PROBING THE EFFECT OF DIFFERENT CROSS SECTIONS IN ASYMMETRIC SYSTEMS

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We present a complete systematic theoretical study of the multifragmentation for asymmetric colliding nuclei in heavy-ion reactions in the energy range between 50 and 1000 MeV/nucleon by using the isospin-dependent quantum molecular dynamics (IQMD) model. We have observed an interesting outcome for asymmetric colliding nuclei. The comparison between the symmetric and asymmetric colliding nuclei for the isospin-independent and isospin-dependent cross sections has been performed. We have found the pronounced effect of different cross sections and mass asymmetry on the nuclear reaction dynamics.

1. Introduction

Heavy-ion collisions offer a possibility to probe the nuclear matter under different conditions of densities and temperature. At high excitation energies and temperature, the colliding nuclei can break up into many fragments known as multifragmentation [1]. In the recent time, a lot of researches is going on for the study of collisions of mass-asymmetric nuclei at intermediate energies. Multifragmentation is, by essence, associated to the emission of several fragments. Any study of the phenomenon requires a coincident efficient detection of these fragments and associated particles ($Z \leq 2$).

With the availability of radioactive ion beam (RIB) facilities, the GSI facility for Antiproton and the Ion beam Research (FAIR) [2], GANIL in France [3], RIB facility at Rikagaku Kenyusho (RIKEN) in Japan [4], at the Cooler Storage Ring (CSR) (China) [5], and the upcoming facility for RIB at Michigan State University [6], one has the opportunity to study properties of the nuclear matter under extreme conditions.

The growing study of the interaction of radioactive beams at many laboratories over the world and the use of radioactive beams with large neutron or proton excess have offered an excellent tool to investigate the isospin dependence of heavy-ion collisions. This helps the scientific community to obtain the information about the equation of state for the asymmetric nuclear matter and on the isospin dependence of medium nucleon-nucleon cross sections, which are important not only to study the nuclear reaction dynamics, but also to explore the supernova explosion mechanism and the colliding rate of neutron stars. The study of heavy-ion collisions at intermediate energies has now become an important tool to investigate the reaction mechanism behind various phenomena. The study of heavy-ion collisions at intermediate energies (50 MeV/nucleon $\leq E \leq$ 1000 MeV/nucleon) provides a rich source of information on many rare phenomena such as the multifragmentation, collective flow, and particle production.

The term “isospin” refers to a pair of similar particles, e.g., protons and neutrons, which are almost identical in the nuclear matter, where the difference in electric charges is ignored. In many transport simulations, the difference in nuclear interactions between protons and neutrons is simply ignored. In other words, these simulations explore the reactions in the symmetric nuclear matter limit only [7]. The isospin effects come into the results in terms of the symmetry energy and the cross section, which affect the multifragmentation, collective flow, and related phenomena to a great extent.

The isospin effects of the in-medium *NN* cross section on the physical quantities arise from the difference between the isospin-dependent in-medium *NN* cross section denoted by $\sigma_{\rm iso}$, in which $\sigma_{np} > \sigma_{nn} = \sigma_{pp}$ and the isospin-independent *NN* cross section denoted by $\sigma_{\rm noiso}$, in which $\sigma_{np} = \sigma_{pp} = \sigma_{nn}$. Here, σ_{np}, σ_{nn}, and σ_{pp} are the neutron-proton, neutron-neutron and proton-proton cross sections, respectively.

For symmetric and asymmetric reactions, various experimental studies offer a unique opportunity to explore the mechanism for the breaking of nuclei into pieces. At the same time, the heavy ion reactions can also be used to extract the information about the nature of matter.

Jian-Ye Liu *et al.* studied the isospin effects of one-body dissipation and two-body collision on the number of protons (neutrons) emitted during a nuclear reaction. Their studies show strongly that the isospin-dependent in-medium *NN* cross section has a much stronger influence on the number of proton (neutron) emissions (*NP(NN)*) [8].

Multifragmentation has been observed both experimentally and theoretically. We will trace this effect on the mass-asymmetric systems. The mass asymmetry of a reaction can be defined by the asymmetry parameter $\eta = |(A_\mathrm{T} - A_\mathrm{P})/(A_\mathrm{T} + A_\mathrm{P})|$ [9], where A_T and A_P are the masses of the target and the projectile, respectively. The case $\eta = 0$ corresponds to the symmetric reactions, whereas nonzero values of η define various asymmetries of a reaction.

