any more are selected. This mode is called as “M-II”.

FIG. 4: Kinetic energy distribution of \( \Delta^0 \) and \( \Delta^{++} \) resonances at freeze-out which is “found” by the two methods depicted in Fig. 3 from central \( ^{132} \text{Sn} + ^{132} \text{Sn} \) collisions at \( E_b = 0.8 \text{A GeV} \). The SM-EoS with a stiff symmetry potential (“g15”) is adopted. The rapidity cut of pions \( |y_\pi| < 0.5 \) is used.
of HICs. In the UrQMD model there is a standard OSCAR-formatted output file (“ftn20”) which includes complete event history, that is, besides the initial and the final freeze-out states, all binary collisions, string-fragmentations, and hadronic decays of particles are recorded into this file. From this file, one can easily find the Δ decay channel $\Delta \rightarrow N\pi$. It is known that the produced daughters nucleon and pion from this channel will probably collide further with other particles [27]. Thus it is not easy to detect Δ resonances at freeze-out time experimentally. Currently there exist two methods in experiments which are employed to “find” baryon resonances: (1) the one-pion $p_\pi$ distribution is defolded to yield the mass distribution; (2) the correlated proton and charged pion pairs are analyzed to yield the invariant mass distribution [23]. In Fig. 4 we also show two methods for “finding” Δ resonance at freeze-out: (1) in “M-I”, the Δ in which decay channel the pion daughter will not further rescatter is found out while, it is not concerned if the other nucleon daughter rescatters or not. This mode can be taken as a “contaminated” reconstructing mode. (2) in “M-II”, both the pion and the nucleon from the decay of the Δ resonance at freeze-out are confirmed, the Δ resonance is thus taken to be reconstructable. And this mode is a “clean” reconstructing mode. Fig. 4 illustrates the kinetic energy $E_{\text{kin}}$ distribution of $\Delta^0$ and $\Delta^{++}$ resonances at freeze-out “detected” by the above two methods for central $^{132}\text{Sn} + ^{132}\text{Sn}$ collisions at $E_b = 0.8\text{A GeV}$. The SM-EoS with a stiff symmetry potential (“g15”) is adopted as an example. The rapidity cut of pions $|y| < 0.5 \quad (y = \frac{1}{2} \log(\frac{E_{\text{cm}} + p_{/\|}}{E_{\text{cm}} - p_{/\|}}), E_{\text{cm}} \text{ and } p_{/\|} \text{ are the energy and longitudinal momentum of the pion in the center-of-mass system})$ is used. With the “M-I” method the amount of Δs at small kinetic energies is much larger than that with the “M-II” method, which is due to the high chance of rescattering of the produced nucleon with others. The difference of the Δ yields with the two methods is seen to disappear at large $E_{\text{kin}}$ due to the fact that the rescattering probability of the fast nucleons becomes rather rare.

IV. THE INFLUENCE OF DIFFERENT RECONSTRUCTION CRITERIA ON SENSITIVE OBSERVABLES

Fig. 5 shows the transverse momentum $p_t$ dependence of the $n/p$ ratio of free nucleons from central Pb+Pb collisions at $E_b = 0.4\text{A GeV}$. Two sets of density dependent symmetry potential “g15” (hard) and “DDHg” (very soft) are adopted in calculations. And three modes “RP-I”, “RP-II”, and “Re” are taken into account for constructing clusters at the cut-time $t_c = 100\text{fm}/c$. No rapidity cut is selected. First of all, it is known that the $n/p$ ratio at low and high transverse momentum reflects the behavior of symmetry potential at subnormal and supranormal densities, which has been systematically studied in our previous work [17], in which the “RP-II” is used in the coalescence-model analysis. With shorter relative phase-space distances used in the “RP-I” mode, more nucleons are counted into free nucleons, which drives the $n/p$ ratio at small $p_t$ to approaching the initial $n/p$ ratio of the system (=1.54). Surprisingly, although the total amount of free nucleons from “RP-I” mode is seen almost same as that from “Re” mode, the $n/p$ ratio of free nucleons is visibly different from each other at small $p_t$: the “Re” mode gives a larger $n/p$ ratio. It implies that the two methods of constructing clusters used for transport models are not equivalent at small $p_t$ and bring more uncertainties when one hopes to evaluate the sensitivity of nucleon-related probes to the symmetry potential. One also finds that the softer the symmetry potential is, the more sensitive to the free $n/p$ ratio the methods of constructing clusters are. It is easy to understand since the soft symmetry potential has larger value than the stiff one at subnormal densities, thus the softer symmetry potential influences the freeze-out of particles more obviously at the late stage. Then, let us move on to see the $n/p$ ratio in the large $p_t$ region ($p_t > 0.6 GeV/c$), it is interesting to see that all of the three constructing modes have almost no different effect on the values of the $n/p$ ratio. It is obviously due to the fact that the free nucleons with large $p_t$ are dominantly emitted from high densities at early stage and are influenced very weakly by the late stage. It also shows that the $n/p$ ratio of free nucleons at large $p_t$ is a (relatively) clean and sensitive probe to the symmetry potential at high densities.

