Vol 16 No 8, August 2007
1009-1963/2007/16(08)/2338-05

Chinese Physics

© 2007 Chin. Phys. Soc.
and IOP Publishing Ltd

Optimal reactions for synthesis of nuclides of element 108*

Liu Zu-Hua (刘祖华)[a)†] and Zhou Hong-Yu(周宏余)[b)]

[a)] *China Institute of Atomic Energy, Beijing* 102413, *China*
[b)] *Key Laboratory of Beam Technology and Material Modification of Ministry of Education, Beijing Normal University, Beijing* 100875, *China*

(Received 23 February 2006; revised manuscript received 4 December 2006)

The cross sections for the production of nuclides of element 108 via hot fusion evaporation reactions are studied using a two-parameter Smoluchowski equation. The optimal reactions for the synthesis of new nuclides of element 108 with mass numbers from 266 to 271 are suggested. The macroscopic-microscopic approach predicts a strong deformed shell closure at $Z \approx 108$ and $N = 162$. The synthesis of more nuclides of element 108 is meaningful to the confirmation of the existence of this deformed shell closure.

Keywords: diffused barrier, Smoluchowski equation, superheavy nuclei
PACC: 2410, 2460, 2570J, 2790

1. Introduction

The superheavy elements (SHE) are of great interest in the fundamental study of the stability limit of heavy nuclei.[1,2] The nuclear shell model predicts the next double magic shell closure beyond ^{208}Pb at $Z = 114 - 126$ and $N = 172 - 184$.[3] To date, the region of the 'island of superheavy nucleus' extends up to element $Z = 116$ or probably $Z = 118$ using the ^{48}Ca-induced hot fusion reactions with actinide targets.[4] Additionally, the macroscopic–microscopic approach[5] predicts a strong deformed shell closure at $Z \approx 108$ (Hs) and $N = 162$. Three isotopes of element 108 have been produced in 'cold fusion'[6,7] and 'hot fusion'.[8] These are ^{264}Hs[7] with half-life $T_{1/2} \approx 0.08$ ms, ^{265}Hs[7] with $T_{1/2} = 1.8$ ms, and ^{267}Hs with $T_{1/2} = 19$ ms[8]. It is worth noting that as Hs increases three neutrons, i.e. the number of neutrons increases from $N = 156$ (^{264}Hs) to $N = 159$ (^{267}Hs), the half-life increases by more than two orders of magnitude. This provides an indication of the existence of a relatively strongly bound 'double-magic' deformed shell at $Z \approx 108$ and $N = 162$. In addition, Dullman *et al*[9] claimed that they had synthesized ^{269,270,271}Hs. In order to confirm the existence of this 'double-magic' deformed shell, it is necessary to synthesize more nuclides of element 108, and to investigate their structures experimentally.

The cross sections for the production of superheavy nuclei are on the picobarn (10^{-12} barn) level. Due to the extremely small cross section, the production of superheavy nuclei is quite difficult experimentally. In order to successfully synthesize the superheavy nucleus it is very important to select the optimal combination of target and projectile, and the most favourable bombarding energy. In this paper, we will present such optimal selections for the synthesis of the new nuclides of element 108. In the following, we treat the whole reaction process in three stages: the capture, formation of spherical compound nucleus, and nucleus surviving against fission decay and cooling down by particle evaporation.

2. Capture cross section

The capture cross section for the transition of the colliding nuclei over the Coulomb barriers is given by

$$\sigma_{\rm capt}(E) = \pi\lambda\!\!\!^{-2} \sum_{J=0}^{\infty} (2J+1) T(E, J), \qquad (1)$$

where $\lambda\!\!\!^{-}$ is the wave-length, and J is the angular momentum of the system. The transmission probability is calculated using a 'diffused-barrier formula'[10,11]

*Project supported by the National Natural Science Foundation of China (Grants Nos 10235020 and 10235030).
†E-mail: zhliu@iris.ciae.ac.cn

$$T(E,J)=\int_{B_0-E_{\rm th}}^{B_0+E_{\rm th}}P(B)\left[1+\exp\left\{\frac{2\pi}{\eta\omega_{\rm B}}\left(B+\frac{J(J+1)\hbar^2}{2\mu R_{\rm B}^2}-E\right)\right\}\right]^{-1}{\rm d}B. \quad (2)$$

The normalized barrier distribution $P(B)$ is assumed to have a Gaussian shape with a threshold value $E_{\rm th}$[12] and average barrier height B_0. The barrier radius $R_{\rm B}$ and thickness $\hbar\omega_{\rm B}$ are calculated at the average barrier B_0. As an example, we present in Fig.1 the capture excitation function for the system ^{26}Mg+^{244}Pu.

