Dynamical Properties of the New Ternary Fission in Collisions of $^{197}\text{Au}+^{197}\text{Au}$ at 15 MeV/Nucleon

Xian Li,1 Chengqian Wang,1 and Yaohui Xu2

1Institute of Mathematics and Physics, Leshan Normal University, Leshan, 614000 Sichuan, China
2Institute of Electronics and Materials Engineering, Leshan Normal University, Leshan, 614000 Sichuan, China

Correspondence should be addressed to Chengqian Wang; wangchengqiancq@163.com

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The dynamical properties of the new ternary fission in heavy $^{197}\text{Au}+^{197}\text{Au}$ at 15 MeV/nucleon have been investigated by using the improved quantum molecular dynamics model. The dependencies of the production probability, lifetime, the time interval, and angular distribution on the impact parameter are carefully studied. The calculation results show that the characteristics of these are very different between the small and the large impact parameter. Comparing the theoretical results with the experimental data, one can obtain that the fast ternary breakup likely occurs at the impact parameter region $b = 7-9$ fm. The nonisotropic of angular distribution and the short time interval among two fissions indicates that the fast ternary fission is a nonequilibrium and violent process.

1. Introduction

Heavy-ion collisions have been paid much attention for several decades, and multifragmentation is a common phenomenon in the intermediate-energy heavy-ion collisions. In the low incident energy region, middle-mass nucleus-nucleus systems predominantly lead to these reactions: fusion, fusion-fission, quasi-fission, deep-inelastic, and quasi-elastic scattering with the two heavy fragments produced in the exit channel. Also, the normal ternary fission, which has two bigger fragments and a light-charged particle emitted from the neck, occurs on the peripheral collision. However, for the very heavy collision system at the incident energy around 20 MeV/nucleon, there exists a new ternary reseparation mode which is very different from the normal ternary fission, and many experiments have verified this reaction mode in heavy nuclear reaction system [1, 2]. This ternary fission of the new fission mode is considered as a transition from the low-energy fusion-fission collision to the high-energy multifragmentation. Studying this questions can reveal some very interesting phenomena of the dynamical and energy dissipation mechanisms [1–3] in the heavy-ion collisions.

The experimental researches on collisions of a very heavy system $^{197}\text{Au}+^{197}\text{Au}$ have been carried out at energy of 15 MeV/nucleon, by using the CHIMERA multidetector array arranged in 4π geometry at the Laboratori Nazionali del Sud (LNS) in Catania. Their preliminary result showed that a violent process of reseparation into three fragments with comparable size was founded in this heavy system. This ternary fission was called fast ternary breakup [4, 5] and clearly different from normal ternary fission. Then, a series of deep experiments and analyses have demonstrated that the fragments of this ternary breakup are almost exactly aligned and the time scale of these two separations is very short, about 70-80 fm/c [6–8].

In order to understand and observed the new ternary fission mechanism, it is necessary to use suitable dynamical model of nucleus-nucleus collision from the many theoretical simulation model [3, 9–11]. For example, the Los Alamos finite-range macroscopic dynamical description [3] is static and concludes that the ternary fission only happens on strong two-body dissipation existed. Then in the low energies, the classical dynamical model HICOL of Feldmeier [9] based on the one-body dissipation dynamics is widely used for analysis of deep-inelastic reactions.
But for the ternary fission in heavy reaction system at low energy, there seems still having some unsuitable when studying the energy dissipation mechanism. In addition, the quantum molecular dynamics (QMD) code of Lukasik was used to the Au+Au system and failed to reproduce the characteristic of the collinear emission pattern of the ternary fission [12, 13], maybe because of the lack of important improvements on the nucleon-nucleon interaction term. Finally, the improved quantum molecular dynamics (ImQMD) model, which both the mean-field and the nucleon-nucleon collisions as well as the Pauli principle are treated properly and may be a suit way to simulate the nuclear action in low energy. Both the experimental and the theoretical studies on the new ternary fission indicate that it is worthwhile and meaningful to research the dynamical mechanism of the new ternary fission.