As noted by the FOPI group, the reaction dynamics in a symmetric reaction ($\eta = 0$) can be quite different as compared with an asymmetric reaction ($\eta \neq 0$). This is valid both at low and intermediate energies. This difference emerges due to the different depositions of the excitation energy (in the form of compressive and thermal energies) in symmetric and asymmetric reactions. The symmetric reactions lead to a higher compression, whereas the asymmetric reactions lack the compression energy, since a large part of the excitation energy is in the form of thermal energy.

As the little information is known about the in-medium *NN* cross section and its isospin dependence on the mass asymmetry up to now, it is thus desirable to do the theoretical study to gain knowledge about the isospin dependence on the mass asymmetry. On the basis of a theoretical scenario, one has the dynamical model, where the reaction dynamics starts the simulation from well-defined nuclei to the end of the reaction, where a practically cold and scattered nuclear matter is in the form of nucleons and light or heavy mass fragments. As a result, no dynamical model simulates the fragments; rather, one has the phase space of nucleons and constructs the fragments at the end of simulations. Therefore, we look for secondary models of clusterization algorithms, e.g., the minimum spanning tree (MST).

2. The Model

The dynamical model used for the present study is the isospin-dependent quantum molecular dynamics (IQMD) [10] model. The IQMD model is a refinement of the QMD model [11] based on the event-by-event method. The reaction dynamics is governed by the mean field, two-body collision, and Pauli blocking. The IQMD model [10, 12] treats different charge states of nucleons, deltas, and pions explicitly [13], as is inherited from the BUU model [14]. The IQMD model has been used successfully for the analysis of a large number of observables from low to relativistic energies [10, 15]. The isospin degree of freedom enters into the calculations via the symmetry potential, cross sections, and Coulomb interactions. The details about the elastic and inelastic cross-sections for proton-proton and neutron-neutron collisions can be found in [10, 16, 17].

In this model, baryons are represented by the Gaussian-shaped density distributions

$$f_i(\mathbf{r},\mathbf{p},t) = \frac{1}{\pi^2\hbar^2} e^{\frac{-(r-r_i(t))^2}{2L}} e^{\frac{-(p-p_i(t))^2 . 2L}{\hbar^2}}. \tag{1}$$

Nucleons are initialized in a sphere with radius $R = 1.12A^{1/3}$ fm, in accordance with the liquid drop model. Each nucleon occupies a volume of $\hbar^3$ so that the phase space is uniformly filled. The initial momenta are randomly chosen between 0 and the Fermi momentum p_F. The nucleons of the target and the projectile interact via the two- and three-body Skyrme forces and the Yukawa potential. The isospin degrees of freedom are treated explicitly by employing a symmetry potential and explicit Coulomb forces between protons of the target and the projectile. This helps in achieving the correct distribution of protons and neutrons within the nucleus. The propagation of hadrons is described by the Hamilton equations of motion

$$\frac{d\mathbf{r}_i}{dt} = \frac{d\langle H\rangle}{d\mathbf{p}_i}, \qquad \frac{d\mathbf{p}_i}{dt} = -\frac{d\langle H\rangle}{d\mathbf{r}_i}. \tag{2}$$

The total Hamiltonian function with a kinetic energy T and a potential energy V is given by

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

$$= \sum_i \frac{p_i^2}{2m_i} + \sum_i \sum_{j>i} \int f_i(\mathbf{r},\mathbf{p},t) V^{ij}(\mathbf{r}',\mathbf{r}) f_j \times$$

$$\times (\mathbf{r}',\mathbf{p}',t) d\mathbf{r} d\mathbf{r}' d\mathbf{p} d\mathbf{p}'. \tag{3}$$

In the above relation, the baryon-baryon potential V^{ij} reads

$$V^{ij}(\mathbf{r}' - \mathbf{r}) = V^{ij}_\mathrm{Skyrme} + V^{ij}_\mathrm{Yukawa} + V^{ij}_\mathrm{Coul} + V^{ij}_\mathrm{Sym} =$$

$$= t_1\delta(\mathbf{r}' - \mathbf{r}) + t_2\delta(\mathbf{r}' - \mathbf{r})\rho^{\gamma-1}\left(\frac{\mathbf{r}' + \mathbf{r}}{2}\right) +$$

$$+ t_3 \frac{\exp(|\ \mathbf{r}' - \mathbf{r}\ |/\mu)}{(|\ \mathbf{r}' - \mathbf{r}\ |/\mu)} + \frac{Z_i Z_j e^2}{|\ \mathbf{r}' - \mathbf{r}\ |} +$$

$$+ t_4 \frac{1}{\rho_o} T_3^i T_3^j . \delta(\mathbf{r}'_i - \mathbf{r}_j), \tag{4}$$