3. Competition between compound nucleus formation and quasifission

The system, originally in the fusion valley, is injected into the asymmetric fission valley when captured. The dynamics in the second stage is assumed to be described by a two-parameter Smoluchowski equation:[13,14]

$$\frac{\partial W(x,y,t)}{\partial t}=\left[L_x(x,y)+\gamma L_y(x,y)\right]W(x,y,t). \quad (3)$$

Here $x=s$ denotes the relative length between the effective surfaces of the approaching nuclei, and $y=N$ represents the neutron number of the light nuclei. The operators L_x and L_y are defined in Refs.[13,14].

In Eq.(3) we have introduced a parameter γ to indicate the different time scales. In the limit $\gamma\gg 1$, which is consistent with the assumption that y decays very rapidly to an equilibrium value $y_{\rm eq}$, Eq.(3) can be reduced to a one-parameter Smoluchowski equation,[13,14]

$$\frac{\partial}{\partial t}W(x,t)=L_{0,0}W(x,t). \quad (4)$$

The operator $L_{0,0}$ has the form

$$L_{0,0}=-\frac{\partial}{\partial x}\bar{D}_x(x)+D_{xx}\frac{\partial^2}{\partial x^2}, \quad (5)$$

with

$$\bar{D}_x(x)=\int D_x(x,y)\,\phi_0(y,x)\,{\rm d}y. \quad (6)$$

Here $\phi_0(y,x)$ is the eigenfunction of the operator $L_y(y,x)$ for $n=0$.[13,14] We assume that the diffusion coefficient, D_{xx}, is a constant, i.e. $D_{xx}=kT/\alpha_x$, where α_x is proportional to the dissipation happening in the degree of freedom x. For $t\to\infty$, the final results are independent of it. The potential, $V_{\rm af}(x,y)$ in the asymmetric fission valley is calculated by using the formulae in Ref.[15] and approximated by a repulsive parabolic potential $V_{\rm af}(x,y)=-a(y)\left(x-x_{\max}(y)\right)^2/2$ with $x_{\max}(y)$ being a maximum value in $V_{\rm af}$. By means of this potential, we obtain a drift coefficient $D_x=a(y)\left(x-x_{\max}\right)/\alpha_x$.

The solution of the Fokker–Planck equation (4) turns out to have a Gaussian shape. The probability to reach the compound nucleus configuration is equal to the area under the distribution's tail in the region of $x\le x_{\max}$[15]

$$P_{\rm CN}=\frac{1}{2}{\rm erfc}\sqrt{\bar{\beta}}, \quad (7)$$

where $\bar{\beta}=\bar{B}/kT$, and erfc is the error function complement, equal to (1-erf). According to Eq.(6), the average barrier height reads

$$\bar{B}=\int B(y)\phi_0(y,x_{\max})\,{\rm d}y, \quad (8)$$

with $B(y)$ being the barrier height in the asymmetric fission valley for different values of y. Figure 1 shows the cross sections of capture (solid line) and compound nucleus formation (dashed line) as functions of the centre-of-mass energy E for the system ^{26}Mg+^{244}Pu. It may be seen from the figure that the competition between the compound nucleus formation and quasifission inhibits the cross section for the fusion increased by more than two orders of magnitude.

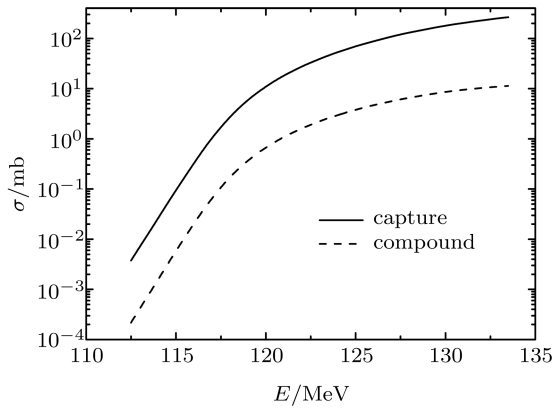


Fig.1. The cross sections of capture (solid line) and compound nucleus formation (dashed line) as functions of the centre-of-mass energy E for the system ^{26}Mg+^{244}Pu.

