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SEARCH FOR POSSIBLE WAY OF PRODUCING SUPER-HEAVY ELEMENTS: DYNAMIC STUDY ON DAMPED REACTIONS OF ^{244}Pu + ^{244}Pu, ^{238}U + ^{238}U and ^{197}Au + ^{197}Au

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By using the Improved Quantum Molecular Dynamics model, the ^{244}Pu + ^{244}Pu, ^{238}U + ^{238}U and ^{197}Au + ^{197}Au reactions at the energy range of $E_{\rm c.m.} = 800$ MeV to 2000 MeV are studied. We find that the production probability of superheavy fragments (SHFs) with $Z \geq 114$ for the ^{244}Pu + ^{244}Pu reaction is much higher compared with that for the ^{238}U + ^{238}U reaction and no product of SHF is found for the ^{197}Au + ^{197}Au. The production probability of SHFs strongly depends on the incident energy and a narrowly peaked energy dependence of production probability is found. The decay mechanism of the composite system of projectile and target is studied and the time scale of decay process is explored. The binding energies and the shapes of SHFs are studied. The binding energies of SHFs are broadly distributed and the shapes of SHFs are strongly deformed.

Keywords: ImQMD; ^{244}Pu + ^{244}Pu, ^{238}U + ^{238}U and ^{197}Au + ^{197}Au; superheavy fragments; decay mechanism; strongly deformed fragments.

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There are two approaches proposed for producing superheavy elements (SHEs) through accelerators. One approach of the complete fusion reaction is very successful in producing SHEs. Since the '70s the elements from $Z = 107$ to 116 were synthesized by the "cold fusion" reactions with lead and bismuth targets[1] and "hot fusion" reactions with actinide targets.[2] A lot of research works on this approach have been done both experimentally and theoretically. However, it is well known that further experimental extension of the region of SHEs to the central area of superheavy "island" by means of the complete fusion reaction is limited by the number of available projectiles and targets, and also by the very low production cross-section.[1,3] In order to approach the center of superheavy "island", which is very neutron-rich, radioactive ion beams will have to be utilized, but up to now the intensive radioactive ion beams are not available. An alternative pathway to the synthesis of superheavy elements is the strongly damped collision process between massive nuclei, for instance, ^{238}U + ^{238}U. The strongly damped collisions of the ^{238}U + ^{238}U and the ^{238}U + ^{248}Cm at the energies near the Coulomb barrier were studied in the '70s and the early '80s for searching superheavy nuclei.[4–8] It was reported in Ref. 9 that for the ^{238}U + ^{238}U at $E = 7.5$ AMeV, the upper limit of the cross-section for producing superheavy elements was about 2×10^{-32} cm^2 for half lives between milliseconds and month by looking for spontaneous events from reaction products. In Ref. 10 the reaction of ^{238}U + ^{248}Cm at 7.4 AMeV was studied and it was found that the cross-sections for ^{100}Fm, ^{99}Es and ^{98}Cf with target of ^{248}Cm are three to four orders of magnitude higher than with target of ^{238}U. It means that the strongly damped reaction with two nuclei heavier than uranium could be very beneficial for producing superheavy nuclei. The theoretical study about this approach was mainly carried out by diffusion model[7] and quantum fluctuations within the fragmentation theory[6] at the '70s and the early '80s. Only recently, Maruyama *et al.* studied the dissipative reaction of ^{197}Au + ^{197}Au by the constrained molecular dynamics model[11] in which it was found that the super-heavy composite system formed in head-ion collisions of ^{197}Au + ^{197}Au might survive for a long time. However, the dependence of the production probability of superheavy fragments in strongly dissipative massive nuclear reactions on energies and combinations of projectile and target has never been studied, which is very important and useful for producing superheavy elements experimentally. Therefore, it is necessary to make a more extensive study on the approach of strongly damped reactions of massive nuclei for producing superheavy elements. In this paper, we will study reactions of ^{244}Pu + ^{244}Pu, ^{238}U + ^{238}U and ^{197}Au + ^{197}Au at the energy range of $E_{\rm c.m.} = 800$–2000 MeV by the microscopically dynamical model. We will concentrate on: (1) the energy-dependence of the production probability of SHFs (here, SHFs are defined as the fragments with charge larger than or equal to 114), (2) the decay mechanism of the composite system of projectile and target, and (3) the binding energies and shapes of SHFs.

