Effects of N/Z on survival probability of heavy nuclei *

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Abstract The excitation functions of the evaporation residue formation probability of three heavy nuclei ^{194}Pb, ^{200}Pb and ^{206}Pb are calculated by using a Langevin equation coupled with a statistical decay model. The results show that the neutron-to-proton ratio (N/Z) of a compound nucleus has an effect on survival probability and this effect becomes larger with increasing N/Z. This is because the fission barrier and the pre-saddle particle emission depend on the N/Z ratio of the system.

Key words N/Z effect, survival probability, pre-saddle particle multiplicity, Langevin equation

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1 Introduction

In recent years, by measuring the excitation function of light particle emission in the fission process and evaporation residue cross section, it is well established that dissipation enhances pre-scission particle multiplicity and evaporation residue formation probability relative to expectations based on the statistical model description[1—7]. Although it turns out that the evaporation residue cross section is a more sensitive probe of nuclear dissipation than light particles[8], it is only a very small fraction of total fusion cross section[9, 10], which is, to a considerable extent, because of small survival probability of heavy compound systems. Considering that increasing the survival probability will usually increase the evaporation residue cross section and hence facilitate the experimental analysis and the theoretical investigation, studying those factors that affect survival probability, besides dissipation, are therefore interesting and necessary. In this work, the Langevin equation is employed to calculate the excitation functions of survival probability of ^{194}Pb, ^{200}Pb and ^{206}Pb nuclei in order to explore the effect of the neutron-to-proton ratio (N/Z) of the system on the survival probability.

2 Theoretical model

A combined dynamical Langevin equation and a statistical model (CDSM)[9] are utilized to study the survival probability. Here a brief introduction to the model is given. The dynamical part of the CDSM model is described by the Langevin equation which is expressed by the free energy F. In the Fermi gas model, F is related to the level density parameter $a(q)$[11] by

$$F(q,T)=V(q)-a(q)T^2\,, \qquad (1)$$

where $V(q)$ is the fission potential and T is the nuclear temperature.

The one-dimensional overdamped Langevin equation reads

$$\frac{\mathrm{d}q}{\mathrm{d}t}=-\frac{1}{M\beta(q)}\frac{\partial F(q,T)_T}{\partial q}+\sqrt{D(q)}\Gamma(t)\,, \qquad (2)$$

where q is the dimensionless fission coordinate and is defined as half of the distance between the center of mass of the future fission fragments divided by the radius of the compound nucleus. $\beta(q)$ is the reduced friction parameter. The fluctuation strength coefficient $D(q)$ can be expressed according to the fluctuation-dissipation theorem as

$$D(q)=\frac{T}{M\beta(q)}\,, \qquad (3)$$

where M is the inertia parameter and is independent of q. $\Gamma(t)$ is a time-dependent stochastic variable with the Gaussian distribution. Its average and correlation function are written as

$$\langle\Gamma(t)\rangle=0$$

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$$\langle \Gamma(t)\Gamma(t')\rangle = 2\delta(t-t')\,. \tag{4}$$

The potential energy $V(Z,A,L,q)$ is obtained from the finite-range liquid-drop model[12]

$$V(A,Z,L,q) = a_2\left[1-k\left(\frac{N-Z}{A}\right)^2\right]A^{2/3}[B_s(q)-1]+ c_3\frac{Z^2}{A^{1/3}}[B_C(q)-1]+c_r L^2 A^{-5/3}B_r(q)\,, \tag{5}$$

where $B_s(q)$, $B_C(q)$ and $B_r(q)$ are the surface, Coulomb, and rotational energy terms, respectively, which depend on the deformation coordinate q. a_2, c_3, k, and c_r are parameters not related to q[9].

After the fission probability flow over the fission barrier attains its quasi-stationary value, the decay of the compound system is described by a statistical model, which is called statistical part of CDSM. In the CDSM model, the light-particle evaporation is coupled to the fission mode by a Monte Carlo procedure allowing for the discrete emission of light particles. The widths for light particles (n, p, α) are given by the parametrization of Blann[13].

3 Results and discussions

In the current work three Pb systems are chosen as examples for the study of N/Z effect in the framework of CDSM. The N/Z values for ^{194}Pb, ^{200}Pb and ^{206}Pb are 1.365, 1.439 and 1.512, respectively. Additionally, to accumulate sufficient statistics 10^7 Langevin trajectories are simulated though doing so needs much CPU time.