4. Evaporation residues

The survival probability $W_{\rm sur}(E,J)$ is the probability for compound nucleus to decay to the ground state of a final residual nucleus via evaporation of light particles and γ rays thus to survive fission. The survival probability of emitting x neutrons can be written as

$$W_{\rm sur}\left(E^*_{\rm CN},J\right)=G_{\rm xn}\left(E^*_{\rm CN},J\right)\prod_k\left[\frac{\Gamma_n\left(U^{\rm max}_{k,n},J\right)}{\Gamma_f\left(U^{\rm max}_{k,f},J\right)+\Gamma_n\left(U^{\rm max}_{k,n},J\right)}\right]_k, \tag{9}$$

where $E^*_{\rm CN}$ is the excitation energy of compound nucleus, and $G_{\rm xn}$ is the probability of realization of x neutron evaporation.[16,17] The partial widths of neutron emission and fission are calculated by using the formula of Refs.[14, 16, 18]. In these calculations, the level density parameter is taken as $a_n = A/12.0$ and the ratio of the level density parameters in the fission and neutron evaporation channels is equal to $a_f/a_n = 1.07$,[16] where a_f is the level density parameter at a saddle point. The values of neutron separation energy are taken from Ref.[19]. The rotational energies are calculated under the assumption of the rigid-body moments of inertia with the ground-state and saddle-point deformations.[19,20] The fission barrier depends on the excitation energy of the nucleus as follows:

$$B_f\left(k\right)=B_{\rm LD}\left(k\right)-\Delta_{\rm sh}\left(k\right)\exp(-E^*_k/E_{\rm d}), \tag{10}$$

where $E_{\rm d}=25\,{\rm MeV}$ is the shell-damping energy.[21] The fission barrier B_f contains the macroscopic liquid drop energy part $B_{\rm LD}$ and microscopic shell correction part $\Delta_{\rm sh}$. The values of $B_{\rm LD}$ are estimated in the liquid drop approximation,[22] and those of $\Delta_{\rm sh}$ are taken from Ref.[19].

The cross section of evaporation residue can be written as

$$\sigma_{\rm ER}\left(E\right)=\pi\lambda\!\!\!^{-2}\sum_{J=0}^{\infty}(2J+1)T\left(E,J\right)\times P_{\rm CN}\left(E,J\right)W_{\rm sur}\left(E,J\right). \tag{11}$$

We have calculated the evaporation residue cross sections in the $3n$ and $4n$ channels for the fusion reactions ^{26}Mg+^{244}Cm, ^{27}Al+^{243}Am, ^{30}Si+^{244}Pu, ^{34,36}S+^{238}U, ^{40}Ar+^{232}Th and ^{44,48}Ca+^{226}Ra. The results are shown in Figs.2, 3 and 4.

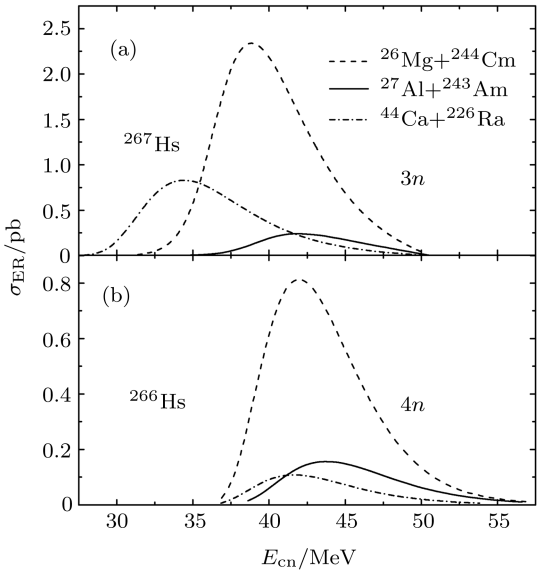


Fig.2. The calculated excitation functions for the $3n$ and $4n$ channels of the fusion reactions ^{26}Mg+^{244}Cm (dashed lines), ^{27}Al+^{243}Am (Dash-dotted lines) and ^{44}Ca+^{226}Ra (solid lines).