The Improved Quantum Molecular Dynamics (ImQMD) model[12–14] is employed in this study. Concerning the parameters for the energy density functional (see Ref. 15) a new set of parameter IQ2 is developed for studying fusion reactions of heavy systems. Like parameter set IQ1 given in Ref. 15, the IQ2 can also describe the fusion reactions of light and intermediate heavy nuclei and the properties of nuclear ground state (binding energies and the root mean square radii) well. In addition, with IQ2 both the capture cross-sections and the process of quasi-fission for fusion reactions of heavy nuclei can be described well. Figure 1 shows the capture cross-sections of the ^{16}O + ^{208}Pb and ^{48}Ca + ^{208} Pb at the energies near and above Coulomb barrier calculated with IQ2. One can see that the capture cross-sections

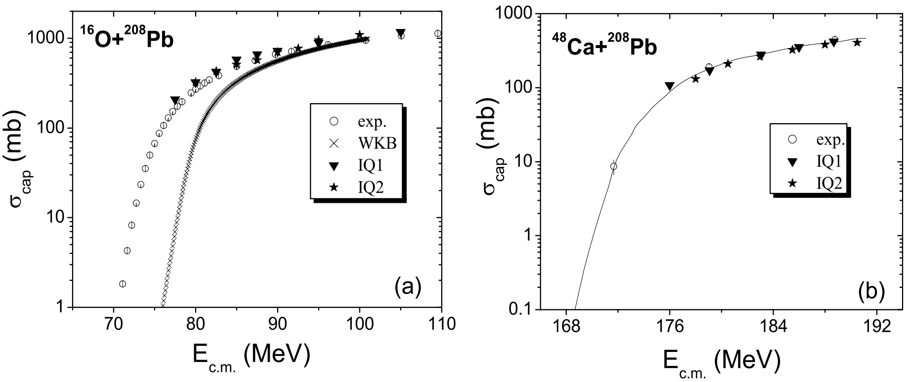

Fig. 1. The capture cross-sections of the reactions of ^{16}O + ^{208}Pb and ^{48}Ca + ^{208}Pb as a function of incident energies.

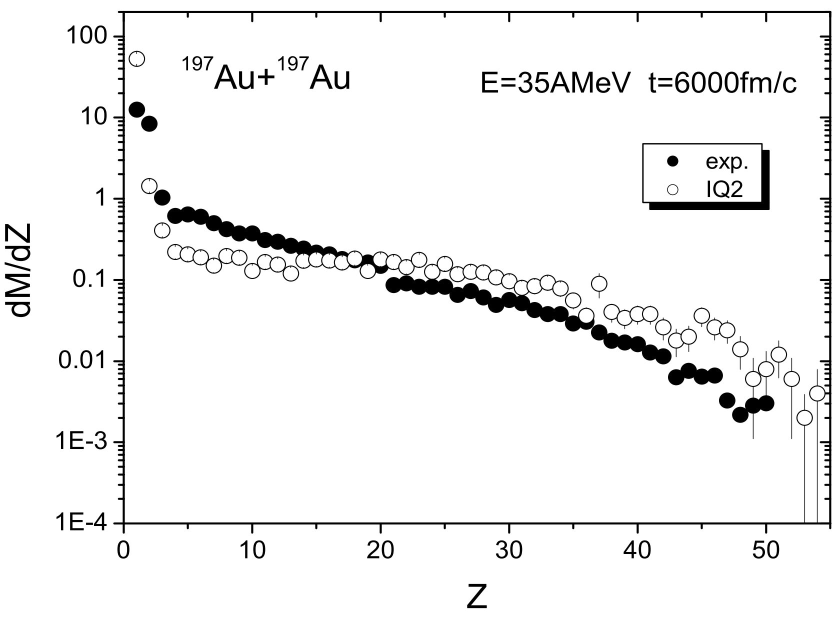

Fig. 2. The charge distribution of the central collisions of ^{197}Au+^{197}Au at 35 AMeV. The simulation ends at 6000 fm/c. The open and solid circles denote the calculated results and experimental data,[18] respectively.