In Ref. [9], in order to simultaneously reproduce the pre-scission particle multiplicity and survival probability, a special form of deformation-dependent friction was adopted, which reads

$$\beta(q) = \begin{cases} \beta_{0q} & \text{if } q \leqslant q_{\rm neck}, \\ \beta_{0q} + \dfrac{\beta_{\rm sc}-\beta_{0q}}{(q_{\rm sc}-q_{\rm neck})}(q-q_{\rm neck}) & \text{if } q_{\rm neck} < q \leqslant q_{\rm sc}. \end{cases} \tag{6}$$

This kind of friction is weak for compact shapes, $\beta_{0q} = 2\text{zs}^{-1}$. After the necking in is starting (at $q_{\rm neck} = 0.6$), the friction is assumed to increases linearly up to the value of $\beta_{0q} = 30\text{zs}^{-1}$ at scission (at $q_{\rm sc} = 1.2$). Here, $1\text{zs} = 10^{-21}$s. Such a friction is used in the present calculation.

Figure 1 shows the evaporation residue formation probability ($P_{\rm sur}$) of the ^{194}Pb, ^{200}Pb and ^{206}Pb nuclei as a function of excitation energy. As can be seen, the survival probability of these systems exhibits an analogous behavior with energy, that is, with the rising of the energy the survival probability decreases and then rises slightly with further increasing energy. Also, the symbol △ is above ◯, and the latter is above □. This means that $P_{\rm sur}$ increases with the ratio of N/Z of the system. This is caused by two reasons. One reason stems from the significant difference of pre-saddle particles, especially neutrons, of three Pb systems. To better understand this point, we display in Table 1 and Fig. 2 the multiplicity of pre-saddle charged particles ($p_{\rm gs}$ and $\alpha_{\rm gs}$) and neutrons ($n_{\rm gs}$) of the nuclei ^{194}Pb, ^{200}Pb and ^{206}Pb. It is obvious that ^{194}Pb evaporates the least neutrons and the most charged particles, which is opposite to the case of ^{206}Pb. In addition, by comparing Table 1 and Fig. 2, we notice that not only the magnitudes of charged particles but also their differences between two Pb nuclei are much smaller than the case of neutrons. For example, at $E^* = 92$ MeV the differences of $p_{\rm gs}$ and $\alpha_{\rm gs}$ between ^{194}Pb and ^{206}Pb are 0.0464 and 0.0038, respectively, far below the case of neutrons, where the corresponding difference amounts to 1.504.

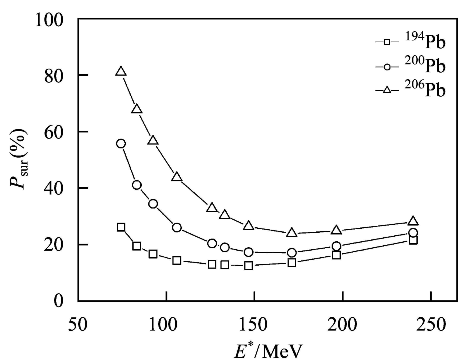

Fig. 1. The evaporation residues formation probability of compound nuclei ^{194}Pb, ^{200}Pb and ^{206}Pb as a function of excitation energy.

Table 1. The calculated pre-saddle multiplicity of protons ($p_{\rm gs}$) and α-particle ($\alpha_{\rm gs}$) of ^{194}Pb, ^{200}Pb and ^{206}Pb nuclei at different excitation energies.

E^*/	^{194}Pb		^{200}Pb		^{206}Pb	
MeV	$p_{\rm gs}$	$\alpha_{\rm gs}$	$p_{\rm gs}$	$\alpha_{\rm gs}$	$p_{\rm gs}$	$\alpha_{\rm gs}$
74	0.02680	0.01650	0.00427	0.00281	0.00007	0.00005
84	0.04010	0.03120	0.00879	0.00829	0.00147	0.00169
92	0.04970	0.04210	0.01380	0.01450	0.00332	0.00396
106	0.06850	0.06270	0.02350	0.02710	0.00695	0.00995
126	0.09410	0.08880	0.04030	0.04840	0.01460	0.02200
133	0.10300	0.09800	0.04640	0.05630	0.01800	0.02650
147	0.12000	0.11300	0.05850	0.07200	0.02470	0.03730
171	0.16100	0.14900	0.08860	0.10700	0.04270	0.06260
196	0.22000	0.19700	0.13400	0.15500	0.07000	0.09900
240	0.32900	0.28700	0.22500	0.24000	0.13200	0.17300