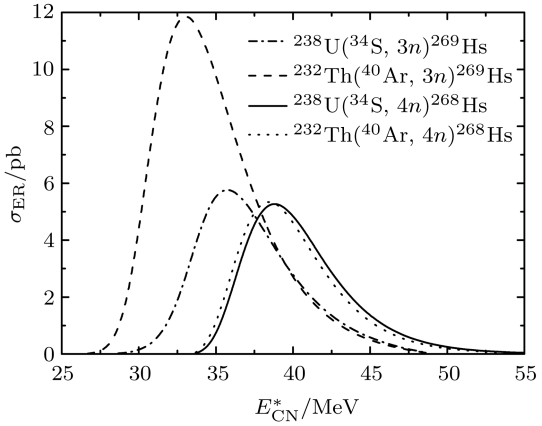


Fig.3. The fusion–evaporation excitation functions for the reactions ^{238}U(^{34}S, $3n$)^{269}Hs (dash-dotted line), ^{232}Th(^{40}Ar, $3n$)^{269}Hs (dashed line), ^{238}U(34S,$4n$)^{268}Hs (solid line) and ^{232}Th(^{40}Ar, $4n$)^{268}Hs (dotted line).

The maximal evaporation residue cross sections and the corresponding excitation energies for the optimal reactions are listed in Table 1.

Table 1. The optimal reactions for the synthesis of new nuclides of element 108, the maximal evaporation residue cross sections ($\sigma_{\rm ER}$), the corresponding excitation energies of the compound nuclei ($E^*_{\rm CN}$) and the centre-of-mass energies (E).

Nuclide	Reaction	σ_{ER}/pb	$E^*_{\rm CN}$/MeV	E/MeV
^{266}Hs	^{244}Cm(^{26}Mg,4n)^{266}Hs	0.81	41.88	123.0
^{267}Hs	^{244}Cm(^{26}Mg,3n)^{267}Hs	2.35	38.88	120.0
^{268}Hs	^{238}U(^{34}S,4n)^{268}Hs	5.29	38.66	148.0
	^{232}Th(^{40}Ar,4n)^{268}Hs	5.34	38.44	164.8
^{269}Hs	^{232}Th(^{40}Ar,3n)^{269}Hs	11.90	33.19	159.5
^{270}Hs	^{238}U(^{36}S,4n)^{270}Hs	396.0	34.99	149.5
	^{226}Ra(^{48}Ca,4n)^{270}Hs	600.0	34.30	186.0
^{271}Hs	^{226}Ra(^{48}Ca,3n)^{271}Hs	873.0	28.3	180.0

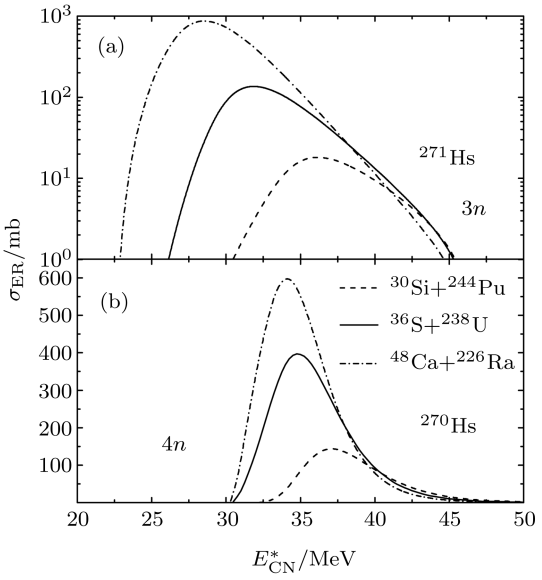


Fig.4. The description same as that in Fig.2, but for the fusion reactions ^{30}Si+^{244}Pu (dashed lines), ^{36}S+^{238}U (solid lines) and ^{48}Ca+^{226}Ra (dash-dotted lines).

5. Summary

The cross sections ($\sigma_{\rm ER}$) for the production of new nuclides of element 108 via hot fusion evaporation reactions are studied using a two-parameter Smoluchowski equation. The cross section $\sigma_{\rm ER}$ depends sensitively on the combination of projectile and target. Therefore, in order to synthesize superheavy nuclei successfully, it is quite necessary to theoretically search for the optimal reactions and favourable bombarding energies before the experiment. From our results, the optimal reactions for the synthesis of new nuclides of element 108 with mass numbers from 266 to 271 are selected. The macroscopic-microscopic approach[3] predicts a strong deformed shell closure at $Z \approx 108$ (Hs) and $N = 162$. Hence it is of interest to synthesize new nuclides of element 108. Our results may be helpful to the future experiments in the production of new nuclides of element 108.

