Directed flow of isospin sensitive fragments within a modified clusterization algorithm in heavy-ion collisions (Postprint)

Authors: KUMAR Sanjeev, MA Yugang

Date: 2023-06-18T00:00:00+00:00

Abstract

By extending the minimum spanning tree (MST) clusterization algorithm for the binding energy cut, the isospin asymmetry dependence of directed flow for isospin sensitive isobar pairs (neutrons-protons, 3H-3He) is studied from low towards high incident energies. The modified clusterization method (MSTB) has the advantage to identify the fragments at quite early time. It enhances (reduces) the production of free nucleons (fragments) over MST method. The directed flow of isobaric pair 3H-3He is more sensitive towards isospin asymmetry caused by MSTB than isobaric pair n-p. This sensitivity becomes quite strong towards the high incident energy and neutron-rich reaction system. In conclusion, the inclusion of binding energy in clusterization method for the flow studies has been uniquely important for understanding the isospin physics, especially for high density behavior of symmetry energy.

Full Text

Preamble

Nuclear Science and Techniques 24 (2013) 050509

Directed flow of isospin sensitive fragments within a modified clusterization algorithm in heavy-ion collisions

KUMAR Sanjeev[1,2], MA Yugang[2,*]

[1]Amity Institute of Nuclear Science and Technology, Amity University, Noida, Uttar Pradesh-201303, India
[2]Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Jiading Campus, Shanghai 201800, China

Abstract

By extending the minimum spanning tree (MST) clusterization algorithm with a binding energy cut, we investigate the isospin asymmetry dependence of directed flow for isospin-sensitive isobar pairs (neutrons-protons, ^{3}H-^{3}He) from low to high incident energies. The modified clusterization method (MSTB) offers the advantage of identifying fragments at quite early times. It enhances (reduces) the production of free nucleons (fragments) compared to the MST method.

The directed flow of the isobaric pair ^{3}H-^{3}He exhibits greater sensitivity to isospin asymmetry caused by MSTB than the isobaric pair n-p. This sensitivity becomes particularly strong at high incident energies and in neutron-rich reaction systems. In conclusion, the inclusion of binding energy in the clusterization method for flow studies is uniquely important for understanding isospin physics, especially regarding the high-density behavior of symmetry energy.

Key words Binding energy, Isospin Physics, Symmetry energy, Directed flow

Introduction

With the availability of radioactive beam facilities, isospin physics has attracted the entire nuclear physics community over the last decade. In intermediate-energy heavy-ion collisions, dynamical models such as Quantum Molecular Dynamics (QMD) and Boltzmann-Uehling-Uhlenbeck (BUU) statistical models have been employed to extract rich information about isospin physics. These dynamical models are uniquely important due to their ability to follow the time evolution from initialization through compression and expansion to the equilibrium state. However, it is well known that dynamical models do not naturally simulate fragments. To address this limitation, secondary algorithms must be coupled with dynamical models. In efforts to reproduce experimental data, many secondary algorithms have been developed to study nuclei near the drip line, but very few exist for nuclei away from the drip line.

The most commonly and widely used algorithm depends on the spatial and momentum coordinates of nucleons and is known as the minimum spanning tree (MST) algorithm. According to this method, two nucleons undergo cluster formation if the relative distance (|R -R |) and relative momentum (|P -P |) between them are less than 3.5–4 fm and 250–268 MeV/c, respectively. These parameters can be obtained by fitting experimental data for global observables such as the multiplicity of intermediate mass fragments with theoretical results. Recently, the MST method was further extended to isospin-dependent MST, in which the momentum space cut remained the same, but the spatial coordinate cut was constrained based on particle type. The distance between different kinds of particles was taken as follows: |R -R | = 3 fm for like particles and 6 fm for unlike particles.

Since the MST method only depends on constraints from position and momentum, concerns arise regarding the stability of fragments due to the formation of artificially weakly bound fragments. To avoid this problem, more complicated methods such as the Stimulated Annealing Clusterization Algorithm (SACA) and Early Cluster Recognition Algorithm (ECRA) were also developed. These methods were found to be quite successful but very complicated. Moreover, due to the choice of parameters such as cooling parameters, iteration procedures, and choice of minima, they can follow totally different fragment configurations. Due to the limitation of sharp minima, the scope of these two methods was found to be restricted at some points for mildly excited or asymmetric systems. The best possible method for avoiding artificial fragment formation appears to be constraining fragments using an average binding energy cut of 4 MeV/nucleon. One can further improve the method by using realistic binding energy rather than a fixed 4 MeV/nucleon. This method was found to be as simple as MST and capable of reproducing results from complicated methods like SACA and ECRA.