The $p_t$ dependence of the $n/p$ ratio from $^{132}\text{Sn} + ^{132}\text{Sn}$ and $^{112}\text{Sn} + ^{112}\text{Sn}$ systems are also calculated. The results from the two systems are shown in the left plot of Fig. 6 separately. In this figure, the results with modes “RP-I” and “Re” are compared and a rapidity cut $|y| < 0.2$ is employed. The results are similar to those in Fig. 5. The effects of the symmetry potential and the freeze-out criteria on the $n/p$ ratio are weak in the more isospin-symmetric system $^{112}\text{Sn} + ^{112}\text{Sn}$. The right plot of Fig. 6 illustrates the double ratio expressed as the $n/p$ ratio from $^{132}\text{Sn} + ^{132}\text{Sn}$ system divided by the $n/p$ ratio from $^{112}\text{Sn} + ^{112}\text{Sn}$ system, and is dubbed as $(n/p)_{^{132}\text{Sn}} / (n/p)_{^{112}\text{Sn}}$. Similar to the single $n/p$ ratio shown in the left plot of Fig. 6 the effect of freeze-out criteria is still seen at small $p_t$, especially for the soft symmetry potential case, while at $p_t > 0.6 GeV/c$, it almost disappears. Therefore, both the single and the double ratios at large transverse momenta are visibly affected by the density dependence of the symmetry potential but invisibly influenced by the different criteria of constructing clusters and can be taken as good observables for symmetry potential at high densities.

Let us finally check the effect of the different analyzing methods of reconstructing Δ resonances at freeze-out on its particle ratio $\Delta^0/\Delta^{++}$. In Fig. 7 (left plot) we present the kinetic energy ($E_{\text{kin}}$) distribution of the $\Delta^0/\Delta^{++}$ ratio at freeze-out where Δs are collected with the methods “M-I” and “M-II” introduced above. The symmetry potentials...
FIG. 5: Transverse momentum $p_t$ dependence of the $n/p$ ratio for central Pb+Pb collisions at $E_b = 0.4A$ GeV. Two sets of symmetry potential “g15” and “DDH$\rho^*$” are adopted in calculations. Three modes “RP-I”, “RP-II”, and “Rc” are taken into account for constructing clusters at the cut-time $t_c = 100fm/c$.

FIG. 6: Left plot: Transverse momentum $p_t$ dependence of the $n/p$ ratio of free nucleons for central $^{132}$Sn+^{132}Sn and $^{112}$Sn+^{112}Sn collisions at $E_b = 0.4A$ GeV. Two sets of symmetry potential “g15” and “DDH$\rho^*$” are adopted in calculations. Two modes “RP-I” and “Rc” are taken into account to construct clusters. The rapidity cut $|y| < 0.2$ is chosen. Right plot: The double ratio between $n/p$ ratios from the $^{132}$Sn+^{132}Sn system and from the $^{112}$Sn+^{112}Sn system.
FIG. 7: Left plot: Kinetic energy distribution of the $\Delta^0/\Delta^{++}$ ratio at freeze-out. The $\Delta$s are determined with two methods “M-I” and “M-II” (see context). The central $^{132}\text{Sn}+^{132}\text{Sn}$ collisions at $E_b = 0.8\text{A GeV}$ are calculated. The rapidity cut of pions $|y_\pi| < 0.5$ is chosen. Right plot: The $\Delta^0/\Delta^{++}$ ratio from $^{132}\text{Sn}+^{132}\text{Sn}$ is scaled by the $\Delta^0/\Delta^{++}$ ratio from $^{112}\text{Sn}+^{112}\text{Sn}$.

“g05”, “g15”, and “DDH$\rho^*$” are adopted. For each case 0.36 million central $^{132}\text{Sn}+^{132}\text{Sn}$ collisions at $E_b = 0.8\text{A GeV}$ are calculated. And a rapidity cut of pions $|y_\pi| < 0.5$ is adopted as well. First of all, the “crossing” behavior of the ratios with soft and stiff symmetry potentials can hardly be seen from the “M-I” reconstruction mode. It implies that the $\Delta^0/\Delta^{++}$ ratio versus $E_{\text{kin}}$ is sensitive to the density dependent symmetry potential at high densities. However, in the “clean” “M-II” mode, the “crossing” behavior re-occurs which means the symmetry potential at low densities shows its role. Actually, the two modes give a quite different $\Delta^0/\Delta^{++}$ ratio especially at the small $E_{\text{kin}}$. Even at the large $E_{\text{kin}} (>0.5\text{GeV})$, the difference does not disappear. The “clean” mode “M-II”, which implies that the selected $\Delta$s come from more outer space where densities are low, gives a much large ratio at all $E_{\text{kin}}$ due to the fact that these $\Delta$s are produced from more neutron-rich region. Even in the scaled ratio by the ratio from $^{112}\text{Sn}+^{112}\text{Sn}$ system (dubbed as $(\Delta^0/\Delta^{++})_{\text{Sn132}} - (\Delta^0/\Delta^{++})_{\text{Sn112}}$) shown in the right plot of Fig. 7 the huge effect of different reconstructing criteria on the scaled ratio still exists. Although the $\Delta^0/\Delta^{++}$ ratio indeed shows its sensitivity to the density dependence of symmetry potential, the detailed process of the reconstruction for $\Delta$s at freeze-out should be paid much more attention.

In summary, different criteria of constructing free nucleons and tracing back $\Delta$ resonances from the intermediate-energy neutron-rich HICs are discussed with the help of the UrQMD model. It is found that both the parametrization of relative phase-space distances used in the coalescence model and the coordinate density cut for free nucleons modify visibly the single and the double $n/p$ ratios at small transverse momenta, but the influence is weak at large transverse momenta. Hence, the single and the double $n/p$ ratios of free nucleons at large transverse momenta can be taken as sensitive probes for symmetry potential at supranormal densities. The momentum dependence of the symmetry potential might complicate this situation and deserves further careful investigation [28]. Methods of reconstructing $\Delta$ resonances affect the $\Delta^0/\Delta^{++}$ ratio versus kinetic energy strongly, which should be paid more attention if one wishes to employ it as a probe to detect the symmetry potential of the nuclear matter at high densities.
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