This comparison clearly indicates that when we discuss the effect of pre-saddle particle emission on the survival probability, the emphasis should be placed on the difference of neutron multiplicity. Fig. 2 gives the pre-saddle emitted neutrons as a function of excitation energy. Apparently, the difference of N/Z of three Pb systems yields a difference of emitted pre-saddle neutrons. This has an important consequence for the change of $P_{\rm sur}$ with N/Z. As mentioned before, the higher the N/Z is, the more the pre-saddle neutrons are emitted and hence the more the angular momenta and the excitation energy are carried away from the compound system. As a result, the spin of compound nucleus and its excitation energy are much reduced at a larger N/Z value. Both aspects decrease the fission probability[9, 14]. In other words, they increase evaporation residue formation probability.

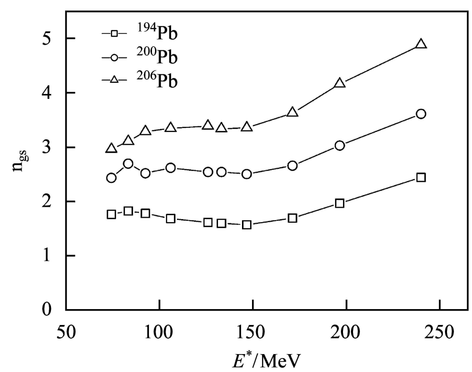

Fig. 2. The pre-saddle neutron multiplicity of compound nuclei ^{194}Pb, ^{200}Pb and ^{206}Pb as a function of excitation energy.

The second reason is that the fission barrier is a function of N/Z. From Fig. 3 one can observe that the higher the N/Z is, the larger the fission barrier is. Here, the fission barrier has two important effects on the survival probability. One direct effect is that, as expected, the higher barrier lowers the fission probability and increases the survival probability. A side effect is that the higher barrier protects the decay system from disintegrating quickly. That means the compound system stays longer inside the saddle point as the fission barrier becomes larger. A longer time will provides more time to evaporate neutrons, and this strengthens the N/Z effect on neutron emission. As more neutrons are emitted within the barrier, it lowers the angular momentum of the system and the excitation energy used in the compound nucleus decay. These two factors are favorable for the formation of evaporation residues. Note that at the present energy domain, shell corrections to fission barrier are basically washed out. Moreover, as the magnitude of the shell corrections to the fission barrier gradually becomes larger for the nuclei ^{194}Pb, ^{200}Pb and ^{206}Pb, thus according to the analysis demonstrated above, the inclusion of shell corrections will enhance the N/Z effect on the survival probability.

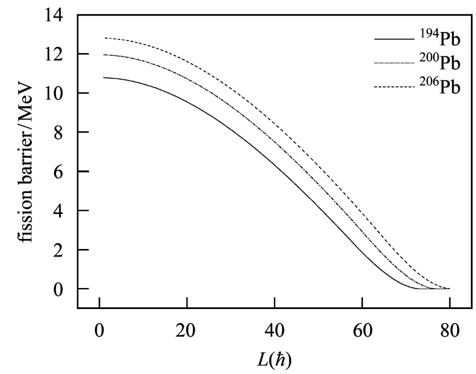

Fig. 3. The fission barrier of compound nuclei ^{194}Pb, ^{200}Pb and ^{206}Pb as a function of angular momentum.

In Fig. 1, the excitation function of the survival probability is also depicted. Evidently, the gap of $P_{\rm sur}$ among three Pb nuclei at a lower excitation energy is wider than that at a higher energy, which means that the N/Z effect on the survival probability becomes weak with the increment of the energy. It is because at a higher E^*, the excitation energy influences the competition between particle emission and fission more strongly than that of the differences of the particle separation energy and the fission barrier that arise from the N/Z difference of three Pb systems.

4 Summary and conclusions

In summary, by computing the evaporation residue formation probability of ^{194}Pb, ^{200}Pb and ^{206}Pb systems with the Langevin equation, it is found that the neutron-to-proton ratio of the system affects the formation probability and that this probability becomes larger with increasing N/Z. This is a consequence of the N/Z effect on the fission barrier and the pre-saddle particle emission. High excitation energy weakens this N/Z effect.

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