Extensive studies of fragment multiplicities with different clusterization methods have been performed, while flow parameters have been poorly studied. In the last two decades, the collective flow of nucleons in non-central collisions has proven to be a useful tool for extracting the nuclear equation of state (NEOS) of symmetric nuclear matter. Over time, efforts have been made to extract information about isospin physics in terms of symmetry energy using both directed and elliptic flow. These studies showed that experimental results of directed flow can be reproduced by (1) changing the mean field or nucleon-nucleon (NN) cross sections in the transport model, or (2) using the nucleon phase space for calculations. Most studies were found to obey a hard equation of state, which contradicts other literature. In a recent study, a soft equation of state was predicted, but the comparison was made between directed flow extracted from the phase space of nucleons and directed flow of fragments having $Z \leq 2$. Within BUU calculations, the importance of directed flow of isospin-sensitive fragments n, p, ^{3}H, and ^{3}He over the directed flow of nucleon phase space has already been highlighted. The elliptic flow extracted with the simple MST method was also found to be quite sensitive for determining symmetry energy at supra-saturation densities. These results indicated that both directed and elliptic flow can be useful tools for understanding isospin physics or symmetry energy.

The main problem with previous studies is that isospin physics with directed and elliptic flow has been investigated either from nucleon phase space or using the simple MST method. It is worth mentioning that one cannot guarantee the stability of fragments formed with the simple MST method. Due to these concerns about fragment stability, it is presently essential to study the importance of isospin physics from directed and elliptic flow using stable fragments. In the present study, stable fragments are first formed by applying a binding energy cut to pre-clusters generated with the simple MST method. Subsequently, the sensitivity of directed flow for isospin-sensitive fragments n, p, ^{3}H, and ^{3}He is investigated from low to high incident energies with variation in the isospin asymmetry of the reaction systems. The methodology is explained in Section 2, results and discussions are presented in Section 3, followed by conclusions in Section 4.

2 Methodology

In the present work, the IQMD model is used, which is discussed in detail in our recent publications and was originally developed by Hartnack and co-workers. The model has been modified by the authors for the density dependence of symmetry energy, having the form:

$$E_{\text{sym}} = C_{s,k}\left(\frac{\rho}{\rho_0}\right)^{\gamma_i} + C_{s,p}\left(\frac{\rho}{\rho_0}\right)^{2/3}$$

with parameters $C_{s,k} = 25$ MeV and $C_{s,p} = 35.2$ MeV. When we set $\gamma_i = 0.5$ and 1.5, respectively, it corresponds to soft and stiff symmetry energy.

The Minimum Spanning Tree method with Binding Energy Check (MSTB) is employed. This method is a modified version of the normal MST and old MSTB method. The difference between old MSTB and this MSTB is the inclusion of energy from momentum-dependent interactions as well as symmetry energy along with Skyrme interactions. The procedure is as follows: the phase space obtained from IQMD is analyzed with the simple MST method and pre-clusters are sorted out. Since we are not aware of the stability of pre-clusters formed at this stage, the pre-clusters from the simple MST are now subjected to the binding energy condition as follows:

$$E_{\text{Bind}} = \frac{1}{N_f}\sum_{i=1}^{N_f}\left[E(i) - \frac{p_z^2(i)}{2m}\right] - \frac{P^2}{2N_{fm}} < E_{\text{Bind}}^{\text{cut}}$$

where $E(i)$ and $p_z(i)$ are the total energy and longitudinal momentum of the ith particle, respectively.

The second method is to study the directed transverse in-plane flow. The quantity v_1^x is defined as follows:

$$v_1^x = \langle \text{sign}\{Y(i)\} \cdot P_x(i)/A \rangle$$

where $Y(i)$ is the rapidity distribution and $P_x(i)$ is the transverse momentum of the ith particle in the x-direction. This v_1^x is defined over the entire rapidity region and therefore presents an easier way of measuring the in-plane flow rather than complicated P_x/A plots.

Here, we take $E_{\text{Bind}}^{\text{cut}} = 4.0$ MeV/nucleon if $N_f \geq 3$ and $E_{\text{Bind}}^{\text{cut}} = 0$ otherwise. In this equation, N_f is the number of nucleons in a fragment, and P is the average momentum of the nucleons bound in the fragment. The requirement of a minimum binding energy excludes loosely bound fragments that would decay later. The realistic value of E_{Bind} changes the fragment multiplicity only slightly at intermediate times but has no influence on the qualitative behavior or asymptotic results. However, if one uses realistic binding energy to search for the most bound configuration, the results will be affected. At present, we have focused on bound configurations, and hence -4 MeV/nucleon is justified.

