Probing the Dissipation Mechanism in Ternary Reactions of ^{197}Au+^{197}Au by Mean Free Path of Nucleons *

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Collision of very heavy nuclei ^{197}Au+^{197}Au at 15 A MeV has been studied within the improved quantum molecular dynamics model. A class of ternary events satisfying nearly complete balance of mass numbers is selected. The experimental mass distributions for the system ^{197}Au+^{197}Au ternary fission fragments: the heaviest (A_1), the intermediate (A_2) and the lightest (A_3) are reproduced well. The mean free path of nucleons in the reaction system is studied and the shorter mean free path is responsible for the ternary fission with three mass comparable fragments, in which two-body dissipation mechanism plays a dominant role.

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Nuclear energy dissipation, i.e. the conversion of energy of collective nuclear motion into internal single particle excitation energy, has received much attention.[1−8] It is commonly believed that at low and intermediate energy nuclear reactions, there are two different mechanisms of energy dissipation: one-body[1−5] and two-body dissipations.[6−8] In one-body process, nucleons collide with the nuclear potential wall generated by a common self-consistent mean field, and the two-body dissipation proceeds from collisions between individual nucleons. In the early work,[9] Carjan, Sierk and Nix proposed that observation of the partitioning of heavy nuclear system might be a suitable way to distinguish these two kinds of dissipation mechanisms. In the case of two-body dissipation, the formation of a large third fragment was predicted in a very heavy nuclear system. On the contrary, in the case of one-body dissipation, the third fragment should be expected to be much smaller. Recently, the ternary partitions of a very heavy system ^{197}Au+^{197}Au at 15 A MeV were carried out by Skwira-Chalot *et al.*[10] in 4π geometry using the multidetector array CHIMERA at LNS Catania. The mass number distributions of fragments were shown according to the mass A_1 (the heaviest), A_2 (the intermediate) and A_3 (the lightest), and the peak of mass number distribution of fragments A_3 was very close to 100. This result can serve as experimental evidence for clarifying that two-body dissipation process is more important than one-body dissipation in this ternary reaction. However, up to date, the microscopic description of these two types of dissipation mechanisms in nuclear dynamics is still not very clear. Choosing mean free path of nucleons to probe the energy dissipation mechanism is a possible way. One-body nuclear dissipation connects with the long mean free path of nucleons inside a nucleus, which arises from nucleons colliding with the moving potential wall rather than with another nucleon.[1−5] Two-body dissipation proceeds from collisions between individual nucleons, which should apply only to systems for which the mean free path is smaller compared to the spatial dimensions.[6−8]

In this Letter, we apply the improved quantum molecular dynamics (ImQMD) model[11−14] to calculate the mean free path in the process of ternary fission for heavy nuclear systems. The quantum molecular dynamics (QMD) model successfully used in intermediate energy heavy-ion collisions was successfully extended to heavy ion collisions at energies near barrier by making a series of improvements.[11,12] The main improvements introduced are as follows: (1) The surface and surface symmetry energy terms are introduced in the potential energy density functional in the mean field. (2) A system size dependent wave packet width is introduced in order to consider the evolution of the wave packet width. (3) An approximate treatment of anti-symmetrization, namely, the phase space occupation constrain is adopted.[15] The initial nuclei for projectile and target are sampled according to the density, binding energy and root-mean-square radius of nuclei, which are obtained from calculation of

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mean-field theory or experimental data, so that a part of structure effect of the projectile and target is taken into account. In the model both the nuclear mean field and collision term allowing for nucleon-nucleon scattering are treated properly. Thus, in principle, the dissipation, diffusion and correlation effects are all included without introducing any freely adjusting parameters. With the ImQMD model the fusion dynamics at energies near and above the barrier have extensively been studied and can reproduce a series of experimental data.[11−14]

