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Dynamics Study on the Intermediate Energy Heavy Ion Collisions

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The collision dynamic and the multifragmentation mechanism of the intermediate energy heavy ion have been studied by means of improved quantum molecular dynamics (IQMD) via studying dynamical observables which identify dynamical properties of the intermediate energy heavy ion collisions, such as the time development of the transverse momentum, collision number, density of nuclear matter and thermalization. At the same time, the dynamical ingredients governing the collision dynamics of heavy ion collisions, such as the equation of state, momentum dependent interaction and medium effect, have been analyzed and discussed.

Key words: collision dynamics, multifragmentation, equation of state, momentum dependent interaction, medium effect.

1. INTRODUCTION

The hot researching of topics in intermediate energy heavy ion collisions, such as multifragmentation process and the dynamical ingredients governing multifragmentation process, was studied in [1]. Because of the limitation of paper content, only the questions on the multifragmentation were studied in that paper. In our paper, in order to understand the collision dynamics of heavy ion collisions as well as the dynamical process of multifragmentation mechanism in more details, the time development of the observables identifying the collisions dynamics, such as transverse momentum,

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collision number, density of nuclear matter and thermalization, as well as property and interacting characteristics of the dynamical ingredients governing the collision dynamics, such as the equation of state, momentum dependent interaction and the medium effect, have been compared to each other and discussed deeply by using the improved quantum molecular dynamics. And then some suggestions on the questions which have to be solved in future have been proposed.

2. MODEL AND MONTE CARLO SIMULATION CALCULATIONS

The more details about IQMD model is in [1-3]. Only the main physical idea of the model is introduced briefly here. We make a Gaussian wave packet in the phase space to indicate each nucleon in the two colliding nuclei. The distribution function for the total system is the sum of all nucleon wave packets

$$f_i(\boldsymbol{r}, \boldsymbol{p}) = \frac{1}{(\pi\hbar)^3}\exp\{-[\boldsymbol{r} - \boldsymbol{r}_i(t)]^2/2L - [\boldsymbol{p} - \boldsymbol{p}_i(t)]^2 \cdot 2L/\hbar^2\}, \tag{1}$$

$$f(\boldsymbol{r}, \boldsymbol{p}) = \sum_i f_i(\boldsymbol{r}, \boldsymbol{p}). \tag{2}$$

The centers of the Gaussian wave packet, namely the mean position and mean momentum of nucleons are propagating according to the Hamilton equation

$$\begin{aligned} \dot{\boldsymbol{p}}_i &= -\{\boldsymbol{r}_i, H\}, \\ \dot{\boldsymbol{r}}_i &= \{\boldsymbol{p}_i, H\}, \end{aligned} \tag{3}$$

where V^{loc} indicates the Skyrme-type short range interaction of two-body and three body; V^{yuk} is a long range Yukawa interaction which is necessary to reproduce surface effects; V^{coul} is Coulomb interaction and V^{momen} is a momentum dependent interaction due to nonlocal effects of the nuclear force.

$$H = \sum_i \frac{p_i^2}{2m} + V^{\mathrm{loc}} + V^{\mathrm{Yuk}} + V^{\mathrm{Coul}} + V^{\mathrm{momen}}. \tag{4}$$

The two set to parameters of effective interactions, which express the soft equation of state with the compression coefficient $K = 240$ MeV and hard-equation of state with $K = 380$ MeV, are determined by using the calculations on the ground state properties of nuclei such as the nuclear binding energy, nuclear matter density and root mean squared radius. When considering two body collisions of nucleons the Pauli blocking effects in final states are determined by using the overlapping of the two colliding nucleons with all other nucleons in the phase space. The parametrized formulas of free nucleon-nucleon (N-N) collision cross section by Cugnon [4] are used in the calculations of two body collisions. At the same time, the in-medium elastic N-N cross section given by Ter Haar [6] and the in-medium inelastic N-N cross section by Bertsch and Brown [5] are used. To sum up, the total N-N cross section in medium is smaller than that in the free space in the energy region $E_l/A < 800$ MeV. And then the total trend is that the elastic N-N cross section decreases and the inelastic N-N cross section increases with increasing beam energy. Beyond a certain energy the total N-N cross section in medium is close to or larger than that in free space due to interplay between two kinds of the N-N cross sections, especially the inelastic N-N cores section is more and more important with increasing incident energy.

To avoid making non-physical filamental nuclei during forming fragments by using QMD we made use of restructured aggregation model RAM given by Ngo coupling with QMD to form the clusters. The RAM has already been described in details in [3].

