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On the Relative Role of Isospin-Dependent Interactions in Fragmentation of Super Heavy Colliding Nuclei

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***Abstract* — Using isospin-dependent quantum molecular dynamics (IQMD) approach, we here check the role of isospin interactions on various fragments formed in the collisions of lighter to super heavy nuclei at intermediate energies. We demonstrated the direct impact of symmetry energy stiffness factor and Coulomb interactions on the final yield of fragments, simultaneously. The effects of Coulomb and different forms of density dependence of symmetry energy show an enhanced sensitivity for superheavy involved reactions compared to the earlier stable systems**

***Index Terms* — Isospin quantum molecular dynamical (IQMD) model, symmetry energy, super-heavy nuclei.**

I. Introduction

The fragmentation mechanism (i.e. break-up of colliding nuclei) in heavy-ion reactions at low, as well as at intermediate energies is extremely useful to explore the isospin dependent part of the nuclear equation of state. A vast and rich literature is available in this regard where the role of isospin for wide range of system mass, incident energy and colliding geometry on fragmentation is reported since last couple of decades [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14],[15], [16], [17]. In the recent times, major interest of nuclear physics community is to explore the density dependence of symmetry energy at sub- and supra-saturation density regions. Based on various studies reported in the literature, the most general form of density dependence of symmetry energy reads as [6], [7]:

$$E_{Sym}(\rho) = E_{Sym}(\rho_0).\left(\frac{\rho}{\rho_0}\right. \quad (1)$$

Here $E_{\mathrm{Sym}}(\rho_0)$ (= 32 MeV) corresponds to symmetry energy at normal nuclear matter density and smaller (larger) value of the parameter γ corresponds to soft (stiff) density dependence of symmetry energy. Various investigations have been performed to find the behavior of symmetry energy at sub and supra-saturation densities [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17]. Till now, no definite evidence is available about the actual high density behavior of symmetry energy. Many collaborations reported in the literature contradict each other [9], [10], [11], [12]. Since fragmentation is a low density phenomena, therefore,
it is used to extract the in-depth knowledge about the low density behavior of symmetry energy. In fragmentation, direct fragment yields [1], [3], neutron-to-proton ratio [13], [14], double neutron-to-proton ratio [15] and isospin fractionation ratio [16], [17] are among the commonly used observables for exploring the density dependence of symmetry energy. An accurate information regarding the density-dependent part of the symmetry energy is not only useful to understand the dynamics of the reactions, but is also extremely helpful for precise and realistic determination of many phenomena such as giant dipole resonance, pygmy dipole resonance [18], [19], [20] and cooling mechanism of neutron stars [21], [22]. It is worth mentioning that all attempts to constrain density dependence of symmetry energy have involved projectile/target nuclei up to ^{238}U only.

At the same time, much interest has been gathered in synthesizing super heavy elements and studying their properties [23], [24]. Many exclusive studies are being performed to manifest the island of stability, deformation, the critical value of neutron/proton content, radii and binding energies of super heavy elements [25], [26], [27], [28]. These properties have been extensively studied at low energies and proved to enjoy tremendous success in exploring various aspects of normal nuclear matter. As reported in various studies, Coulomb interactions play a decisive role in synthesizing super heavy elements and pinning down their various properties [25], [26], [27], [28], [29].Though many studies involving heavy and super heavy nuclei are available at low incident energies, one wonders about the outcome of the collisions of super heavy nuclei at intermediate energies where multifragmentation [1], [2], [3], [4], [5], [13], [14], [15], [16], [17], collective flow[30], [31], [32], particle production [33] etc. are the crucial phenomena. Moreover, since super heavy nuclei have larger neutron content, they are far away from the N = Z symmetry line. One, therefore, also expects larger role of isospin physics in the reactions involving super heavy elements. Very recently, Puri *et al.*, [34] performed a study of first kind where collective flow and ultimately the energy of vanishing flow was predicted for the reactions involving super heavy nuclei. Very interestingly, the behavior of energy of vanishing flow of super heavy involved reactions was reported to deviate drastically [34] from the

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usual $A^{-1/3}$ mass dependence known for the collisions of normal stable nuclei [31], [32].

A detailed investigation revealed the huge repulsive Coulomb interactions to be the main cause behind this drastic deviation [34]. It would, therefore, be interesting and important to see whether the fragment structure involving super heavy reactions yield different structure or not.