In this paper, ImQMD model has been applied to simulate the heavy \(^{197}\text{Au}^{+197}\text{Au}\) collisions at 15 MeV/nucleon, and the new ternary fissions are selected. The dynamical properties of them are comprehensive studied, such as the fission modes and their probabilities, the angular distributions of fragments, and the time scale of the secondary fission.

### 2. Theoretical Approach

For the reader’s convenience, let us first briefly introduce our model. The QMD model is a microscopic transport model based on a molecular dynamics picture and has been successfully used in intermediate energy heavy-ion collisions [14, 15]. By making serious improvements, it has been extended to apply to heavy-ion collisions at low energies near barrier and called the ImQMD model. The main improvements include the three terms: the surface and surface symmetry energy terms, which are introduced in the potential energy density functional in the mean field; a system-size-dependent wave packet width, which is introduced in order to consider the evolution of the wave packet width; and an approximate treatment of antisymmetry, which is carried out by the phase space occupation constrain [15, 16].

In the ImQMD model, each nucleon is expressed by a Gaussian wave packet

\[
\phi_i(\vec{r}) = \frac{1}{(2\pi\sigma_i^2)^{3/4}} \exp\left[-\frac{(\vec{r} - \vec{r}_i)^2}{4\sigma_i^2}\right] \exp\left[\frac{i\vec{p}_i \cdot \vec{r}}{\hbar}\right], \tag{1}
\]

where \(\vec{r}_i, \vec{p}_i\) are the centers of ith wave packet in coordinate and momentum space, respectively. \(\sigma_i\) is the spread of the wave packet. Then the density distribution of the system can be written as

\[
\rho(\vec{r}) = \int f_i(\vec{r}, \vec{p}) d\vec{p} = \frac{1}{(2\pi\sigma_i^2)^{3/2}} \exp\left[-\frac{(\vec{r} - \vec{r}_i)^2}{2\sigma_i^2}\right]. \tag{5}
\]

The propagation of nucleons in reaction system under a self-consistently generated mean-field is governed by Hamiltonian equations of motion:

\[
\frac{\hbar}{\partial \tau} \vec{r} = \frac{\partial H}{\partial \vec{p}_i}, \quad \frac{\hbar}{\partial \tau} \vec{p}_i = -\frac{\partial H}{\partial \vec{r}_i}. \tag{6}
\]

The Hamiltonian \(H\) consists of the kinetic energy \(T\), the nuclear local interaction potential energy \(U_{\text{loc}}\), and Coulomb interaction potential energy \(U_{\text{coul}}\) and is expressing as

\[
H = T + U_{\text{loc}} + U_{\text{coul}}, \tag{7}
\]

where

\[
T = \sum_i \frac{\vec{p}_i^2}{2m_i}, \tag{8}
\]

in which \(\vec{p}_i\) is the center of ith wave packet in momentum space and \(m_i\) is the mass of ith nucleon.

And

\[
U_{\text{loc}} = \int H_{\text{loc}}(\vec{r}) d\vec{r} = \left\{\frac{\alpha p^2}{2\rho_0} + \frac{\beta}{\gamma + 1} \rho^\gamma + \frac{g_\rho}{2} (\nabla \rho)^2 + g_\gamma \rho^\gamma \right\} d\vec{r},
\]

\[
U_{\text{coul}} = \frac{1}{2} \int \rho_{\rho}(\vec{r}) \frac{e^2}{\left|\vec{r} - \vec{r}'\right|} \rho_{\rho}(\vec{r}') d\vec{r} d\vec{r}' - e^2 \frac{3}{4} \frac{3^{1/3}}{\pi} \int \rho_\rho(\vec{r})^{4/3} d\vec{r}, \tag{9}
\]

where \(\delta = \rho_n - \rho_p/\rho_n + \rho_p\) is the isospin asymmetry. \(\rho, \rho_\rho, \rho_p\) are the nucleon, neutron, and proton densities, respectively.
In the local interaction potential energy equation, the first and second terms are two-body and three-body parts, the \(g_0, \tau_0\) terms are the surface and momentum-dependent terms, and the last part is the symmetry energy. The parameters named IQ2 in the Hamiltonian energy density function are shown in Table 1. In addition, we adopt a system-size-dependent wave packet width in our simulation:

\[
\sigma_r = 0.09A^{1/3} + 0.88\text{fm}. \tag{10}
\]