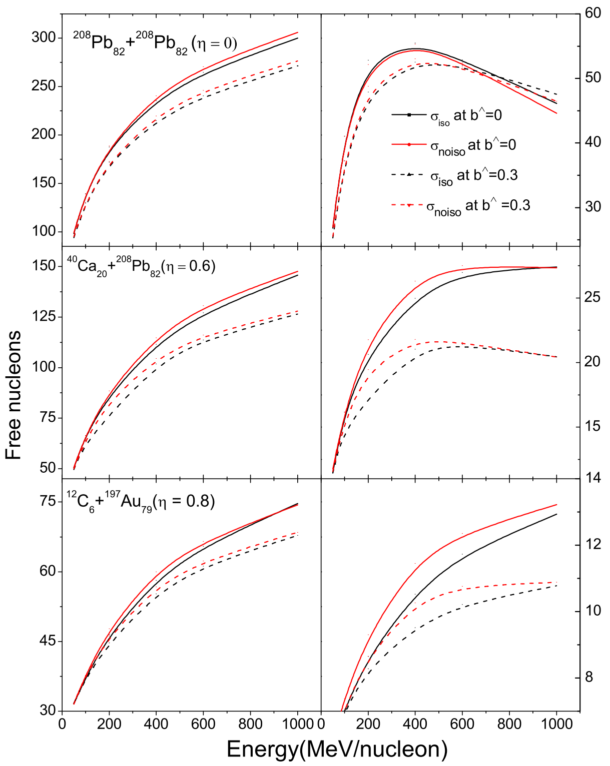

Fig. 1. Multiplicity of free nucleons and LMFs as a function of the energy

where $\mu = 1.5$ fm, $t_3 = -6.66$ MeV, $t_4 = 100$ MeV. The values of t_1 and t_2 depend on the values of α, β, and γ [1]. Here, Z_i and Z_j denote the charges of the i^{th} and j^{th} baryons, and T_3^i, T_3^j are their respective T_3 components (i.e. 1/2 for protons and $-1/2$ for neutrons). The parameters μ and $t_1, \ldots, t_6$ are adjusted to the real part of the nucleonic optical potential. It is worth mentioning that, as shown by Puri and coworkers, the Skyrme forces are very successful in the analysis of low-energy phenomena such as fusion, fission, and cluster-radioactivity, where the nuclear potential plays an important role [12]. The clusterization method used here is the minimum spanning tree (MST) one [18]. The normal MST method depends on the spatial distance. Hence, the fragments, thus created, can have nucleons with very large relative momenta (with no momemtum cut).

3. Results and Discussions

The simulations have been carried out for three systems $_{82}Pb^{208}$+$_{82}Pb^{208}$ having $\eta = 0$, $_{20}Ca^{40}$+$_{82}Pb^{208}$ having $\eta = 0.6$, and $_6C^{12}$+$_{79}Au^{197}$ having $\eta = 0.8$ within the IQMD model for central and semicentral impact parameters at the energy ranging from 50 to 1000 MeV/nucleon. The soft equation of state is used for the whole study. The phase space obtained is analyzed usng the MST method [18].

Figure 1 shows the multiplicity of free nucleons and light mass fragments (LMFs) as a function of the energy at scaled impact parameters. The effect of two cross sections (the isospin-dependent cross section σ_{iso}, i.e., $3\sigma_{nn} = 3\sigma_{pp} = \sigma_{np}$, and the isospin-independent cross section σ_{noiso}, i.e., $\sigma_{nn} = \sigma_{pp} = \sigma_{np}$) and the difference coming out for asymmetric reactions are seen. As the free nucleons are produced from the interaction zone, there is a little effect of the isospin-independent cross section at low energies. As the energy increases, the multiplicity of free nucleons increases for the isospin-independent cross section.