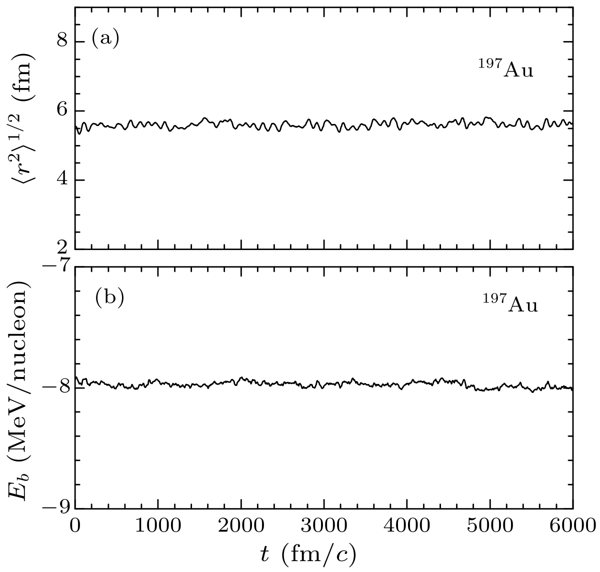

Fig. 1. Time evolution of the rms radius (a) and the binding energy (b) for ground states of ^{197}Au.

A proper initial condition for making the initial nuclei in the real ground state is of crucial importance because considerable excitation of initial nuclei will lead to unreal nucleon emission and affect the products of low energy nuclear reactions. By using the ImQMD model with the IQ2 (see Table 1) force parameters,[13,14] we elaborately select 20 projectile and target nuclei from thousands of prepared systems for researching very heavy system ^{197}Au+^{197}Au. In this work the procedure of making initial nuclei of projectile and target is similar to that in Refs. [11-14]. The binding energies and root-mean-square (rms) radii for ^{197}Au are required to be 7.92 ± 0.05 MeV/nucleon and 5.35 ± 0.2 fm, respectively. Figure 1 shows the time evolution of the binding energy and rms radius of the initial nucleus for ^{197}Au. From Fig. 1, one can see that the binding energy and the rms radius of ^{197}Au remain constant with a very small fluctuation and the bound nucleus evolve stably without spurious particle emission for a period of time of about 6000 fm/c, which is essential for applications to reactions of heavy nuclei. Only those satisfying the above requirements will be taken as the "initial nuclei" and are stored for usage in reaction simulations. By rotating these prepared projectile and target nuclei around their centers of mass by a Euler angle chosen randomly, we create more than 4000 bombarding events for each small impact parameter (b = 0–6 fm), 7000 bombarding events for b = 7–9 fm and at least 10000 events for each large impact parameter (b = 10–12 fm) at the energy of 15 A MeV, since the probability of ternary events is decreasing with the increasing impact parameter in this energy region. The distance from the projectile to the target at the initial time is taken to be 50 fm.

Table 1. The model parameters IQ2.

α (MeV)	−356
β (MeV)	303
γ	7/6
g_0 (MeV fm^2)	7.0
g_τ (MeV)	12.5
η	2/3
C_S (MeV)	32.0
κ_s (fm^2)	0.08
ρ_0 (fm^{-3})	0.165

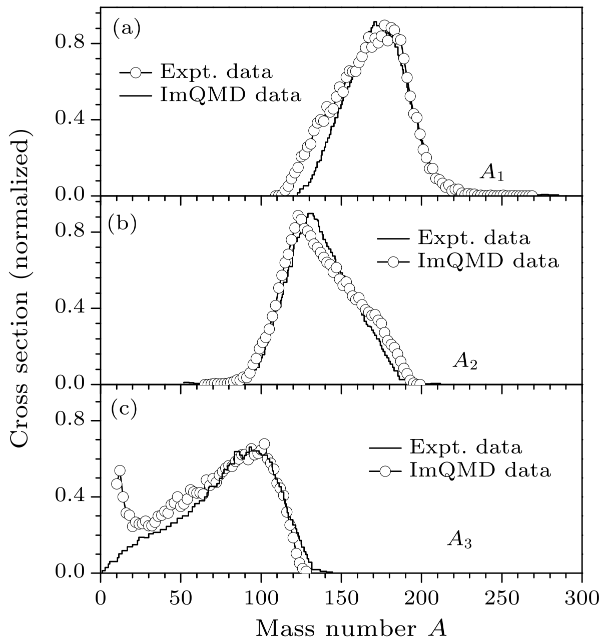

Fig. 2. Mass number distributions of (a) the heaviest A_1, (b) intermediate A_2, and (c) the lightest A_3 fragments in selected ternary reactions of ^{197}Au+^{197}Au at 15 A MeV. The histograms denote the experimental data are taken from Ref. [10], the lines with open circles are the calculation results with the ImQMD model.