### 3. Results and Discussions

Making the initial nuclei in the real ground state is crucial important, because unreal nucleon emission of initial nuclei will affect the production in the nuclear reaction. By using the ImQMD model with IQ2 parameters, we selected 20 projectile and target initial nuclei. Their binding energies were 7.92 \(\pm\) 0.05 MeV/nucleon and the root-mean-square radii 5.35 \(\pm\) 0.2 fm, respectively. The bound of the nuclei evolved stably without spurious emission within 6000 fm/c. We have simulated more than 200,000 bombarding events, by rotating these projectile and target nuclei around their centers of mass with a Euler angle chosen randomly. For each small impact parameter (0-3 fm), we have simulated 4000-7000 reactions, 10000-15000 reactions for each medium impact parameter (4-6 fm), and 20000-30000 reactions for each peripheral impact parameter (7-12 fm).

As the same with the experiment research [7], a class of ternary fissions were selected under the condition:

\[
A_{\text{projectile}} + A_{\text{target}} - 70 \leq A_1 + A_2 + A_3 \leq A_{\text{projectile}} + A_{\text{target}}, \tag{11}
\]

where \(A_1, A_2,\) and \(A_3\) are the masses of three fragments in a ternary fission, respectively. This condition showed the characteristics of the nuclear reactions were that the nearly complete balance of mass allowing for up to 70 mass units to be lost because of the evaporation of undetected nucleons and \(\alpha\) particles. Conditions on the balance of longitudinal and transversal momenta are imposed:

\[
\sum_{i=1}^{3} p_{\text{long}}(i) > 0.8 p_0, \quad \sum_{i=1}^{3} p_{\text{trans}}(i) < 0.04 p_0, \tag{12}
\]

where \(p_0\) is the momentum of \(^{197}\text{Au}\) projectiles.

In our previous work [18], we have calculated the mass distributions of fragments in the new ternary fission of \(^{197}\text{Au} + ^{197}\text{Au}\) collisions at 15 MeV/nucleon and compared with experimental result [4]. We can find that the theoretical results are in good agreement with experimental data. In addition, the result is shown in the data supplement part of figures S1. The results show that the ImQMD is suitable to study the heavy nuclear reaction of \(^{197}\text{Au} + ^{197}\text{Au}\) system at an energy of 15 MeV/nucleon.

### 3.1. The Modes and Production Probabilities of New Ternary Fissions

In our simulation, we have found the production probability of the new ternary fission is different at each impact parameter, and it is worthwhile to clarify this question. The dependence of the production probability about the new ternary fission on the impact parameter is shown in Figure 1. In small parameter region (0-2 fm), the production probability nearly rises up, then appears a plateau in the region (3-6 fm), and decreases rapidly after \(b = 7 \text{ fm}\) almost to zero. This result implies the new ternary fissions of \(^{197}\text{Au} + ^{197}\text{Au}\) system mainly happen in the semicentral region of impact parameter.

Further experimental studies [7, 8] indicate that any new ternary fission of \(^{195}\text{Au} + ^{197}\text{Au}\) collision will break up into projectile-like (PLK) and target-like (TLK) fragments in first separation, and then the PLK or TLK will break into two fragments in the second separation. The time interval between these two separations of all the ternary fissions is not the same. If the time interval between the two separations is less than 100 fm/c, then we call it a direct ternary fission, and if not, call it a sequential ternary fission. To discover the characteristics of these two breakup modes, we have drawn and analyzed the snapshots of the time evolution of several typical ternary fissions by using the same method in Ref. 18. The results show that there exist two preformed necks already in the direct mode before the first breakup of reaction system; thus, the time interval will be very short in the following reaction process. However, for a sequential mode ternary fission that has no feature and after the first separation, the reaction system needs more time to form another neck and breaks up again. These snapshots are shown in the data supplement part of figures S2, S3.