Even for the mass asymmetric cases, the trend is the same for free nucleons as that for symmetric cases. It is clear from the figure that the number of free nucleons increases with the energy. This is due to the reason that, for the central geometry, all the nucleons are taking part in the collision. The collisions becomes more violent, as the energy increases. The maximum number of free nucleons will be produced at high energies due to the more compressed zone produced. With increase in the energy, the Pauli blocking effect decreases. The correlations among the nucleons are destroyed at high energies, and, hence, the larger number of free nucleons are produced. With increase in the value of scaled impact parameter, the multiplicity of free nucleons decreases as compared with the case of central collisions. It would be interesting to see the effect of the isospin-independent cross section (σ_{noiso}, which leads to the enhanced production of free nucleons at all the energies and for all asymmetries. For the symmetric reactions, the difference in the production of free nucleons is more for the energy range 400–1000 MeV/nucleon. Even for the mass asymmetric cases, the trend is the same for free nucleons as that for symmetric cases. But, for asymmetric reactions, the influence is more from 200 to 600 MeV/nucleon.

The light mass fragments (LMFs) are produced from the participant zone. From Fig. 1, it is clear that the number of LMFs firstly increases with the energy, reaches a peak value at 200 MeV/nucleon, and then decreases, as the energy increases. In the mass asymmetric systems, the number of LMFs increases with the energy. The opposite effect is observed in the case of free nucleons. For asymmetric systems, the difference is more, because the

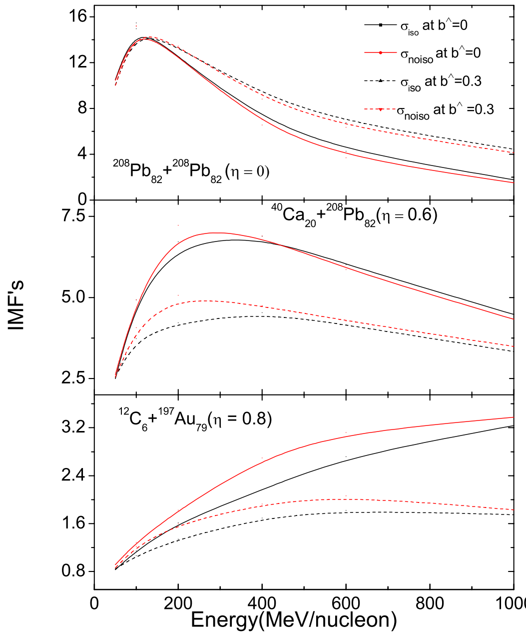

Fig. 2. (Color online) Multiplicity of intermediate mass fragments as a function of energy

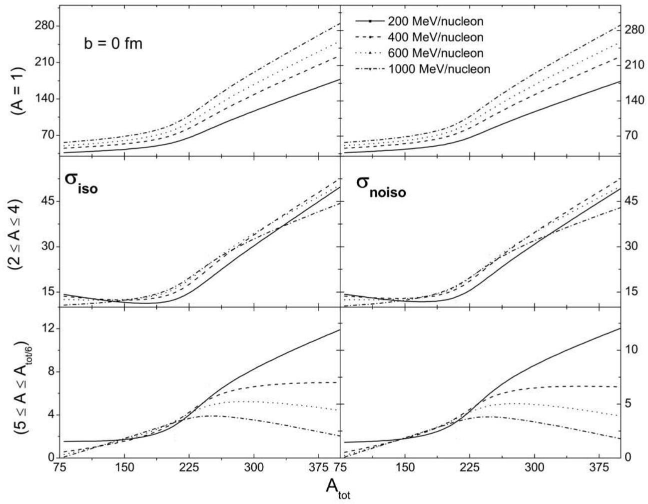

Fig. 3. (Color online) Multiplicity of various fragments vs the total mass of the system ($A_{\rm tot}$) at various energies

mass asymmetry plays a significant role in the reaction dynamics, as studied in [9].

It has been observed that there is a more considerable effect of the cross section on the mass asymmetric systems than on the symmetric systems. It can be seen from the Fig. 1 that the number of light mass fragments formed without isospin-dependent nucleon nucleon cross section is more as compared with that for symmetric systems. In the case of the symmetric systems, the number of LMFs decreases for isospin-independent cross section, as the energy increases.

Figure 2 shows the multiplicity of intermediate mass fragments (IMFs) as a function of the energy for symmetric and asymmetric reactions. As the asymmetry of the reaction increases, the trend of rise and fall in the multiplicity of IMFs is not followed.

