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ANALYZING THE ROLE OF FRAGMENT CHARGE ON NUCLEAR STOPPING FOR SYMMETRIC COLLIDING NUCLEI*

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We study the role of fragment charge on nuclear stopping using Isospin-dependent Quantum Molecular Dynamics model. The analysis is carried out for the reactions of $^{40}_{20}$Ca + $^{40}_{20}$Ca, $^{58}_{28}$Ni + $^{58}_{28}$Ni, $^{129}_{54}$Xe + $^{129}_{54}$Xe, and $^{197}_{79}$Au + $^{197}_{79}$Au, at an incident energy between 90 MeV/nucleon and 1.5 GeV/nucleon. For fragment formation, we use three different clusterization algorithms namely minimum spanning tree, minimum spanning tree with momentum constraint, isospin-dependent minimum spanning tree. We conclude that the influence of various clusterization algorithms is small on nuclear stopping for the fragments having charge $Z = 1, 2, 3$ and 4 and shows small influence only at lower incident energies. Moreover, minimum spanning tree algorithm yields higher stopping compared to other clusterization techniques. The theoretical calculations follow the similar trend given by experimental findings.

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1. Introduction

One of the primary goal in studying heavy-ion reactions at intermediate energies is the investigation of the properties of nuclear matter at supra-normal densities and/or high temperatures. Among the various phenomena of heavy ion collisions (HICs) at intermediate energy, nuclear stopping enjoyed the special status. It can be viewed as a measure of the degree to which the energy of the relative motion of the two colliding nuclei is transformed into other degree of freedom. Higher nuclear stopping will cause more thermalization of the system. A complete knowledge about the degree

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of stopping is very important to understand the properties and dynamics of the colliding system, and provides new predictions that can be probed by experimentalists for further investigations.

In earlier attempts, lots of work has been done both theoretically as well as experimentally on nuclear stopping. Zhang *et al.* [1] gave a unified description of the nuclear stopping in central HICs at incident energy between $E = 10$ MeV/nucleon and 1.2 GeV/nucleon. Li *et al.* [2] studied the dependence of nuclear stopping on system size, neutron to proton ratio, isospin symmetry potential, and medium corrections of two-body cross-sections. They found that the influence of the initial N/Z ratio, as well as isospin symmetry potential, is weak on nuclear stopping. The excitation function of Q_{ZZ}/A and R, however, depends on the form of the medium corrections of two-body cross-sections and on the equation of state (EOS) of nuclear matter. Liu *et al.* [3] studied the nuclear stopping for various colliding systems with different neutron–proton ratio over large domains of incident energy and reported that nuclear stopping is sensitive towards the isospin content of in-medium nucleon–nucleon cross-section above the Fermi energy. In another study by Kumar *et al.* [4], a complete systematics *i.e.* excitation function, impact parameter, system size, isospin asymmetry, and EOS dependencies of global stopping and fragment production for heavy-ion reactions in the energy range between 50 and 1000 MeV/nucleon, have been carried out in the presence of symmetry energy and isospin-dependent nucleon–nucleon cross-section. Their study revealed that the degree of stopping depends weakly on the symmetry energy and strongly on the isospin dependence of nucleon–nucleon cross-section. Singh *et al.* [5] studied the formation of fragments using different clusterization techniques using the Quantum Molecular Dynamics (QMD) model and later on the influence of isospin dependence of nucleons in the formation of clusters was further investigated by Zhang *et al.* [6]. It is well known that the fragments are formed after time of few hundreds of fm/c in heavy ion collisions and the nuclear stopping is also influenced by the compression produced during the collision of two nuclei. By using different clusterization algorithms, one can simulate results which would slightly differ in the degree of stopping. In the present manuscript, our aim is to study the influence of fragment charge formed by using three different clusterization algorithms namely MST (minimum spanning tree) [8], MSTP (minimum spanning tree with momentum constraint) [9], and iso-MST (isospin dependent minimum spanning tree) [10] on nuclear stopping. The whole study is performed within the framework of an Isospin-dependent Quantum Molecular Dynamics model (IQMD) [7].

2. Results and discussion

Once the phase space is generated by the IQMD model, the different nucleons are clusterized or grouped in the form of fragments according to various conditions. This is done through different clusterization algorithms. These algorithms impose constraints on the relative distance or momentum (or both) between two particles and form fragments accordingly. In the MST [8] method, two nucleons share the same fragment if their centroids are closer than a distance of 4 fm. An improvement over MST is MSTP which puts restriction on the spatial as well as momentum space of the nucleons as discussed by Kumar *et al.* [9]. Further, the isospin nature of the nucleons is considered while imposing the constraint between two nucleons. This method is dubbed as iso-MST [10]. In this method

$$|r_\alpha - r_\beta| \leq d_{\min}\,, \tag{1}$$

where $d_{\min}$ is the distance between the nucleons forming a fragment having value 3 fm between proton–proton and 6 fm between neutron–neutron and neutron–proton.