3 Results and Discussions

Several thousand events for the reactions ^{112}Sn+^{112}Sn and ^{124}Sn+^{124}Sn between incident energies of 50 and 600 MeV/nucleon for nearly central collisions have been simulated using the IQMD model coupled with MST and MSTB algorithms. The soft momentum-dependent equation of state with soft symmetry energy and isospin-energy dependent cross sections is employed.

There are two methods in the literature used to calculate directed flow. In the first case, directed flow is extracted from the mid-rapidity slope of P_x/A versus rapidity distribution $Y_{\text{c.m.}}/Y_{\text{beam}}$ plots. The rapidity distribution is calculated as follows:

$$Y(i) = \frac{1}{2}\ln\frac{E(i)+p_z(i)}{E(i)-p_z(i)}$$

[Figure 1: see original paper] Time evolution of different kinds of fragments: free nucleons (upper), LCPs (middle), and IMFs (bottom) for central collisions at 50 MeV/nucleon with MST and MSTB algorithms. The left (right) panels are for neutron-poor (neutron-rich) ^{112}Sn+^{112}Sn (^{124}Sn+^{124}Sn) reaction systems. All results are with soft symmetry energy.

To check the stability of fragments and the effect of isospin physics, Fig. 1 displays the time evolution of free nucleons, light charged particles (LCPs), and intermediate mass fragments (IMFs) for neutron-poor and neutron-rich reaction systems at 50 MeV/nucleon with MST and MSTB algorithms. In the high-density phase, the MSTB algorithm does not find any fragments with reasonable binding energy, and hence most particles remain free, while many artificial fragments appear with MST. After the high-density phase ends, MSTB begins recognizing fragments that are real, bound, and stable. In all cases, MSTB helps identify fragments quite early. The figure clearly shows that MSTB enhances the production of free particles while reducing the production of LCPs and IMFs. Moreover, as fragment size increases, MST requires less time to match MSTB results, and the difference between MST and MSTB decreases throughout the time evolution.

[Figure 2: see original paper] Importance of MSTB in flow calculations by plotting the rapidity distribution dependence of P_x/A for neutrons, protons, and ^{3}H particles with MST and MSTB algorithms at 100 MeV/nucleon for the ^{124}Sn+^{124}Sn reaction system.

Using the first method, Fig. 2 plots the rapidity distribution of P_x/A for neutrons, protons, and ^{3}H particles at 100 MeV/nucleon for central collisions of the ^{124}Sn reaction system. The mid-rapidity slope of P_x/A represents the directed flow. The flow is found to be affected only for heavier fragments, while neutron and proton flows are least affected. This is due to the isotropic (anisotropic) distribution of free nucleons (LCPs). Naturally, the yield must be compared between neutron-poor and neutron-rich reaction systems. It is found that enhanced fragment production occurs for the more neutron-rich system. This enhancement is quite effective for free nucleons and LCPs compared to IMFs. We have also recently shown that free nucleons and LCPs are more sensitive to symmetry energy than IMFs. In this regard, the sensitivity of free nucleons and LCPs with MSTB to neutron-rich systems can also play an important role in predicting symmetry energy, which is a topic for separate discussion. After assessing this sensitivity, we use the isospin-sensitive free nucleons and LCPs—namely, n, p, ^{3}H, and ^{3}He—for further study.

[Figure 3: see original paper] (Color online) Isospin asymmetry dependence of directed flow for isobaric pairs neutrons, protons with MST and MSTB method. The different panels are at different incident energies ranging from 50 to 600 MeV/nucleon.

To study the role of MSTB at higher incident energies and its effect on isospin physics, Fig. 3 plots the more reliable flow quantity v_1^x for isobaric pairs (n, p) and (^{3}H,^{3}He) with MST and MSTB algorithms from 50 to 600 MeV/nucleon. With increasing incident energy, the isospin asymmetry dependence of directed flow for n, p is found to be more affected by the clusterization method than by the type of particles. In all panels, protons (neutrons) have more (less) positive directed flow with both MST and MSTB methods. This is due to the contribution of Coulomb repulsion in proton production. The directed flow of both protons and neutrons becomes more positive with MSTB over MST towards high incident energy. This occurs because there is increased content of unstable fragments with MST at high incident energy. MSTB breaks these unstable fragments into free particles (as specified earlier), leading to dominance of collisions. Moreover, the higher positive flow of neutrons at high incident energy can serve as a tool for studying isospin-dependent cross sections. Furthermore, these findings suggest a shift in the balance energy with different kinds of fragments. These points indicate that clusterization methods will play an important role in understanding isospin physics and must be handled carefully during symmetry energy determination.