In fragmentation at intermediate energies, a significant competition between the symmetry energy and Coulomb interactions was reported by one of us and collaborator [35]. One would rather expect a much drastic role of Coulomb interactions on the fragmentation pattern when super heavy nuclei are considered. To gauge a clear picture of the response of fragmentation towards isospin effects, we here carry a systematic study over wide span of incident energy involving super heavy nuclei. For comparison, we also study the reactions involving stable nuclei. The present study will also be useful to pin down the direct effect of the stiffness of symmetry energy and Coulomb interactions on the fragment yield in intermediate energy super-heavy ion reactions. For the current analysis, we have implemented a much exclusive and widely acceptable form of the density-dependent parametrization at sub-saturation densities [36], [37]. The aim of present paper is therefore, at least, two-fold:

1) To acknowledge the role of density-dependent part of symmetry energy and Coulomb interactions in fragmentation of heavy and super heavy involved reactions. and
2) To inspect whether any specific or distinct fragment structure exists when collision of super heavy nuclei is undertaken or not.

The present analysis is performed using the isospin-dependent quantum molecular dynamics (IQMD) model as phase space generator [38]. This paper is organized as follows: Section II gives a brief overview of the IQMD model. Our results are discussed in Section III and we conclude our work in Section IV.

II. THE FORMALISM

In isospin-dependent quantum molecular dynamics (IQMD) [30], [32], [33], [34], [35], [38], [39], [40] methodology, nucleons interact via two-and-three body mutual interactions. This microscopic model describes the reaction from the initial to final stage. The isospin degree of freedom which is one of the main component of the model enters into the methodology via symmetry energy, cross-section and Coulomb interactions between the nucleons. Here each nucleon propagate under the Hamilton equations of motion:

$$\frac{dr_i}{dt} = \frac{\partial <H>}{\partial p_i} \quad ; \quad \frac{dp_i}{dt} = -\frac{\partial <H>}{\partial r_i} \tag{2}$$

with

$$\langle H \rangle = <T> + <V>$$

$$\langle H \rangle = \sum_i \frac{p_i^2}{2m_i} + V_{ij} \tag{3}$$

here V_{ij} is the baryon-baryon potential, which have contribution from Skyrme, Yukawa, Coulomb as well as symmetry energies. For the present work, a soft (S) equation of state together with 20% reduced isospin-dependent nucleon-nucleon cross-section has been employed. The phase space information of nucleons generated by the IQMD model [38] is converted to fragment information by secondary clusterizing algorithm namely minimum spanning tree (MST) method [41]. An additional momentum cut of 150 MeV/c is also employed to get rid of the unbound fragments [42].

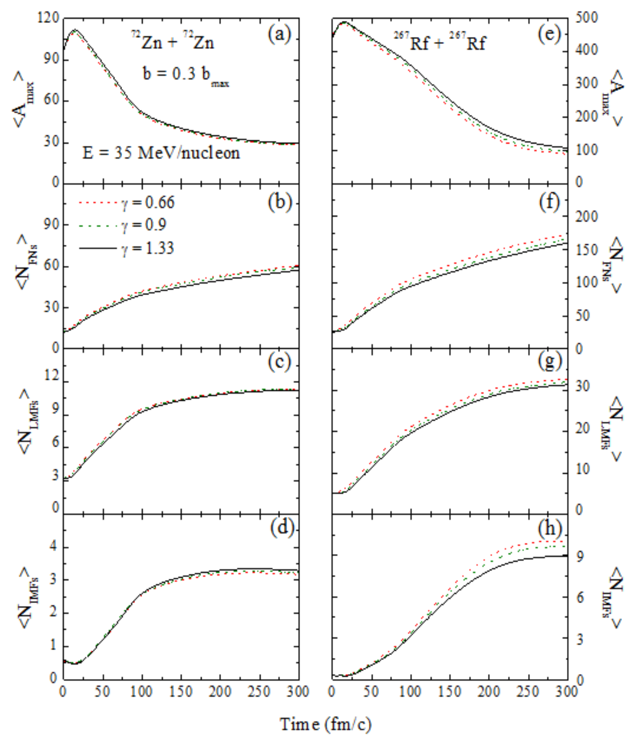

Fig. 1. The time evolution of mean size of $< A_{max} >$ and multiplicities of free nucleons (FNs), light mass fragments (LMFs) and intermediate mass fragments (IMFs) for different forms of symmetry energy for ^{72}Zn + ^{72}Zn (left panels) and ^{267}Rf + ^{267}Rf (right panels) reactions at an incident energy of 35 MeV/nucleon at semi-central geometry ($\hat{b}$ = 0.3) .

