Search for possible way of producing super-heavy elements

–Dynamic study on damped reactions of $^{244}\text{Pu} + ^{244}\text{Pu}$, $^{238}\text{U} + ^{238}\text{U}$ and $^{197}\text{Au} + ^{197}\text{Au}$

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Abstract

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

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There are two approaches proposed for producing superheavy elements (SHE) through accelerators. One approach of the complete fusion reaction is very successful in producing SHE. Since the 70’s the elements from \( Z = 107 \) to 116 were synthesized in the ”cold fusion” reactions with lead and bismuth targets \([1]\) and ”hot fusion” reactions with actinide targets \([2]\). A lot of research work on this approach have been done both experimentally and theoretically. However, it is well known that further experimental extension of the region of SHE to the central of superheavy ”island” with 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 explore new more neutron-rich superheavy regions the 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 superheavy elements is the strongly damped collision process between massive nuclei, for instance \(^{238}\text{U} + ^{238}\text{U}\). The strongly damped collisions between \(^{238}\text{U} + ^{238}\text{U}\) and \(^{238}\text{U} + ^{248}\text{Cm}\) at the energies near Coulomb barrier were studied in 70s and early 80s for searching superheavy nuclei \([4, 5, 6, 7, 8]\). It was reported in \([9]\) that for \(^{238}\text{U} + ^{238}\text{U}\) at \( E = 7.5 \text{MeV/nucleon} \), the upper limit of the cross-section for producing superheavy elements was about \( 2 \times 10^{-32} \text{cm}^2 \) for half lives between milliseconds and month by looking for spontaneous events from reaction products. In \([10]\) the reaction of \(^{238}\text{U} + ^{248}\text{Cm}\) at \( 7.4 \text{MeV/nucleon} \) was studied and it was found that cross sections for \(^{100}\text{Fm}, ^{99}\text{Es}, \) and \(^{98}\text{Cf}\) with target of \(^{248}\text{Cm}\) are three to four orders of magnitude higher than with \(^{238}\text{U}\). It means that the strongly damped reaction with two nuclei heavier than uranium could be very benefit for producing superheavy nuclei. Compared with the approach of complete fusion this approach was much less studied. Furthermore, considering the fact that the fast development of the experimental facilities for searching superheavy nuclei and deepening understanding of structure properties of superheavy nuclei in recent years \([11, 12, 13]\), the approach of the strongly damped massive nuclear reaction should be further studied. In this letter we will study reactions of \(^{244}\text{Pu} + ^{244}\text{Pu}\), \(^{238}\text{U} + ^{238}\text{U}\) and \(^{197}\text{Au} + ^{197}\text{Au}\) at the energy range of \( E_{c.m.} = 800 \text{MeV-2000 MeV} \) by the microscopically dynamical model. We will concentrate on 1)the energy-dependence of the probability of producing the superheavy fragments (SHF) which 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 the superheavy fragments.

The Improved Quantum Molecular Dynamics (ImQMD) Model [14, 15, 16] is employed in this study. The application of this model to light and intermediate mass nuclear fusion reaction was given in [17]. In order to apply it to the study of massive nuclear reactions we first make test if this model is suitable for heavy nuclear fusion reactions. Concerning the parameters for the energy density functional (see [17]) a new set of parameter IQ2 is developed with which both the capture cross sections and the process of quasi-fission for heavy nuclear fusions can be described well, in addition to the parameter set of IQ1 used in [17]. The study on the process of the quasi-fission in heavy nuclear fusion reactions will be given in other work. Both IQ2 and IQ1 can describe the fusion reaction of light and intermediate nuclei well. All the calculation results given in this work are obtained with IQ2, which is given in table 1. Fig.1 shows the capture cross sections of the $^{16}\text{O}+^{208}\text{Pb}$ and $^{48}\text{Ca}+^{208}\text{Pb}$. One can see that the capture cross sections obtained from the ImQMD model are in good agreement with the experimental data [18, 19] at the energies near and above Coulomb barrier. Another relevant test to our present study is the charge distribution of products in reactions between two heavy nuclei. As an example in Fig.2 we show the charge distribution of products in the central collisions of the $^{197}\text{Au}+^{197}\text{Au}$ at 35 AMeV and compared with experimental data[20]. The agreement is quite satisfied. We have also calculated the charge distribution for reactions of light and intermediate mass systems. The nice agreement is also obtained, which will shown in other publications.