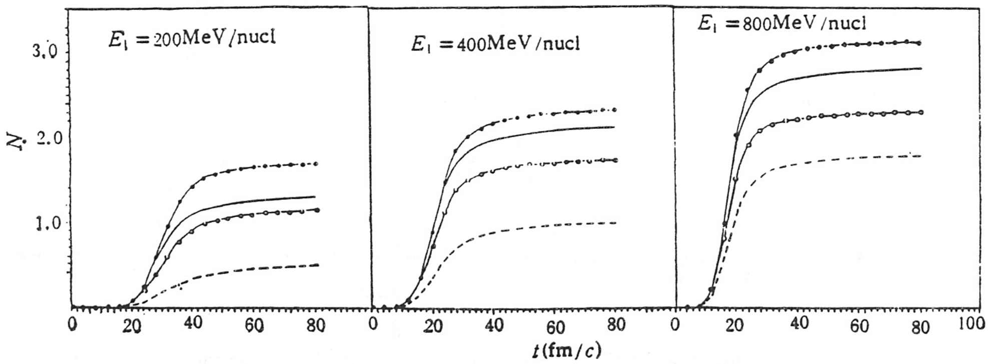

Fig. 1
Time development of the collision number for the reaction Nb + Nb E_l/A = 200, 400, and 800 MeV and impact parameter b = 3.0 fm. —— H; –•–•– S; --- SI; –○–○– SM.

In addition to the calculations of the mean transverse momentum $\langle p_x/A \rangle$, the center density of the target nucleus ρ/ρ_0 and the collision number, the thermalization is calculated as follows:

$$R = \frac{2}{\pi} \frac{\sum_i |p_\perp(i)|}{\sum_i |p_{//}(i)|}, \tag{5}$$

where R is the ratio of the transverse component to the parallel component of the nucleon momentum.

3. CALCULATION RESULTS AND DISCUSSIONS

To make the comparisons and analyses among the influences of all of the dynamical ingredients on the collision dynamics and multifragmentation process, the physical quantities for the reaction ^{93}Nb + ^{93}Nb at E_l/A = 200 MeV, 400 MeV, 800 MeV and the impact parameter b = 3 fm are calculated

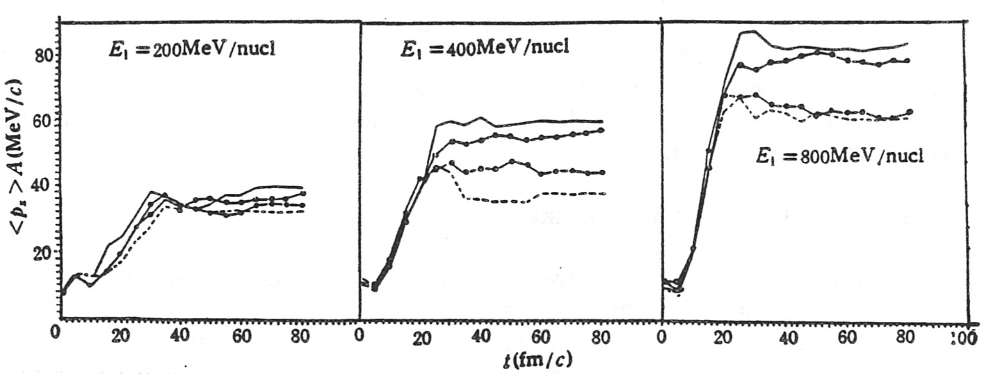

Fig. 2
Time evolution of the mean transverse momentum per nucleon for the same case as Fig. 1. —— H; –•–•– S; --- SI; –○–○– SM.

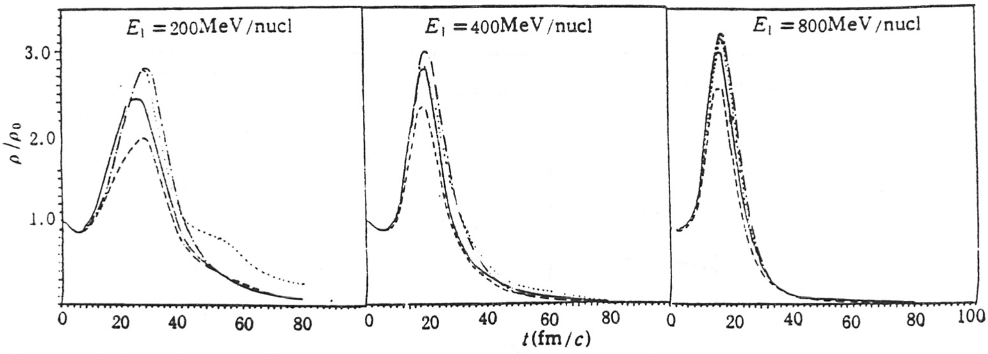

Fig. 3

Time evolution of the nuclear matter density for the same case as Fig. 1.
—— H; —·—·— S; --- SI; · · · SM.