calculated with IQ2 are in good agreement with the experimental data.[16,17] In order to apply the ImQMD model to study massive nuclear reactions we make further test, i.e. the charge distribution of products in reactions of heavy nuclei. As an example, in Fig. 2 we show the charge distribution of the products in the central collisions of the ^{197}Au + ^{197}Au at 35 AMeV with IQ2 and the comparison with experimental data.[18] The agreement is quite satisfactory. We have also calculated

Table 1. The model parameter IQ2.

α (MeV)	β (MeV)	γ	g_0 (MeV fm^2)	g_τ (MeV)	η	C_s (MeV)	κ_s (fm^2)	ρ_0 (fm^{-3})	c_0 (fm)	c_1 (fm)
−356	303	7/6	7.0	12.5	2/3	32.0	0.08	0.165	0.88	0.09

the charge distribution for reactions of light and intermediate mass systems and the nice agreement is also obtained. The study on the process of the quasi-fission in heavy nuclear fusion reactions will be given in other work. All the calculation results given in this work are obtained with IQ2 given in Table 1.

Now let us apply the ImQMD model to study strongly damped reactions of ^{244}Pu + ^{244}Pu, ^{238}U + ^{238}U and ^{197}Au + ^{197}Au at energy range of $E_{\mathrm{c.m.}} =$ 800–2000 MeV. The impact parameters are taken to be 1 fm and 3 fm. The simulation events are taken to be 500 for each energy point and impact parameter. The initial nuclei of projectile and target are prepared by the same procedure as that in Refs. 12 and 15. Since in this work we mainly concern the production of superheavy fragments, for saving CPU time (this type of calculation is very time consuming) the simulation procedure is carried out as follows: for each event, the simulation will be terminated if there is no fragment with $Z \geq 114$, otherwise the simulation will be continued until $t = 6000$ fm/c. In this way we can save a lot of CPU time.

Figure 3 shows the energy dependence of the production probability of SHFs for three reactions of ^{244}Pu + ^{244}Pu, ^{238}U + ^{238}U and ^{197}Au + ^{197}Au with impact parameter $b = 1$ fm. It shows that the production probability of SHFs strongly depends on the reaction systems. The production probability of ^{244}Pu + ^{244}Pu is the highest, and that of ^{238}U + ^{238}U is only half of the Pu + Pu's. For the ^{197}Au + ^{197}Au, the production probability of SHFs is about zero in the present calculations. The another pronounced feature of the figure is the narrowly peaked energy dependence of the production probability of SHFs. The location of the peak is at about $E_{\mathrm{c.m.}} = 1000$ MeV for ^{244}Pu + ^{244}Pu and at $E_{\mathrm{c.m.}} = 950$ MeV for the ^{238}U + ^{238}U. Although the location of peak energy may not be very precise in this primary calculation, such behavior of the energy dependence of the producton probability of superheavy fragments with $Z \geq 114$ should be correct. The narrowly peaked energy dependence means that it is crucial to select the correct incident energy in order to search for superheavy elements experimentally by using the approach of the strongly damped massive reactions. We notice that the energies adopted in the experiments done[8–10] in the '70s and '80s for the reaction of ^{238}U + ^{238}U are lower than the peak energy given in this work. The production probability of SHFs corresponding to the energies adopted in Refs. 8–10 is much lower than that at the peak energy. The behavior of the incident energy dependence of the production probability of SHFs with impact parameter $b = 3$ fm is quite similar to that with $b = 1$ fm. In the inserted figure of Fig. 3 the contour plot of mass and charge distributions of SHFs with $Z \geq 114$ for the reaction of ^{244}Pu + ^{244}Pu at the time $t = 6000$ fm/c is shown. For comparison, the experimental data of isotopes[2]