Figure 2 shows the dependence of the production probabilities for the direct and sequential ternary fissions on impact parameter in reaction \(^{197}\text{Au} + ^{197}\text{Au}\) at 15 MeV/nucleon. From this figure, we can see that the sequential mode reaction dominates in the central and semiperipheral region of the impact parameters, and the direct mode likely appears at large impact parameters. The impact parameter \(b = 6 \text{ fm}\) is a turning point; after that, the tendency of the black-dot line is declining; meanwhile, the red-triangle line is rising.

### 3.2. The Lifetime and the Time Scale of the Second Fission

It is very important and interesting to estimate when the primary breakup happens and how long will elapse from the primary fission to the second separation in a new ternary fission. And it can provide us with significant valuable physical insights on mechanism of heavy nuclear reactions. For the convenience, we define the lifetime as the passing time from the sticking time point of projectile and target nuclei to the primary breakup, and \(\Delta t\) is the time interval elapsing from the primary separation to the second fission. It is necessary to study the relationship of the lifetime or \(\Delta t\) with the impact parameter, and the average value of them is shown in

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**Table 1: The IQ2 parameters used in ImQMD model.**

| \(\alpha\) | \(\beta\) | \(\gamma\) | \(g_0\) | \(g_\tau\) | \(\eta\) | \(C_3\) | \(k_3\) | \(\rho_0\) |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| MeV | MeV | MeV fm\(^2\) | MeV | MeV | fm\(^2\) | fm\(^{-3}\) |
| -356 | 303 | 7/6 | 7.0 | 12.5 | 2/3 | 32.0 | 0.08 | 0.165 |
Figures 3 and 4, respectively. From Figure 3, one can see that the lifetimes in both the direct and sequential ternary fissions decrease with the impact parameter increases and also find that the lifetime of direct ternary reaction is longer than that of the sequential mode, and their gap reduces rapidly along with the impact parameter rising. The longer lifetime of direct mode is due to the two necks that are formed at the breakup time point, and it needs more time to rearrange nucleons to be in a lower energy configuration. However, the difference nearly disappears at large impact parameter; this is because more nucleons take part in the reaction at small impact parameter and fewer nucleons at large impact parameter, that is to say, the spectator effect becomes more and more obvious. Then, the difference between the direct and sequential mode will be small before the separation. In Figure 4, the time interval $\Delta t$ also falls down quickly from 550 fm/c till the impact parameter $b = 6$ fm, then gets slower when $b = 7, 8$ fm, and it remains unchanged after $b = 9$ fm, about 170 fm/c.

Moreover, according to the analysis dependance of $\Delta t$ on impact parameters, we deduce that the fast sequential ternary reaction, mentioned in Ref. 4–6, probably happens at peripheral collision, so we change the time step of ImQMD code in our previous simulation and choose a smaller time step as 10 fm/c and calculate the fission time scale in the sequential ternary reactions at $b = 7$ fm again, and the time distributions of the primary and second separations are shown in Figure 5. The red line is the primary fission moment, and the blue line is
Figure 4: Correlation between the time interval \( \Delta t \) and the impact parameter.

Figure 5: The distribution of the fission moment in sequential ternary fissions of \(^{197}\text{Au} + ^{197}\text{Au}\) system at \( b = 7 \) fm. The red line is the primary fission moment, and the blue line is the second breakup moment.

Figure 6: The schematic view of the reaction in a sequential ternary fission, in which a TLF and PLF are formed in the primary deep-inelastic process and followed by a consecutive breakup process from one of these two fragments. The definitions of the in-plane (\( \phi \)), the out-of-plane (\( \theta \)), and (\( \Theta_{cm} \)) angles are shown. The normal direction \( \vec{n} \) is the unit vector of reaction plane. The beam, separation and fission axes, and their orientations are displayed, and the orientation of the fission axis is given by the larger \( z \)-axis velocity \( v_{1z} \geq v_{2z} \).
the second breakup moment. The peaks of the distributions correspond to the time of $\tau_1 = 730\text{fm}/c$ and $\tau_2 = 810\text{fm}/c$, respectively, and the interval time $\tau_2 - \tau_1$ of the twice fissions is $80\text{fm}/c$, which is consistent with the time scale reported in Ref. 6. This simulation result supports the conclusion that the fast ternary reaction is a violent process, takes place in a very short time, and likely happens in peripheral collision.