III. RESULTS AND DISCUSSION

For the present analysis, we simulated thousand of events of various reactions involving heavy-ions and super heavy ions. Then we calculate the mean size of the largest fragment ($< A_{max} >$), yield of free nucleons (FNs) [$A_f = 1$], light mass fragments (LMFs) [$2 \leq A_f \leq 4$] and intermediate mass fragments (IMFs) [$5 \leq A_f \leq 30$ % of A_P (A_T); where

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A_P (A_T) is the mass of projectile (target)]. In particular, we simulated the reactions of ^{24}Ne + ^{24}Ne, ^{72}Zn + ^{72}Zn, ^{139}La + ^{139}La, ^{197}Au + ^{197}Au, ^{239}Np + ^{239}Np, ^{267}Rf + ^{267}Rf, and ^{294}Uuo + ^{294}Uuo at reduced impact parameter $\hat{b}$ = 0.3 (here $\hat{b} = b/b_{max}$; b_{max} = 1.12 [$A_P^{1/3}$ + $A_T^{1/3}$]). Our analysis provides us the time evolution, system mass dependence and stiffness factor (γ) dependence of the fragment yield for every reaction, though prime aim is to understand fragmentation in the collisions of super heavy nuclei. We also simulated lighter and medium nuclei heavy-ion reactions to have comparison and for systematic mass dependence. In Fig. 1, we display the time evolution of various fragments for the reactions of ^{72}Zn + ^{72}Zn and ^{267}Rf + ^{267}Rf at an incident energy of 35 MeV/nucleon for semi-central geometry ($\hat{b}$ = 0.3). As usual, the mean size of the largest fragment (< A_{max} >) tends to decrease because of the consecutive break-up of nuclear matter after overlapping stage (i.e. 20 - 30 fm/c). This break-up tends to appear in the form of various kind of fragments (FNs, LMFs, IMFs). For both the reactions (^{72}Zn +^{72}Zn, ^{267}Rf + ^{267}Rf), the fragment structures do not change much, after 200 fm/c, which we take as observation time. Very interestingly, various density dependencies of symmetry energy show much pronounced role in case of super-heavy reactions in contradiction to medium mass reactions, where almost no effect is visible. As fragmentation is a low density phenomena, the softer form of the density dependence leads to larger break-up of nuclear matter. As a result, one sees an enhanced emission of lighter fragments. The mean multiplicities of these fragments, therefore, increases for soft form compared to stiff form of the density dependence of symmetry energy. There is no doubt that at later stages when the reaction saturates and interaction among nucleon/fragments ceases to exist, the effect of different density dependencies (γ = 0.66, 0.9, 1.33) is still visible. In the following study, we will concentrate on the isospin effects at freeze out time only.

It is also worth mentioning that there are other algorithms based on the energy minimization [43], [44] i.e., simulating annealing clusterization algorithm (SACA), which can identify the fragments at the time of high density. But, all such algorithms are shown to yield nearly same results at the asymptotic stage [45]. We display in Fig. 2, the mean size of the largest fragment (< A_{max} >) and multiplicities of FNs, LMFs and IMFs at an incident energy of 35 MeV/nucleon for semi-central geometries as a function of system mass. As mentioned in the introduction, here, we extend the system mass range up to known super-heavy nuclei. In the figure, the shaded area represents the super heavy-ion reaction region. We here depicts the final fragment yields with different density-dependent symmetry energies. The effect of different density-dependent forms is found to be very small for lighter masses but the difference tends to increase as one move toward super-heavy ion involved reactions. Since Coulomb interactions are known to play a dominant role in the reactions of the heavy and super heavy nuclei, we also display the output of the same reactions by excluding Coulomb interactions in the simulations.

It is evident that Coulomb interaction plays major role in fragmenting super heavy colliding nuclei. On the other hand, little effect is visible for lighter colliding nuclei. Most significant impact of Coulomb interactions is observed on the mean size of < A_{max} > and multiplicities of IMFs, in accordance with previous studies where effect of Coulomb interactions was found to be more for fragments which have major contribution from the nucleons facing lesser number of collisions [35], [49].