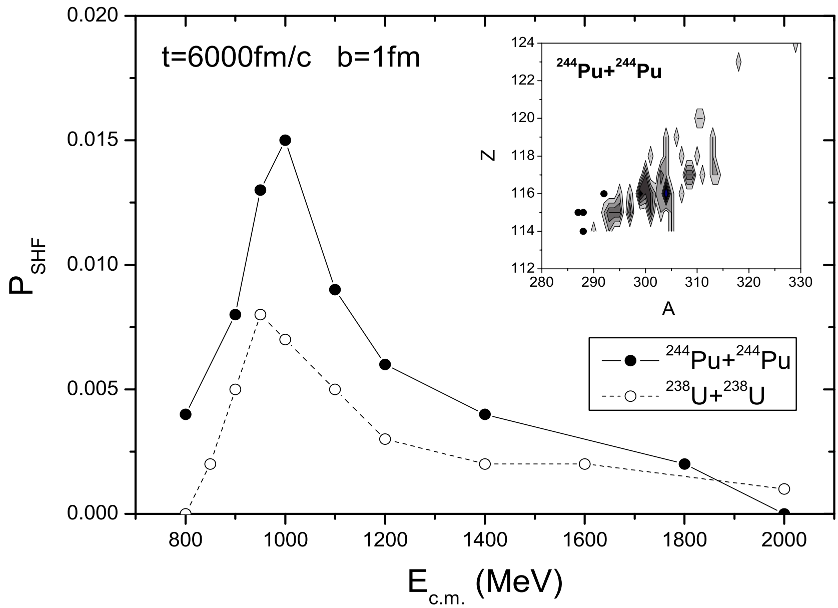

Fig. 3. The incident energy dependence of the production probability of superheavy fragments with $Z \geq 114$ in reactions of ^{244}Pu$+$^{244}Pu and ^{238}U$+$^{238}U with impact parameter $b = 1$ fm. The inserted figure is the contour plot of mass and charge distributions of the products with $Z \geq 114$ at the time $t = 6000$ fm/c for reaction of ^{244}Pu $+$ ^{244}Pu, in which the solid circles denote the experimental data of isotopes of ^{288}114, ^{287,288}115 and ^{292}116.[2]

of ^{288}114, ^{287,288}115 and ^{292}116 are also given in the figure by the black points. One can see from the figure that quite a few SHFs for the reaction of Pu $+$ Pu are very neutron-rich and the corresponding neutron-to-proton ratio is much higher than that of experimentally produced ^{288}114, ^{287,288}115 and ^{292}116. This character seems to be very useful for approaching to the center of superheavy "island".

Now let us discuss the decay mechanism of the composite system of projectile and target. Figure 4 shows the time evolution of the number of SHFs for the reaction of ^{244}Pu $+$ ^{244}Pu at $E_{\rm c.m.} = 1000$ MeV and the ^{238}U $+$ ^{238}U at $E_{\rm c.m.} = 950$ MeV with impact parameters $b = 1$ and 3 fm. The number of SHFs for each impact parameter given in Fig. 4 is obtained within 500 events. From Fig. 4 two stages of the decay process of the composite systems can be distinguished by very different decreasing slope, which implies very different decay mechanism of the composite system. From 1000 fm/c to 1500 fm/c, the number of SHFs decreases quickly as time increases. During this stage, the composite system firstly breaks up into two pieces, which we call the first decay. We have counted the number of the existing composite systems at different time. At $t = 1000$ fm/c, more than 60 percent of events are still in the stage of two reaction partners sticking together, then at 1200 fm/c, about 10–15 percent of events remain in this stage, and at 1500 fm/c few event remains in this stage, i.e. for almost all events, the composite system has