3.3. Angular Distributions and the Correlation with the Impact Parameter. To further understand the dynamical and energy dissipation mechanism [19, 20] of the new ternary fission in $^{197}\text{Au} + ^{197}\text{Au}$ system nuclear reaction, we study their angular distributions. For clarity, we first give the definition of the angles, similar as in Ref. [1]. The velocity of the primary fragment survived in second fission is written as $\bar{v}_3$, and the velocity of the other fragment separated in the second fission is denoted as $\bar{v}_{12}$. The fragments and their velocities formed in second breakup are called $F_1$, $\bar{v}_1$ and $F_2$, $\bar{v}_2$, respectively. And their velocities’ projections onto z-axis satisfying this relation $v_{1z} \geq v_{2z}$. $\bar{v}_{\text{cm}}$ is the velocity of the center-of-mass of the total system. Then, we define the
beam axis, the separation axis (the first separation), and the fission axis (the second separation) by \( \vec{v}_{\text{cm}}, (\vec{v}_1 - \vec{v}_3), \) and \( (\vec{v}_1 - \vec{v}_2), \) respectively. The reaction plane is defined by the beam and separation axes, and the normal direction \( \vec{n} \) of reaction plane is the unit vector of the cross product \( (\vec{v}_1 - \vec{v}_3) \times \vec{v}_{\text{cm}}. \) The out-of-plane angle \( \Theta \) specifies the deflection of the fission axis with respect to the normal direction \( \vec{n}. \) The in-plane angle \( \phi \) is the angle between the separation axis and the projection of fission axis onto the reaction plane. \( \Theta_{\text{cm}} \) is the angle between separation axis and beam axis, also called the center-of-mass scattering angle. The schematic view of the reaction in a sequential ternary fission and the angles of \( \Theta, \Theta_{\text{cm}}, \) and \( \phi \) are shown in Figure 6.

The distributions of \( \Theta, \Theta_{\text{cm}}, \) and \( \phi \) in sequential ternary fissions are displayed in Ref. 21. These figures are shown in the data supplement part of figures S4. Both the theoretical results and experimental data are normalized. In order to make a comparison with the experimental data, only the PLK ternary fissions are chosen and analyzed. The distributions of the out-of-plane angle \( \Theta \) are peaked at 90° in both the experimental and ImQMD results, which indicates that the fission axes of ternary fissions lie in or are very close to the reaction plane at most times. The distribution of \( \Theta_{\text{cm}} \) is peaking around 26°. The distribution of the in-plane angle \( \phi \) both theoretical and experimental curves has two peaks, 15° and -165°, corresponding to the fragments \( F_1 \) and \( F_3 \), separately. It is worthwhile to clarify the question that the new ternary fission is a statistical or dynamical fission process at low bombarding energies. From this figure, we have found that the angular distribution of \( \phi \) is anisotropic, and the peaked angles mean that the separated fragment proceeds a nonequilibrium reaction and still retains a memory of its creation.

For deeper study, the dependence of angular distributions on the impact parameters with respect to both PLF and TLF sequential ternary fissions are discussed systematically in \( ^{197}\text{Au}+^{197}\text{Au} \) system at an energy of 15 MeV/nucleon. In Figure 7, the dependence of angular distributions about \( \Theta_{\text{cm}} \) on the impact parameter is shown. From this figure, we can see that the distributions of \( \Theta_{\text{cm}} \) are peaked at 90° in small impact parameter, such as \( b = 1 \) fm, and this indicates that the separation axis (the direction of the first separation) is likely vertical to the beam direction. With the impact parameter increases, when \( b \geq 3 \) fm, the angular distribution curve appears two complementary peaks, which correspond to PLK ternary fissions for \( \Theta_{\text{cm}} < 90° \) and TLF ternary fissions for \( \Theta_{\text{cm}} > 90° \), and also the curve of the distribution becomes narrow, sharp, and shifts. The probabilities of the two value are similar because the collision system is symmetric. The peak angle tends to be steady at 26° or 154°, which agrees with the “grazing angle” of the classical deflection function for binary dissipation collision [22, 23], indicating that the first separation is a deep inelastic scattering process.