References

[1] Ren Z Z, Tai F and Chen D H 2002 *Phys. Rev.* C **66** 064306

[2] Tai F, Chen D H, Xu C and Ren Z Z 2005 *Chin. Phys. Lett.* **22** 843

[3] Sobiczewski A, Gareev F A and Kalinkin B N 1966 *Phys. Lett.* B **22** 500
Moller and Nix J R 1994 *J. Phys.* G **20** 1681
Sobiczewski 1994 *Phys. Part. Nucl.* **25** 295

[4] Oganessian Yu Ts 2002 *Eur. Phys. J.* A **13** 135
Oganessian Yu Ts 2002 *Eur. Phys. J.* A **15** 201

[5] Patyk Z and Sobiczewski A 1991 *Phys. Lett.* B **256** 307
Patyk Z and Sobiczewski A 1991 *Nucl. Phys.* A **533** 132

[6] Oganessian Yu Ts, Demin A G, Hussonnois M, Tretyakova S P, Kharitonov Yu P, Utyonkov V K, Shirokovsky I V, Constantinescu O, Bruchertseifer H and Korotkin Yu S 1984 *Z. Phys.* A **319** 215

[7] Munzenberg G, Armbruster P, Berthes G, Folger H, Bebberger F P, Hofman S, Keller J, Poppensieker K, Quint A B, Reisdorf W, Schmidt K H, Schott H J, Summerer K, Zychor I, Leino M E, Hingmann R, Gollerthan U and Hanelt E 1987 *Z. Phys.* A **328** 49

[8] Lazarev Yu A, LobanovYu V, Oganessian Yu Ts, Tsyganov Yu S, Utyonkov V K, Abdullin F Sh, LLiev S, Polyakov A N, Rigol J, Shirokovsky I V, Subbotin V G, Sukhov A M, Buklanov G V, Gikal B N, Kutner V B, Mezentsev A N, Sedykh I M and Vakatov D V 1995 *Phys. Rev. Lett.* **75** 1903

[9] Dullmann Ch E, Bruechle W, Dressler R, Eberhardt K, Eichler B, Eichler R, Gaggeler H W, Ginter T N, Glaus F, Gregorich K E, Hoffman D C, Jager E, Jost D T, Kirbach U W, Lee D M, Nitsche M, Patin J B, Pershina V, Pigue D, Qin Z, Schadel M, Schausten B, Schimpf E, Schott H J, Soverna S, Sudowe R, Thorle P, Timokhin S N, Trautmann N, Tueler A, Vahle A, Wirth G, Yakushev A B and

Zielinski P M 2002 *Nature* **418** 859

[10] Siwek-Wilczynska K and Wilczynski J 2004 *Phys. Rev.* C **69** 024611

[11] Swiatecki W J, Siwek-Wilczynska K and Wilczynski J 2005 *Phys. Rev.* C **71** 014602

[12] Siwek-Wilczynska K and Wilczynski J 2001 *Phys. Rev.* C **64** 024611

[13] Liu Z H and Bao J D 2005 *Chin. Phys. Lett.* **12** 3044

[14] Liu Z H and Bao J D 2006 *Phys. Rev.* C **74** 057602

[15] Swiatecki W J, Siwek-Wilczynska K and Wilczynski J 2005 *Phys. Rev.* C **71** 014602

[16] Vandenbosch R and Huizenga J R 1973 *Nuclear Fission* (New York: Academic) p233

[17] Li W F, Wang Z Z, Xu H S, Ma Y, Zhang H F, Zuo W, Li J Q, Wang N, Zhao E G and Sheid W 2004 *Chin. Phys. Lett.* **21** 636

[18] Siwek-Wilczynska K and Skwira I 2005 *Phys. Rev.* C **72** 034605

[19] Moller P, Nix J R, Myers W D and Swiatecki W J 1995 *At. Data Nucl. Dta Tables* **59** 185

[20] Zhang W, Zhang S S, Zhang S Q and Meng J 2003 *Chin. Phys. Lett.* **20** 1694

[21] Adamian G G, Antonenko N V, Ivanova S P and Scheid W 2000 *Phys. Rev.* C **62** 064303

[22] Cohen S and Swiatecki W J 1963 *Ann. Phys.* (N. Y.) **22** 406