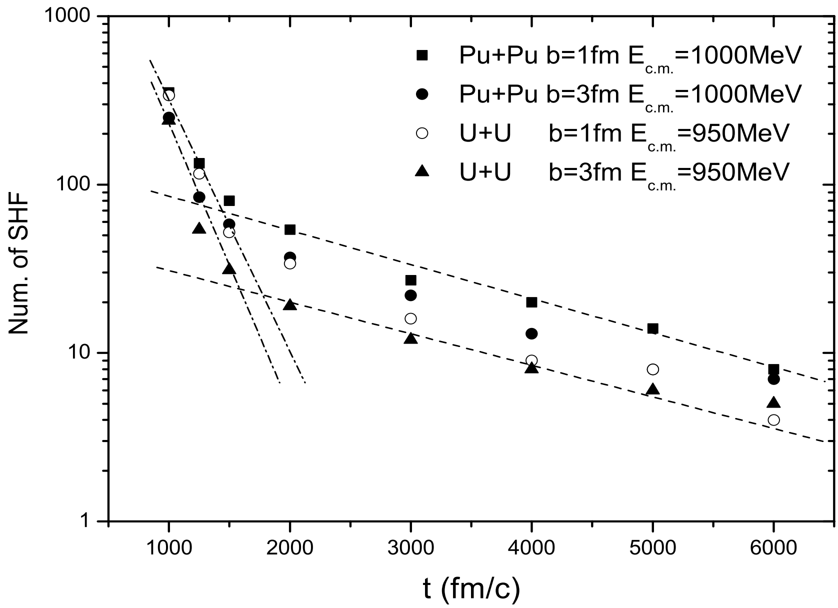

Fig. 4. The time evolution of the number of fragments with $Z \geq 114$ including the heavy residues of composite systems for the reactions of ^{244}Pu + ^{244}Pu at $E_{\rm c.m.} = 1000$ MeV and $b = 1$ and 3 fm, and for the reactions of ^{238}U + ^{238}U at $E_{\rm c.m.} = 950$ MeV and $b = 1$ and 3 fm from time $t = 1000$ to 6000 fm/c.

broken into two pieces. In most of the cases, the composite system breaks up into two pieces with size close to the initial nuclei. In a few cases it breaks up into two pieces with one heavier fragment and another smaller fragment, among which there exists possibility of producing one SHF and another one with $Z \sim 70$. Some of SHFs further break up into two pieces within several tens and hundreds fm/c and some of SHFs survive followed by the slow decreasing stage. In the second stage, the number of SHFs decreases slowly with time through emitting light charged particles, protons accompanying with neutron emission, and also through further breaking into two pieces. The slow reduction of the number of SHFs in the second stage seems to be helpful for the survival of SHFs.

In Fig. 5 we show the distributions of (a) the binding energies and (b) the R_z/R_ρ ratios of SHFs produced in the reaction of ^{244}Pu + ^{244}Pu at $E_{\rm c.m.} = 1000$ MeV and 950 MeV with $b = 1$ fm. The R_z is the long axis and the R_ρ is the short axis of SHF. The figure is drawn as the counting numbers of SHFs in 1000 reaction events versus (a) the binding energies and (b) the values of R_z/R_ρ. From Fig. 5(a) one sees that the binding energies of SHFs are broadly distributed. In the large binding energy side, the binding energy reaches about 7 MeV/nucleon, which is not far from the value of the predicted binding energy of the ground state of corresponding superheavy elements. The feature of the broad distribution of binding energies of SHFs tailing to large binding energy is favorable to have larger surviving probability