under the following four cases:

S: soft EOS and N-N cross section in free space.
H: hard EOS and N-N cross section in free space.
SI: soft EOS and N-N cross section in the medium.
SM: soft EOS, momentum dependent interaction and N-N cross section in free space.

3.1. Thermalization and the Process of Multifragmentation

Thermalization and multifragmentation are not sensitive to the nuclear equation of state (EOS); however their influences on other dynamical quantities are obvious as shown by the following information.

From the time development of the physical quantities in Figs. 1-4 we can see that the collision number and the density of nuclear matter associated with the hard-EOS(H) are less than those with soft-EOS(S) because for the hard-EOS(H) the repulsive interaction increase due to its shallow potential and compression is more difficult. But the hard-EOS(H) in creases the transverse momentum of nucleons because the transverse momentum depends on the compression of the nuclear matter and the compression of the hard-EOS is larger than that in the soft-EOS [7] under the same density of nuclear matter so that the hard-EOS increases the transverse momentum transfer of a nucleon in comparison with the case of soft EOS(S). From the time development of the thermalization.

In Fig. 4, we can see that the process of thermalization is not sensitive to the equation of state except for the case with 200 MeV. This phenomenon implies that the equation of state is not sensitive to the energy exchange and excitation process of nucleons, which leads to that EOS is not sensitive to the process of multifragmentation. They yield distribution of multifragmentation in [1] has given a proof about this conclusion.

3.2. Important Influences of Momentum Dependence Interaction (MDI)

There are several important influences on the momentum dependence interaction (MDI) on the collision dynamics and the multifragmentation process of heavy ion collisions.

Time developments of physical quantities in Figs. 1-4 indicate that the collision number and density of nuclear matter with the case (SM) are less than those in the case (S) and but the transverse momentum of nucleons in the case (SM) is larger than that in the case (S). The reasons are the following: on the one hand, MDI with an additional repulsive interaction between the nucleons leads

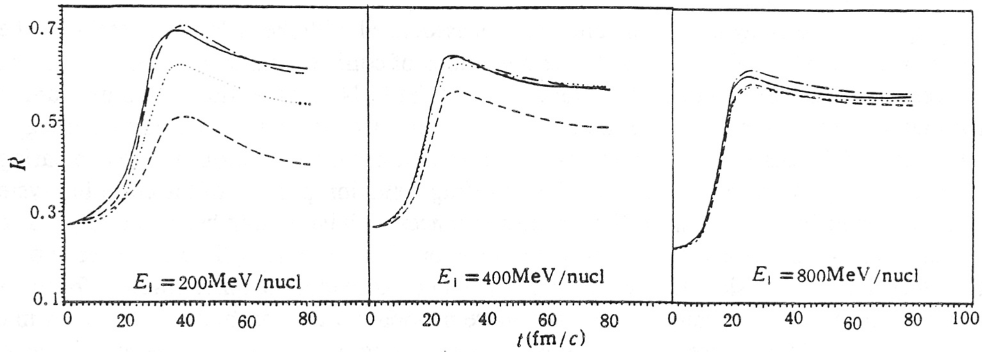

Fig. 4
Time evolution of the thermalization of nuclear matter for the same case as Fig. 1. —— H; —·—·— S; --- SI; · · · SM.

to a visible reduction of the collision number and the density of nuclear matter, on the other hand, it decreases the effective mass of nucleons $m^*/m = 0.6$-0.7 and, therefore, the nucleons in the case (SM) move with a higher velocity than that in the case (S) under a fixed momentum. This means that MDI yields a larger transverse momentum transfer of a nucleon and increases the transverse momentum (see Fig. 2). With increasing incident energy in the case (SM) the transverse momentum increases continuously.

At the same time, because the nucleons in the case (SM) move with a higher velocity it leads to more energy exchange, more excitation process between nucleons and there is more excitation energy stored in the colliding system as compared with the case (S). Finally the colliding system in the case (SM) is easier to fragment. This is the reason why the yield distributions in the case (SM) are narrower than those in case (S).