In Figure 8, the dependence of angular distributions about \( \Theta \) on the impact parameter with respect to sequential ternary fissions is displayed. In small impact parameter region, such as \( b = 1, 4 \) fm, the distributions are more likely to be isotropic; for large parameters, it will have two peaks on symmetrical positions around 90°, and they are 85° and 95°, respectively. It means that the fission axis more likely very close to the reaction plane and not lies in it. Moreover, the angular distributions of \( \phi \) on the impact parameters concerning sequential ternary fissions are drawn in Figure 9. In this figure, we can see that there are three peaks in the distributions: the middle peak represents the direction of \( F_1 \) in PLK ternary fission, and the other two peaks correspond to \( F_1 \) in TLF ternary fission, and the fragments of \( F_2 \) are in the complementary direction of themselves. Also, we can

![Figure 9: The dependence of angular distributions about \( \phi \) on the impact parameter with respect to sequential ternary fissions in \( ^{197}\text{Au}+^{197}\text{Au} \) system at an energy of 15 MeV/nucleon.](image-url)
observe that the three peaks of the distribution move along with the impact parameter increases, such as the middle peak moves from 26° (b = 1 fm) to 15° (b = 9 fm), and the distributions turn sharper at the same time. The distribution of ϕ is nonisotropic and strongly means the fission is very nonstatistical. The peaks of distribution ϕ about F1 are 15° or 165°, and this means the fission axes are very close to the separation axes. Therefore, we can conclude that the secondary fission should be completed in a short time and the three fragments will be collinear.

4. Summary

The new ternary fission of the very heavy 197Au + 197Au system at the incident energy of 15 MeV/nucleon has been studied by using the ImQMD model. Primarily, its production probability depends on the impact parameter, and it mainly occurs at central and semiperipheral collision region. The impact parameter b = 6 fm is a turning point; after that, the tendency of sequential mode is declining; meanwhile, the direct mode is rising. In addition, its lifetime decreases with impact parameter increasing, and the lifetime of direct mode is longer than that of the sequential mode; also, their difference reduces rapidly along with impact parameter rising. The time interval Δt between two breakups of sequential mode also falls down quickly before b = 6 fm and remains unchanged after b = 9 fm, about 170 fm/c. Especially, the value of Δt at b = 7 fm is estimated 80 fm/c, which is a very short time and indicates that this breakup occurs violently and is a nonequilibrium process.

To further study, the angular distributions for both PLF and TLF ternary fissions are analyzed. It is found that the distribution of Θcm is strongly dependent on the impact parameter, which appears isotropic at small impact parameters and presents obvious orientation at the range b > 3 fm, peaking at 25°. The distribution of Θ is approximately isotropic at smaller impact parameter and peaks around 90° (90° ± 5°) when b > 7 fm. Then, the distribution of ϕ is weakly correlated with b, and ϕ distributes in a narrow range round 15° and 165° when b > 7 fm. At last, one can conclude that the new ternary fission in 197Au + 197Au is a nonstatistical and collinear process.

In conclusion, this work has studied the dynamical properties of the new ternary fission, and their dependencies on the impact parameter also obtained the fast ternary fission which the fragments are comparable in size and collinear in space, more likely occurs at the range of b > 7 fm.

Data Availability

For theoretical data in this paper, ImQMD model has been applied to simulate the heavy 197Au + 197Au collisions at 15 MeV/nucleon. Experimental data is part of the references in this paper.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

The supplementary data are shown in the file of “supplement data”, which figures are results of our previous papers, and cited for confirming some description in this paper.

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