Now let us apply the ImQMD model to strongly damped reactions of $^{244}\text{Pu}+^{244}\text{Pu}$, $^{238}\text{U}+^{238}\text{U}$ and $^{197}\text{Au}+^{197}\text{Au}$ at energy range of $E_{c.m.}=800\text{ MeV}-2000\text{ MeV}$. 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 in ref. [14, 17]. Since in this work we mainly concern the production of the superheavy fragments, for saving CPU time (this kind calculation is very time consuming) the simulation procedure is carried out as follows: In each event, the simulation is continued until $t=6000$ $fm/c$ if there exists a superheavy fragment . As soon as it is found that there no superheavy fragment exists then the simulation is terminated. In this way we can save a lot of CPU time.

Fig. 3 shows the energy dependence of the probability of producing superheavy fragments for three reactions of $^{244}\text{Pu}+^{244}\text{Pu}$, $^{238}\text{U}+^{238}\text{U}$ and $^{197}\text{Au}+^{197}\text{Au}$ at impact parameter
$b=1 \text{ fm}$. It shows us that among these three reactions, the yield of superheavy fragments produced in $^{244}{Pu}+^{244}{Pu}$ is the highest, and that produced in $^{238}{U}+^{238}{U}$ is only half of the Pu+Pu’s yield. For the $^{197}{Au}+^{197}{Au}$, we do not find any reaction event which forms a product with $Z \geq 114$ in the present calculations. The very pronounced feature of the figure is that it is narrowly peaked in the energy dependence of the production probability of SHFs and the location of the peak is at about $E_{c.m.} = 1000 \text{ MeV}$ for the $^{244}{Pu}+^{244}{Pu}$ and at $E_{c.m.} = 950 \text{ MeV}$ for the $^{238}{U}+^{238}{U}$. Although the precise location of peak energy may not be very definite in this primary calculation, such behavior of the energy dependence of the probability of superheavy fragments with $Z \geq 114$ should be correct. The narrow peak means that it is crucial to select the correct incident energy in order to search superheavy elements experimentally by using the approach of the strongly damped massive reactions.

We notice that the energies used in the experiments done in the 70s and 80s [8, 9, 10] are lower than the peak energy for the reaction of $^{238}{U}+^{238}{U}$. The production probability of SHFs corresponding to the energies used in [8, 9, 10] is much lower than that at the peak energy. The results about the incident energy dependence of the probability of producing SHFs at impact parameter $b=3 \text{ fm}$ are quite similar with at $b=1 \text{ fm}$. For surveying the proton and neutron numbers in SHF obtained we draw the contour plot of mass and charge distributions of SHFs with $Z \geq 114$ at the time $t=6000 \text{ fm/c}$ for the reaction of $^{244}{Pu}+^{244}{Pu}$ in the inserted figure of Fig.3. For comparison, the experimental data of isotopes of $^{288}114, ^{287}115$ and $^{292}116$ [2] are also given in the figure by the black points. One can see from the figure that quite a few SHFs in the reaction of Pu+Pu are very neutron rich and the corresponding neutron-to-proton ratio is much higher than that obtained experimentally. This character is 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. Fig.4 shows the time evolution of the number of SHFs for the reaction of $^{244}{Pu}+^{244}{Pu}$ at $E_{c.m.}=1000 \text{ MeV}$ and the $^{238}{U}+^{238}{U}$ at $E_{c.m.}= 950 \text{ MeV}$ with impact parameters $b=1, 3 \text{ fm}$. The number of SHFs is obtained within 500 events for each impact parameter. 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 $\text{ fm/c}$ to 1500 $\text{ fm/c}$, the number of SHFs decreases quickly with time increasing. 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 $1500 \, fm/c$ only few remains in this stage, i.e. almost all composite systems break up into two pieces. In the most of 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, and in this case there is possibility to produce one SHF and its partner with $Z \sim 70$. Then some of SHFs further break up into two pieces quickly 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. In this stage, the number of SHFs is reduced through emitting light charged particles, protons accompanying with neutron emission, and also still breaking into two pieces process. The slow reduction of the number of SHFs in the second stage seems to be benefit to the survival of SHFs.