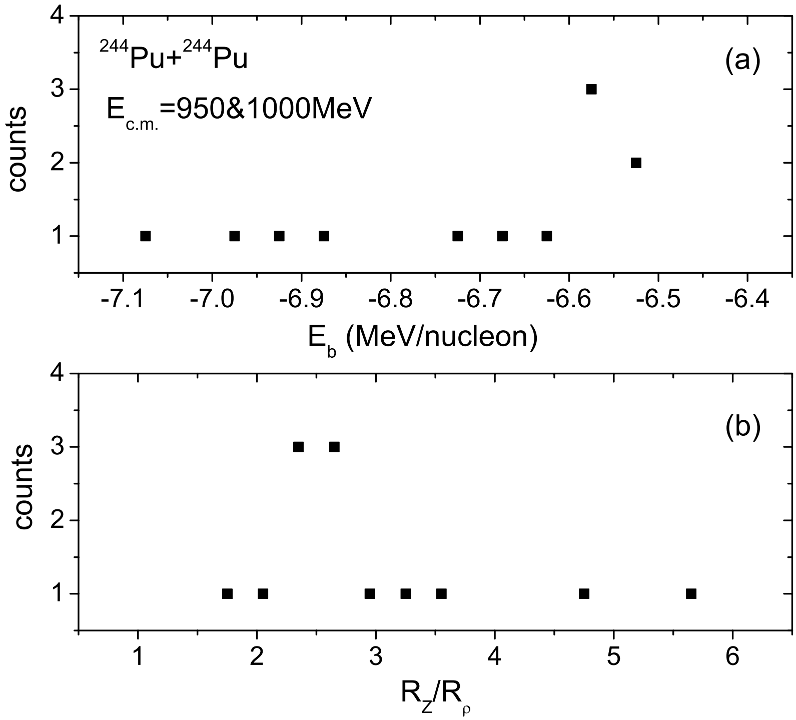

Fig. 5. The distributions of (a) the binding energies and (b) the $R_z/R\rho$ of SHFs produced in the reaction of ^{244}Pu + ^{244}Pu at $E_{\mathrm{c.m.}} = 1000$ MeV and 950 MeV, and $b = 1$ fm. The counting number is obtained in 1000 reaction events.

of SHF. From Fig. 5(b) one sees that the SHFs are strongly deformed. In most of the cases, they are about super-deformation or even hyper-deformation. For those SHFs with super-deformed shape it is found that there are some bubbles in the density distribution (bubble-like). However, there also exist some SHFs with exotic shapes with $R_z/R_\rho \geq 4$. The shape of these SHFs is band-like. It is very surprising that the shape of SHFs has such exotic form. Such exotic forms of SHFs may be attributed to the huge electric charge. Associating the recent structure studies of superheavy nuclei within the RMF and HFB theory[19–21] in which very large deformed isometric states were predicted, the exotic form of SHFs seems to be understandable. However, the subject of exotic (bubble, band-like) configurations in super-heavy elements in which the interplay between Coulomb interaction and nuclear interaction becomes very important needs to be further studied.

In summary, here we have studied the strongly damped reactions of ^{244}Pu + ^{244}Pu, ^{238}U + ^{238}U and ^{197}Au + ^{197}Au by using the ImQMD model. It is found that the production probability of SHFs strongly depends on the reaction systems and the incident energies. The production probability of SHFs in the ^{244}Pu + ^{244}Pu reaction is much higher than that in the ^{238}U + ^{238}U reaction, and no production of SHF has been found for the ^{197}Au + ^{197}Au reaction in the present study.

The incident energy dependence of the production probability of SHFs is narrowly peaked. The peak energy depends on the reaction system. It means that the suitable selection of the incident energy is very important in experimentally searching super-heavy elements by means of strongly damped massive nuclear reactions. The decay process of the composite system is studied. There are two stages in the decay of the composite system. The first one is a fast break process of the composite system. In most cases, the composite system breaks into two pieces of which the sizes are close to initial nuclei. Occasionally, it becomes one super-heavy fragment which will further break into two pieces and a small piece as well. The second stage is a slow process of emitting light charged particles and nucleons as well as further breaking of SHFs. The binding energies and the shapes of SHFs are studied. The binding energies of SHFs are distributed broadly. Its tail at large binding energy side is not far from the predicted binding energy of the corresponding SHE and therefore is favorable to producing superheavy elements. In most cases the shapes of SHFs are strongly deformed. It seems to us that the study on the structure and the fission barrier for such exotic shapes due to extremely strong Coulomb effect is urgently required in order to learn if the stabilized superheavy nuclei can be eventually reached or not. This study is still in progress.

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