The effect of the cross section is more pronounced for free nucleons and LMFs as compared to IMFs, because IMFs are produced from the spectator zone. It is seen that the multiplicity of intermediate and light mass fragments decreases, as the energy increases. But, on the contrary, it increases with the energy for free nucleons. The emission of free nucleons will show the dispersion (vaporization) of the matter [19, 20]. The production of LMFs is highest at low energies and decreases with increase in the energy. Due to a very small overlap at large impact parameters, the system does not receive enough the energy and, hence, cools down after emitting several nucleons/LMF. The production of IMFs is maximum at low energies and at the intermediate impact parameter. In Fig. 3, the multiplicity of various fragments is displayed as a function of the total mass of the system at a time of 200 fm/c at the energy ranging from 200 to 1000 MeV/nucleon. The total masses of these reactions ($_{82}\mathrm{Pb}^{208}$+$_{82}\mathrm{Pb}^{208}$ having $\eta = 0$, $_{40}\mathrm{Ca}^{20}$+$_{208}\mathrm{Pb}^{82}$ having $\eta = 0.6$, and $^{12}\mathrm{C}_6$+$^{197}\mathrm{Au}_{79}$ having $\eta = 0.8$) have been displayed. The universal behavior of the growth in the multiplicity of fragments with the size of the system is observed in the presence of a mass asymmetry, as well as for the isospin-independent cross section. One can see from Fig. 3 that the trends for the isospin-dependent and isospin-independent cross sections are identical.

Both free nucleons and LMFs show increasing trends. With increase in the size of a system, the number of the participant nucleons increases. This will lead to a higher thermalization of the system. For this reason, an increase in the multiplicity of fragments, which originate from the participant zone, will always be observed.

In Fig. 4, the multiplicity of intermediate mass fragments as a function of the impact parameter (b) has been displayed at 600 MeV/nucleon for the C + Au system. The system has the asymmetry parameter equal to 0.8. From Fig. 4, it can be seen that the maximum number of IMFs are obtained for lower values of b. As the value of impact parameter increases, the mean value of the multiplicity of IMFs decreases. The results of calculations have been compared with the experimental data of Aladin group [21]. The open circles in Fig. 4 show the experimental data, and the solid squares are the results of calculations with the use of the IQMD model. It is

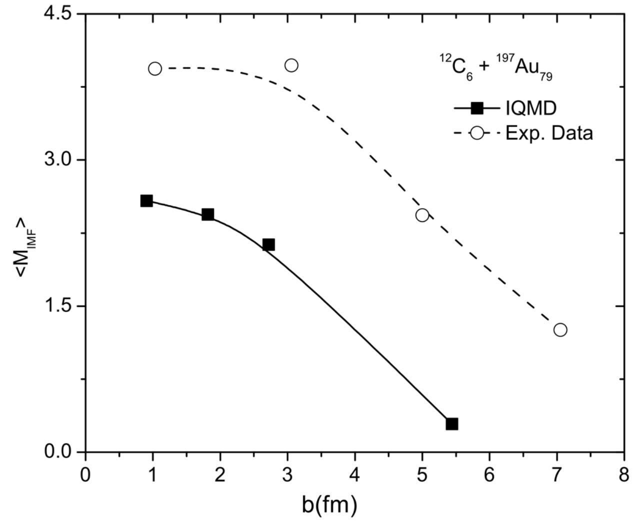

Fig. 4. Mean multiplicity of IMFs vs the impact parameter b, for the experimental data and the IQMD calculations for C + Au at 600 MeV/nucleon

seen that the results of calculations correspond to the available experimental data. The trend of theoretical results follows the experimental data.

4. Summary

We present a complete systematic theoretical study of the multifragmentation for asymmetric colliding nuclei for heavy-ion reactions in the energy range between 50 and 1000 MeV/nucleon using the IQMD model. We have obtained an interesting outcome for asymmetric colliding nuclei. The effects of the isospin-independent and isospin-dependent cross sections have been studied for various mass asymmetries. We have found the pronounced effect of different cross sections and mass asymmetry on the nuclear reaction dynamics. A similar trend is observed between the theoretical calculations and the experimental data of the ALADIN collaboration.

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ПЕРЕВІРКА ЕФЕКТУ РІЗНИХ ПЕРЕРІЗІВ
В АСИМЕТРИЧНИХ СИСТЕМАХ

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Р е з ю м е

Представлено повне теоретичне дослідження мультифрагментації в реакціях, де зіштовхуються асиметричні ядра важких іонів у діапазоні енергій від 50 до 1000 МеВ/нуклон в моделі ізоспін-залежної квантової молекулярної динаміки та отримано нетривіальний результат. Зіставлено випадки зіткнення симетричних і асиметричних ядер ізоспін-незалежного та ізоспін-залежного перерізів розсіювання. Виявлено істотний вплив відмінності у перерізах розсіювання і асиметрії мас на динаміку ядерних реакцій.