In Fig.5 we show the distributions of both a)the binding energies and b)the $R_z/R_\rho$ of SHFs produced in the reaction of $^{244}$Pu+$^{244}$Pu at $E_{c.m.}=1000 \, MeV$ and $950 \, MeV$, and $b=1 \, fm$. The $R_z$ is the long axis and $R_\rho$ is the short axis of SHF. The figure was drawn as the count number in 1000 reaction events vs a)the binding energies and b)the values of $R_z/R_\rho$. From Fig.5a) 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 broad distribution of binding energies of SHFs tailing to large binding energy is favorable to have larger surviving probability of SHF. From Fig.5b one sees that the SHFs are strongly deformed. In the most of cases, they are at 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 exotic forms among the produced SHFs with $R_z/R_\rho \geq 4$. The shape of these SHF 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 \cite{21,22,23} in which very large deformed isomeric 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, within the microscopically dynamical description of the $^{244}\text{Pu}+^{244}\text{Pu}$, $^{238}\text{U}+^{238}\text{U}$ and $^{197}\text{Au}+^{197}\text{Au}$ reactions we explore the dynamic process of the strong damped reaction and find that the production probability of superheavy fragments with $Z \geq 114$ in the $^{244}\text{Pu}+^{244}\text{Pu}$ reaction is much higher than that in the $^{238}\text{U}+^{238}\text{U}$ reaction, and no product of SHF has been found for the $^{197}\text{Au}+^{197}\text{Au}$ reaction in the present study. The narrowly peaked energy dependence of the production probability of SHFs shows that the suitable selection of the incident energy is very important for searching for super-heavy elements by means of strongly damped massive nuclear reactions. The dynamical study shows that there are two different kind mechanisms in the decay of the composite system. The first stage is a fast process composed by breaking the composite system into two pieces and further breaking the heavy fragments into two small pieces. The second stage is a slow process by emitting light charged particles and nucleons as well as further breaking of SHFs. This study also explores that 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. The shape of SHFs is also studied and turns out to be strongly deformed. It seems to us that the study on the structure and the fission barrier for such exotic shape 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.

**ACKNOWLEDGMENTS**

This paper is supported by the China Postdoctoral Science Foundation, the National Natural Science Foundation of China under Grant Nos. 10175093, 10175089, 10235030, 10235020, 10347142, Major State Basic Research Development Program under Contract No. G20000774 and CAS-grant KJ CX2-SW-N02.
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CAPTIONS

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 are ended at 6000 $fm/c$. The open and solid circles denote the calculated results and experimental data [20], respectively.

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 at 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 $t=6000$ $fm/c$, in which the solid circles denote the experimental data of isotopes of $^{288}114$, $^{287}115$ and $^{292}116$ [2].

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 $E_{c.m.}=1000$ $MeV$ and $b=1$ and $3$ $fm$, and for the reactions of $^{238}$U+$^{238}$U at $E_{c.m.}=950$ $MeV$ and $b=1$ and $3$ $fm$ from time $t=1000$ to $6000$ $fm/c$.

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 $E_{c.m.}=1000$ $MeV$ and 950 $MeV$, and $b=1$ $fm$. The count number is obtained for 1000 reaction events.

Table.1  The model parameter IQ2.
\( \sigma_{\text{cap}} \) (mb)

\( E_{\text{c.m.}} \) (MeV)

\( ^{16}\text{O}^{208}\text{Pb} \)

(a)

\( ^{48}\text{Ca}^{208}\text{Pb} \)

(b)

- exp.
- WKB
- IQ1
- IQ2

\( \sigma_{\text{cap}} \) (mb)

\( E_{\text{c.m.}} \) (MeV)
|         | $\alpha$ (MeV) | $\beta$ (MeV) | $\gamma$ | $g_0$ (MeV) | $g_\tau$ (MeV) | $\eta$ | $C_s$ (MeV) | $\kappa$ (fm$^2$) | $\rho_0$ (fm$^3$) | $c_0$ (fm) | $c_1$ (fm) |
|---------|----------------|---------------|---------|-------------|---------------|--------|------------|-------------------|------------------|------------|------------|
| IQ2     | -356           | 303           | 7/6     | 7.0         | 12.5          | 2/3    | 32.0       | 0.08              | 0.165            | 0.88       | 0.09       |
$^{197}\text{Au} + ^{197}\text{Au}$  
$E=35\text{AMeV}$  $t=6000\text{fm/c}$

$dM/dZ$

$Z$
t = 6000 fm/c  \( b = 1 \) fm

- \( ^{244}\text{Pu}^+^{244}\text{Pu} \)
- \( ^{238}\text{U}^+^{238}\text{U} \)

\( E_{\text{c.m.}} \) (MeV)
$\text{Num. of SHF}$

$\text{Pu+Pu b=1fm E}_{c.m.}=1000\text{MeV}$

$\text{Pu+Pu b=3fm E}_{c.m.}=1000\text{MeV}$

$\text{U+U b=1fm E}_{c.m.}=950\text{MeV}$

$\text{U+U b=3fm E}_{c.m.}=950\text{MeV}$

$t (\text{fm/c})$
(a) 

\[ ^{244}\text{Pu} + ^{244}\text{Pu} \]

\[ E_{\text{c.m.}} = 950 \& 1000 \text{MeV} \]

(b) 

Counts vs. \( R_z/R_\rho \)