For the present analysis, simulations are carried out for the reactions of $^{40}_{20}$Ca+$^{40}_{20}$Ca, $^{58}_{28}$Ni+$^{58}_{28}$Ni, $^{129}_{54}$Xe+$^{129}_{54}$Xe, and $^{197}_{79}$Au+$^{197}_{79}$Au at scaled impact parameter of $\hat{b} = b/b_{\max} < 0.15$, where $b_{\max} = 1.15(A_{\rm T}^{1/3} + A_{\rm P}^{1/3})$ fm ($A_{\rm T}$ and $A_{\rm P}$ are the mass of target and projectile respectively), using isospin dependent nucleon–nucleon cross-section. The whole analysis is performed for soft equation of state ($K = 200$ MeV) along with the linear form of density dependent symmetry energy. The time evolution of the reaction is followed up to 200 fm/c. Moreover, in IQMD model, the Gaussian width parameter depends on the mass of the colliding nuclei. Its value is 2.16 fm^2 for Au+Au, 1.08 fm^2 for Ca+Ca and in between these two values for middle mass nuclei. Stopping is calculated in terms of varxz [11] which is defined as the ratio of transverse to the longitudinal variances

$$\mathrm{var}xz = \frac{\mathrm{var}x}{\mathrm{var}z} = \frac{\sigma^2(x)}{\sigma^2(z)}\,, \tag{2}$$

where var$x$ and var$z$ are calculated from the fwhm (full width at half maxima) of the rapidity distribution along transverse and longitudinal directions respectively using the relation

$$\mathrm{fwhm} = 2.36 \times \sqrt{\mathrm{variance}}\,, \tag{3}$$

in which variance may be var$x$ and var$z$.

In Fig. 1, we display the fragment charge dependence of nuclear stopping for different clusterization algorithms. The theoretical calculations follow the similar trend as given by experimental findings. It has been observed that nuclear stopping using MST algorithm predicts a higher stopping compared to MSTP and iso-MST algorithms. This is because MST yields bigger fragments compared to MSTP and iso-MST as this approach is based on simple spatial correlations. Therefore, in this approach, nucleons with large relative momentum will also be a part of the cluster though MSTP method forbids such nucleons to be in the same cluster. The difference is seen quite evidently for ${}^{40}_{20}$Ca+${}^{40}_{20}$Ca (lighter) system. The difference in varxz for simulations with different clusterization algorithms (*i.e.* MST, MSTP and iso-MST) is more evident for lighter systems compared to heavier for central collisions. This is because the spectator matter even at peripheral geometries will be very small for lighter colliding nuclei, therefore the fragments are emitted mostly from the participant zone, where they are unstable and hence momentum constraint plays a significant role at such geometries. Thus, one can see that for lighter systems, the role of different clusterization algorithms is greater whereas for heavier systems, this role diminishes.

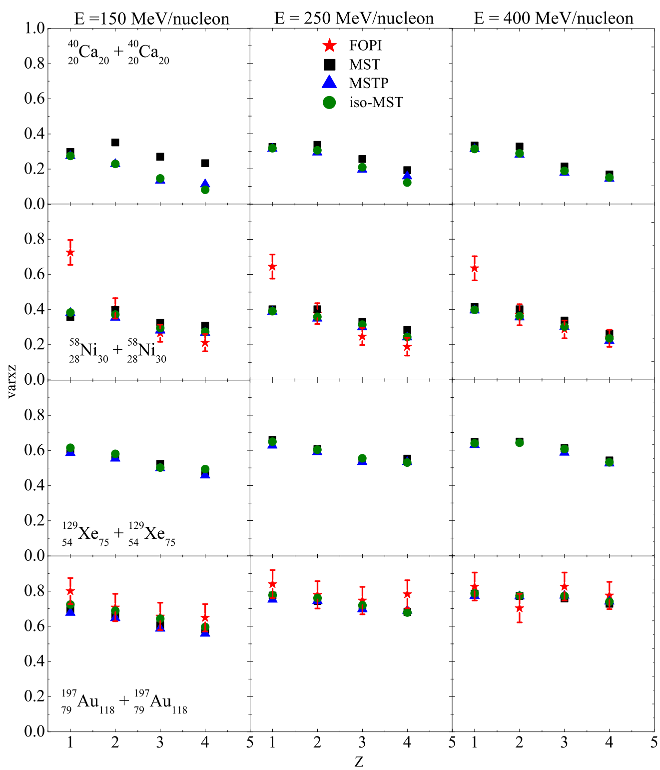

Fig. 1. Fragment charge dependence of varxz at incident energy between $E = 150$, 250 and 400 MeV/nucleon with different clusterization algorithms. Experimental data has been taken from [11].