In the simulation, we select a class of ternary events satisfying nearly complete balance of mass numbers:

$$A_P + A_T - 70 \le A_1 + A_2 + A_3 \le A_P + A_T, \quad (1)$$

where $A_P + A_T$ is the total mass number. This criterion was also adopted in Ref. [10]. By counting the number of A_1, A_2 and A_3 at each impact parameter b, the production cross sections for A_1, A_2 or A_3 are obtained with the expression

$$\sigma(A_i) = 2\pi \int_0^{b_{\max}} bP(A_i, b)db \simeq \sum_{b=0}^{b_{\max}} 2\pi b\Delta b \frac{N(A_i, b)}{N_0}, \quad (2)$$

where $P(A_i, b) = N(A_i, b)/N_0$ is the production probability of fragment A_i with the impact parameter b, $N(A_i, b)$ denotes the number of A_i producing at each impact parameter in ternary events, and N_0 denotes total ternary fission events. Here, $b_{\max} = 12$ fm and $\Delta b = 1$ fm in this calculation.

Figure 2 shows the mass distributions of (a) the heaviest A_1, (b) middle-mass A_2, and (c) the lightest A_3 fragments in the selected ternary reactions of ^{197}Au+^{197}Au at energy of 15 A MeV. The histograms denote the experimental data taken from Ref. [10], the lines with open circles are the calculation results with the ImQMD model. The experimental data and the calculation results are taken in the normalized form for comparison. For comparison of the ImQMD calculation results with experimental data, we calculate the minimal deviation χ square values which equal 0.0069, 0.0047 and 0.012 for fragments of A_1, A_2 and A_3, respectively. From these results, one can see that the calculation results can reproduce the experimental data considerable well without any freely adjusting parameter. The largest deviation is only in the region of small fragments of A_3 (≤ 20), it may due to the approximate treatment of anti-symmetrization in ImQMD model. This means that the ImQMD model is suitable to describe the ternary fission events of the very heavy system ^{197}Au+^{197}Au at 15 A MeV.

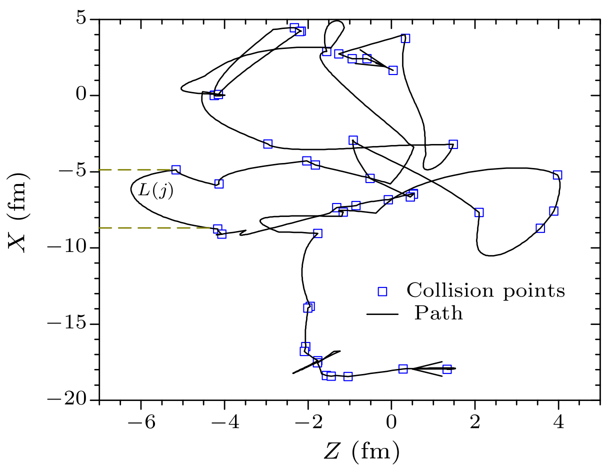

Fig. 3. (Color online) Time evolution of the ith nucleon path in two-dimensional phase space.

For the calculation of mean free path of nucleons in the composite system, we firstly study the nucleon path microscopically. In the microscopic model, we can trace the position (and momentum) of each nucleon at any time and obtain its trajectory between each two sequential collisions. Figure 3 shows a typical path of a nucleon in two-dimensional space. The open squares denote the collision points and the curve shows the path of a nucleon. The feature of the path is created by both mean field and nucleon-nucleon collisions. The time evolution of each nucleon under the self-consistently generated mean-field is governed by the canonical equations of motion, which leads to the path of the nucleon is a curve between two sequential collisions. Only in the case that two sequential collisions take place in one time step, the path is a straight line. Now we study the mean free path of nucleon, which can be used to microscopically characterize whether one-body or two-body dissipation will be dominant or not.