3.3. Difference and Compensation Between EOS and MDI

The soft-EOS is suitable for explaining the properties of neutron star in the astronomy physics. However, one needs the hard-EOS for explaining the experimental data of the transverse momentum in heavy ion collisions. From Fig. 2, we can see that the transverse momentum in the case (SM) is close to that in the case (H) so that soft-EOS + MDI can explain both the properties of the neutron star in the astronomy physics and the transverse momentum in heavy ion collisions. Even though the compression coefficient in the case (SM) (K = 200 MeV) is less than that in the case (H) (K = 380 MeV), the increase of the transverse momentum from MDI compensates the reduction of the transverse momentum coming from the decrease of compression coefficient K, so that the case (SM) is equivalent to that in the case (H) for the transverse momentum, but they are quite different for the multifragmentation process. As mentioned above, the multifragmentation process is not sensitive to the equation of state, but in the case (SM) it is easy for the fragmentation of the colliding system. Why does EOS have visible effects on the transverse momentum, collision number and density of nuclear matter, and but no sensitive effect on the multifragmentation? Why are the transverse momentum for the two cases (SM) and (H) quite similar? The physical mechanism of these problems have to be studied in the future.

3.4. Important Influences of N-N Cross Section

There are several important influences of N-N cross section in medium on the collision dynamics and multifragmentation mechanism.

Figures 1-4 display that the medium effects associated with the N-N cross section in the medium at E_l/A = 200 MeV, 400 MeV lead to the reductions of collision number, density of nuclear matter, transverse momentum and thermalization. Because the N-N cross section in the medium (SI) is less than that in the free space (S) and the elastic N-N cross section is dominant in this energy region so that the case (SI) leads to the reduction of thermalization and the excitation energy comparing with the case (S). Finally the case (SI) weakens the multifragmentation process of the colliding system which is just the results by [1]. All physical quantities enhances with increasing beam energy, and at the same time the thermalization and the transverse momentum for two cases (SI) and (S) are approaching to each other, but the collision number and density of nuclear matter are quite different for the two cases. Because there is more exchange energy and more momentum transfer between nucleons in heavy ion collisions due to the increase of inelastic N-N cross section in medium with increasing beam energy. Although the collision number and density of nuclei matter in the case (SI) are less than those in the case (S), the thermalization and transverse momentum for the two cases are close to each other. It finally leads to similar multifragmentation for the case (SI) and case (S).

4. SUMMARY

The influences of MDI and the medium effects on the collision dynamics and multifragmentation process in heavy ion collisions are obvious but their properties are quite different. The medium effects in low energy region (200 MeV and 400 MeV) lead to the reductions of collision number, density of nuclear matter, thermalization and transverse momentum due to decreasing N-N cross section in the medium. It also weakens the multifragmentation process of colliding system. The inelastic N-N cross section in the medium increases and becomes dominant with increasing incident energy. Comparing with free N-N collisions, although the collision number and density of nuclear matter are still different, the thermalization and transverse momentum are close to each other, which leads to the close multifragmentation. MDI leads to the reduction of collision number and density of nuclear matter due to increasing repulsive interactions, at the same time it increases the transverse momentum and multifragmentation process of the colliding system due to the increase of the exchanging energy and momentum transfer of colliding nucleons. Influences of EOS on the collision dynamics of heavy ion collisions are visible, such as $N(\mathrm{S}) > N(\mathrm{H})$ and $\rho/\rho_0(\mathrm{S}) > \rho/\rho_0(\mathrm{H})$, and $\langle p_x/A\rangle(\mathrm{S}) < \langle p_x/A\rangle(\mathrm{H})$. However, the thermalization and multifragmentation process of the colliding system are not sensitive to it. MDI+soft-EOS are suitable for both astronomy physics and the dynamical process of heavy ion collisions. The effects of case (SM) and the case (H) on the transverse momentum are almost equivalent. The influence of MDI on the multifragmentation process is important, but the influence of EOS on the multifragmentation process is not obvious. Why is the influence of EOS on the dynamical process of multifragmentation not visible? What is the physical mechanism of the equivalence of the transverse momentum for two cases (SM) and (H)? And how does the N-N cross section change in the medium with increasing incident energy? These problems have to study in more details via the cooperation between the experimental research and theoretical study. The neutron and proton were not identified and symmetrical potential was not considered in this paper, especially due to the limitation of computer time we have made only qualitative researches in these papers and could not make comparison with the experimental data. These kinds of word are in progress.

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