Further, in Fig. 2, we display the incident energy dependence of varxz for the fragments having charge $Z = 2$ for the reactions of ${}^{40}_{20}$Ca+${}^{40}_{20}$Ca, ${}^{58}_{28}$Ni+${}^{58}_{28}$Ni, and ${}^{129}_{54}$Xe+${}^{129}_{54}$Xe. One can see that for a heavier system, *i.e.*, ${}^{129}_{54}$Xe+${}^{129}_{54}$Xe, the excitation function of varxz is relatively small at low incident energy (*i.e.*, between 90 and 300 MeV/nucleon), rises to a maximum and then gradually declines. Moreover, varxz does not yield a value of 1 (corresponding to maximum stopping at central collisions) indicating that full thermalization is not achieved even for the heavier system in central collisions. The rising part of the varxz excitation function is due to the decreasing effect of Pauli blocking as the rapidity gap exceeds the Fermi energy [11]. A maximum of stopping is found around 400 MeV/nucleon. On the other hand, when energy exceeds 400–600 MeV/nucleon, a decline in the stopping excitation function is seen. This is because with increase in incident energy the Pauli blocking becomes ineffective and the elementary cross-section drops resulting in less collisions and hence a lower stopping. For lighter systems, *i.e.* ${}^{40}_{20}$Ca+${}^{40}_{20}$Ca and ${}^{58}_{28}$Ni+${}^{58}_{28}$Ni, stopping is more at low incident energy (between 90 and 150 MeV/nucleon), which gradually decreases and then follows similar trend as shown by the heavier systems. As in previous figures, nuclear stopping is more with MST algorithm compared to other clusterization techniques and this difference is more pronounced at low incident energies. This is because at lower energies relatively heavier fragments are formed which would decay further to attain stability. Since different clusterization algorithms impose different constraints for the formation of fragments, this decay further depends on the particular clusterization method used which eventually affects stopping (which depends on the mass

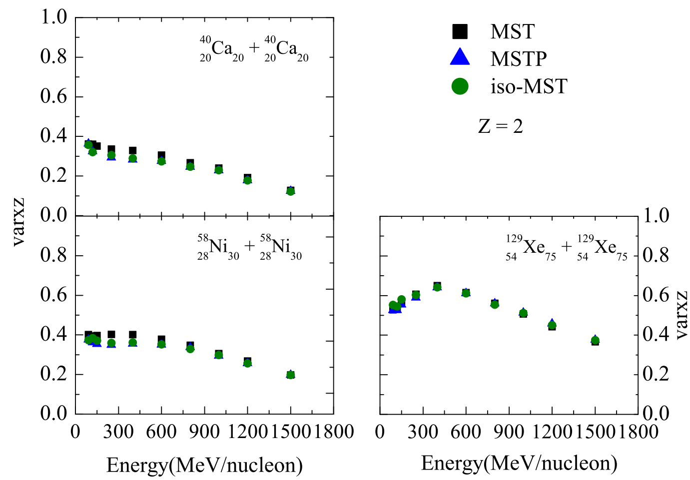

Fig. 2. Incident energy dependence of varxz for the fragments having charge $Z = 2$ with different clusterization algorithms.

of the fragment). However, at higher incident energy, the multiplicity of free nucleons ($A = 1$) increases and the method of clusterization does not play a significant role.

3. Conclusion

In summary, using the Isospin-dependent Quantum Molecular Dynamics (IQMD) model, we have carried out simulations for symmetric reactions and calculated the nuclear stopping for the fragments having charge $Z = 1, 2, 3$ and 4. We found that varxz increases with system mass and the difference in the varxz of various fragments becomes more prominent with the increase in incident energy. The different clusterization techniques show larger difference in stopping magnitude for lighter systems compared to heavier ones. Moreover, nuclear stopping decreases with fragment charge. Finally, it has been observed that clusterization methods affect nuclear stopping only slightly at lower incident energies and MST algorithm shows more stopping compared to other clusterization techniques. But at energies above 400–600 MeV/nucleon (depending on the system), the influence of clusterization is almost negligible.

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