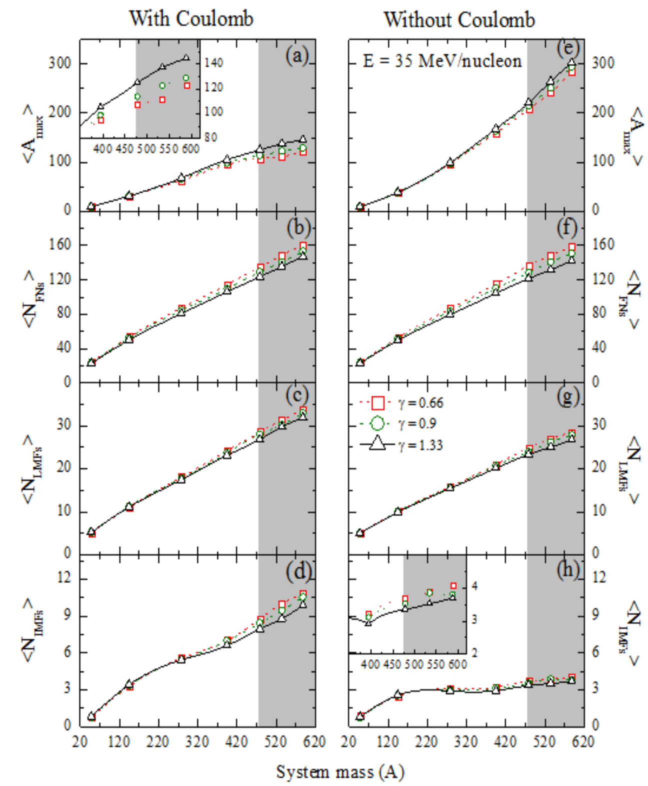

Fig. 2. The system mass dependence of mean size of largest fragment (< A_{max} >) and multiplicities of FNs, LMFs and IMFs for different forms of symmetry for reduced impact parameter $\hat{b}$ = 0.3 at an incident energy of 35 MeV/nucleon. The results are shown for both, with (left panels) and without (right panels) Coulomb interactions.

In contrary, free nucleons (FNs) are not sensitive toward this effect. The multiplicity of LMFs, which by large have contribution from nucleons having faced greater number of collisions, also shows minimal effect. For both the cases (with and without Coulomb interactions), the results indicate that the break-up of bound nuclear matter leads to different results when subjected to different forms of symmetry energy, this is more true as system mass increases. The mean size of < A_{max} > gets enhanced for stiff form (γ = 1.33) of symmetry energy compared to soft form (γ = 0.66). On the other hand, the effect on fragment multiplicity is reversed with greater (lesser) multiplicity for soft (stiff) form, as was observed in Fig. 1. One can also see that the effect of Coulomb as well as different forms of density dependencies of symmetry energy is more noticeable in super-heavy involved reactions.