[Figure 4: see original paper] (Color online) Same as in Fig. 3, but for the ^{3}H and ^{3}He particles.

In Fig. 4, similar to n and p, the isospin asymmetry dependence of directed flow for ^{3}H and ^{3}He is found to be more affected by the clusterization method than by particle type towards high incident energy. Up to 100 MeV/nucleon, ^{3}He (^{3}H) particles have more (less) positive directed flow, but at and after 200 MeV/nucleon, ^{3}H (^{3}He) particles have more (less) positive flow with both MST and MSTB methods. This is due to the dominance of mean field (collisions) at and below (at and above) 100 (200) MeV/nucleon. When the mean field (collisions) dominates, Coulomb interactions (isospin-dependent cross sections) make the flow more positive for proton-rich (neutron-rich) ^{3}He (^{3}H) particles.

Towards higher incident energies, the flow of both ^{3}H and ^{3}He becomes more positive with MST over MSTB method. As with the inclusion of binding energy restrictions in the clusterization algorithm, most ^{3}H and ^{3}He fragments are found to be unstable, especially for ^{3}He, and hence directed flow decreases with MSTB, resulting in increased transverse directed flow for neutrons and protons (as discussed previously in Fig. 3).

4 Conclusion

In brief, the directed flow of isospin-sensitive particles n, p, ^{3}H, and ^{3}He is affected by different clusterization methods. The role of different clusterization methods dominates for the isobaric pair (^{3}H, ^{3}He) compared to (n, p). Moreover, the behavior of directed flow for the (n, p) pair is smooth with incident energy, but a transition is observed for the directed flow of the (^{3}H, ^{3}He) pair with incident energy. The isobaric pairs (n, p) and (^{3}H, ^{3}He) exhibit opposite sensitivity to the type of clusterization method.

The modified clusterization method has a time-saving advantage in providing real, bound, and stable fragments at quite early times. It has the capability to obtain results similar to complicated secondary algorithms SACA and ECRA. Moreover, MSTB overcomes the drawbacks of being time-consuming and having many adjustable parameters. The directed flow of the isobaric pair ^{3}H-^{3}He in comparison to n-p is found to be strongly dependent on the isospin asymmetry caused by MSTB with increasing incident energy as well as isospin of the reaction systems. This indicates it as a robust approach for understanding the high-density behavior of isospin physics or symmetry energy.

References

Gautam S, Kumari R, Puri R K. Phys Rev C, 2012, 86:
Jain A, Kumar S, Puri R K. Phys Rev C, 2012, 85:
Ma Y G, Wei Y B, Shen W Q, et al. Phys Rev C, 2006, 73: 014604.
Kumar S, Ma Y G, Zhang G Q, et al. Phys Rev C, 2011, 84: 044620.
Kumar S, Ma Y G, Zhang G Q, et al. Phys Rev C, 2012, 85: 024620.
Yan T Z, Ma Y G, Cai X Z, et al. Phys Lett B, 2006, 638:
Russotto P, Wu P Z, Zoric M, et al. Phys Lett B, 2011, 697:
Wei Y B, Ma Y G, Shen W Q, et al. Phys Lett B, 2004, 586: 225–231.
Hartnack C, Puri R K, Aichelin J, et al. Eur Phys J A, 1998, 1: 151–169.
Aichelin J. Phys Rep, 1991, 202: 233–360.
Reisdorf W, Leifels Y, Andronic A, et al. Nucl Phys A, 2012, 876: 1–60.
Molitoris J J, Hahn D, Stocker H. Nucl Phys A, 1986, 447:
Sood A D and Puri R K. Phys Rev C, 2006, 73: 067602.
Hartnack C, Oeschler H, Aichelin J. Phys Rev Lett, 2006, 96: 012302.
Vermani Y K and Puri R K. Nucl Phys A, 2010, 847:
Li B A, Chen L W, Ma H R, et al. Phys Rev C, 2007, 76: 051601(R).
Zhang G Q, Cao X G, Fu Y, et al. Nucl Sci Tech, 2012, 23:

Wang J, Ma Y G, Shen W Q, et al. Nucl Sci Tech, 2013, 24: 030501.

Note: Figure translations are in progress. See original paper for figures.