By analyzing the reaction process from touching configuration to its re-separation for each event, we memorize the nucleon-nucleon collision times with the ImQMD model. The mean free path is defined by

$$\lambda = \frac{1}{A} \sum_{i=1}^{A} \lambda(i), \quad (3)$$

where i runs over all nucleons in the reaction system and $A = A_P + A_T$ is the total nucleons, $\lambda(i)$ is the mean free path of the ith nucleon. In the simulation, we trace the path of each nucleon in the reaction system from the formation of composite systems to their re-separation and measure the length of the path between each two sequential collisions. By summing up the total lengths of paths and counting the number of collisions, one can calculate $\lambda(i)$ for each nucleon and obtain the mean free path.

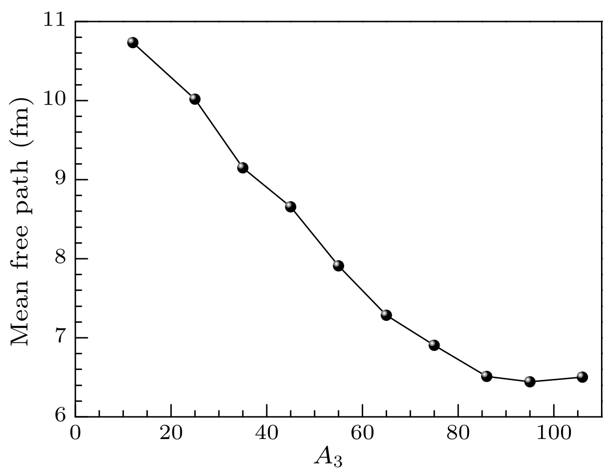

Fig. 4. Mean free path of nucleons in composite systems as a function of the third fragments A_3 at the energy of 15 A MeV.

Now we investigate the correlation between the mean free path and the mass number of the third fragments A_3. In the simulation of ImQMD model, the mass number of fragment A_3 and the mean free path of nucleons can be obtained simultaneously for each ternary event. Then, the average value of the mean free path of nucleons is calculated for those events producing the same mass fragment A_3. Figure 4 shows the mean free path of nucleons in a composite system as a function of the third fragment mass A_3. The results are statistical average value for all of the reaction events. From Fig. 4, we can see that the mean free path decreases with the A_3 mass number increasing until the region the average mass number of $A_3 = 85$–105, where it becomes flatter. The figure clearly shows that the mean free path in the ternary fission process to produce the large mass A_3 is much shorter than the system size. Thus, the ternary process to produce three comparable mass fragments presents short mean free path, that is to say, there is even more nucleon-nucleon collisions leading to the mean free path shorten. In this case, the two-body energy dissipation mechanism will play a significant role. With the decrease of mass number of the third fragment A_3, the mean free path increases considerably. It becomes comparable with the system size. In this case, the effect of one-body dissipation mechanism becomes dominant. We conclude from the correlation between mean free path and the mass number of A_3 that the role of one-body dissipation becomes weaker and two-body dissipation will be dominant with the increase of mass number A_3. This microscopical calculation seems to support the Carjan's results,[9] the mass distribution of the third fragment A_3, displayed in the bottom of Fig. 2, can be interpreted as an indication for the dominance of two-body dissipation mechanism in the observed ternary fission of the Au+Au system.

In summary, the ternary fission of the very heavy system ^{197}Au+^{197}Au has been investigated by using the ImQMD model. The experimental mass distributions of ternary fission fragments at energy of 15 A MeV can be reproduced well without any freely adjust parameters. In order to clarify the energy dissipation mechanism, the mean free path of nucleons is calculated in the period from touching configuration to the composite system re-separating. The calculated results show that the shorter mean free path (shorter than system size) is responsible for the ternary fission with three comparable mass fragments, in which the two-body dissipation mechanism plays a dominant role.

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