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Interestingly, the significant impact of Coulomb interactions is not able to eliminate the influence of symmetry energy on the fragment yield. In-spite of high Coulomb dominance in super-heavy involved reactions, the role of density dependence of symmetry energy is also clearly visible. It is worth mentioning here that the multiplicity of free nucleons observed in the present work is much larger as compared to experimental observations [12], which is due to the absence of shell effects in the IQMD model. The negligence of shell effects causes the lesser yield of alpha particles and overestimation of free nucleons. This is a common problem with the many-body dynamical models and has been pointed out earlier by Nemeth *et al.*, [46] and Ono *et al.*, [47] in their studies. The same can also be observed from Refs. [35], [48]. The incident energy that determines the excitation energy deposited in the system can change the reaction output to a great extent. Therefore, for more in-depth analysis, we display in Fig. 3, the mean size of the largest fragment (< A_{max} >) and multiplicities of FNs, LMFs and IMFs for the reactions of ^{267}Rf + ^{267}Rf at incident energies of 35, 100, 400 and 1000 MeV/nucleon for semi-central collisions with (left panels) and without (right panels) Coulomb interactions as a function of stiffness factor (γ). As noted in Fig. 2, the maximum impact of Coulomb interactions is observed on < A_{max} > followed by intermediate mass fragments (IMFs). This impact is more pronounced at lower incident energies compared to higher incident energies. This is because, at higher incident energies, reaction is extremely violent and the nucleons are emitted with large velocities during the decompression stage, which in turn diminishes the interplay of nucleonic interactions (and therefore, isospin dependence) up to large extent. Similarly, the effect of Coulomb repulsion as well as of different mean field interactions will decreases when the target and projectile collide at very high excitation energies. As a fall out, maximum effect is visible at 35 MeV/nucleon which decreases with increase in incident energy and finally vanishes at 1 GeV/nucleon. As mentioned in the introduction, the phenomenon of fragmentation occurs at low density, due to which the stiffer form of the symmetry energy lead to less repulsion and the size of the < A_{max} > increases with stiffness of the symmetry energy. We observe opposite behavior for the multiplicities of other fragments. The percentage variation for fragment multiplicity tends to increase for higher atomic mass systems and thus, is much greater for super-heavy reactions compared to heavy-ion reactions. In our previous studies, we observe that the impact of Coulomb interactions is greater at peripheral colliding geometries due to lesser number of collisions faced by the nucleons composing the fragments (or participant/spectator picture at high energies) [35], [49]. The same effects will also be observed for superheavy involved reactions, but with enhancement due to the greater number of nuclear matter involved in these reactions.

IV. CONCLUSION

We here presented a systematic study over wide range of incident energies and system mass (which is extended up to known super-heavy nuclei systems) to see the relative role of the isospin interactions on the production of various fragments.

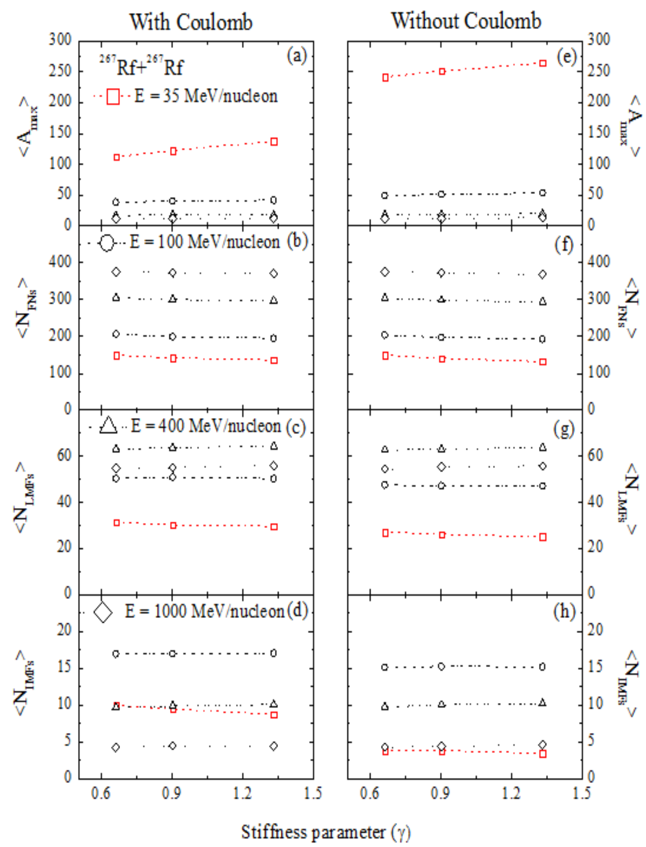

Fig. 3. The mean size of the largest fragment (< A_{max} >) and multiplicities of FNs, LMFs and IMFs as a function of symmetry energy stiffness factor (γ) for semi-central geometry ($\hat{b}$ = 0.3) for the reactions of ^{267}Rf + ^{267}Rf at incident energies of 35, 100, 400 and 1000 MeV/nucleon. The results are shown for both, with (left panels) and without (right panels) Coulomb interactions.

We have checked the relative role of different forms of density dependence of symmetry energy as well as the effect of Coulomb interactions on the multiplicities of fragments consisting of variety of different masses. The effect of Coulomb interactions is found to be drastic for fragments that emerges from the low density region. The effects are more drastic in reactions with super heavy nuclei. We observe that the greater proton and neutron content in case of super heavy ion involved reactions enhanced the isospin effects to significant level that makes the isospin effect in reaction dynamics much clear compared to previous studies.

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