A proposed reaction channel for the synthesis of the superheavy nucleus \(Z = 109\)

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We apply a statistical-evaporation model (HIVAP) to calculate the cross sections of superheavy elements, mainly about actinide targets and compare with some available experimental data. A reaction channel \(^{30}\text{Si} + ^{243}\text{Am}\) is proposed for the synthesis of the element \(Z = 109\) and the cross section is estimated.

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The synthesis of superheavy elements always attract the attentions of the nuclear physicists and chemists since the superheavy island was predicted in 1960. Now it has been taken as one of the major research directions in main laboratories of nuclear physics around the world. So far, the heaviest elements \(Z = 114\) and \(116\) were synthesized and identified in Dubna recently 1, 2, and equilibrium configurations as 19: 3, 4, 5, 6, 7, 8, 9. However, theoretical efforts on the structure and dynamical properties of heavy or superheavy nuclei have been investigated in various aspects 3, 4, 5, 6, 7, 8, 9, 10. Nevertheless, it is still interesting to do some semi-empirical calculations to explore a possible way to help the experimental design. To this end, firstly, we perform the systematical calculations and let them agree with the experimental data well. Based on the good reproduction to some known data, we can make a reasonable extrapolation for the production cross section of some superheavy nuclei. In this paper we would like to explore this possibility with help of a statistical-evaporation model, so-called HIVAP, so that we can make a believable suggestion for the experimental proposal in our national laboratory of Heavy Ion Research Facility in Lanzhou (HIRFL).

HIVAP is a statistical-evaporation model 10, 11, 12, 13, 14, which assumed that the process of synthesizing superheavy nuclei includes two stages: firstly the projectile and target nuclei completely fuse to a compound nucleus, then the compound nucleus de-excites by fission or emitting light particles and \(\gamma\)-rays. The complete cross section \(\sigma(E_{cm})\) is assumed as

\[
\sigma(E_{cm}) = \pi \lambda^2 \sum_{J=0}^{J_{max}} (2J + 1)T(J,E_{cm})P(J, E^*)
\]  

(1)

where \(\lambda\) is the de Broglie wave length of relative motion of the colliding nuclei, \(E_{cm}\) is the energy of center-of-mass, \(E^*\) is the excitation energy. \(J\) is the total angular momentum quantum number, the upper limit \(J_{max}\) is obtained by \(22\). \(T(J,E_{cm})\) is the fusion probabilities of the \(J\)th partial wave through the Coulomb barrier. \(P(J,E_{cm})\) is the survival probability of the residue evaporation nucleus after the compound nucleus de-excites by fission or emitting light particles passes the Coulomb barrier and is captured.

The fusion probabilities \(T(J,E_{cm})\) is assumed by 13 as

\[
T(J,E_{cm}) = \sum_{V'_B} f(V'_B) t_J(E_{cm}, V'_B)
\]  

(2)

where \(f(V'_B)\) is a quasi-gaussian fusion barrier distribution, \(t_J\) is the transmission coefficient obtained by WKB approximation. The fusion potential 14 is given by

\[
V_R = V_{Coul} - V_0 exp[1.33(c_p + c_t - R)/b]c
\]  

(3)

where \(V_{Coul}\) is the Coulomb potential, \(c_p\) and \(c_t\) are the central radii 16 of projectile and target, \(c = c_pc_t/(c_p+c_t)\), \(b\) is the surface diffuseness parameter 16. The \(V'_B\) in eq.(2) is average barrier which was adjusted by a fixed constant \(V_0\) (in MeV/fm) 17 in eq.(3). The fluctuation around \(V'_B\) is scaled by a parameter \(r_0\). We have adopted a Gaussian distribution cut off at both ends at \(r_0 \pm \sigma_B(r_0)\), \(t\) is a cut-off parameter 15. We use \(t = 3\) in our calculation. \(\sigma_B(r_0)\) is standard deviation of \(r_0\) distribution.

The level density is an important factor, the progress of synthesizing superheavy nucleus can be explained by the competition of fusion with a fast fission-like process which can be identified with quasi-fission 18. Then the survival probability of residue evaporation nucleus can be expressed using the level densities in the compound and equilibrium configurations as 19:

\[
P(J,E^*) = \frac{\rho(J,E^*_{cn})}{\rho(J,E^*_{cn}) + \rho(J,E^*_{eq})}
\]  

(4)

where \(\rho(J,E^*_{cn})\) is the level density of compound configuration and \(\rho(J,E^*_{eq})\) is the level density of equilibrium
configuration. The level density is
\[
\rho(J, E^*) = \frac{1}{24} \frac{\hbar^2}{2\theta} (2J + 1) a^{1/2} U_f^{-2} \exp[2(aU_f)^{1/2}],
\]
\[
U_f = E^* - E_r(J) + P_{\text{pair}}
\]

\(P_{\text{pair}}\) is the pairing correction obtained from experimental odd-even mass fluctuations. \(a\) is level density parameter, obtained from
\[
a = \pi[1 + f(E^*) B_f^{\text{shell}} / E^*],
\]
and
\[
f(E^*) = 1 - \exp(-E^*/E_d),
\]
in which \(E_d\) is the damping energy, and
\[
\pi = 0.04543 \gamma^3 A + 0.1355 \gamma^2 A^{2/3} + 0.1426 \gamma A^{1/3},
\]
where \(E_r(J)\) is the yrast energy of either the equilibrium configuration (light-particle and \(\gamma\)-emission) or the saddle-point configuration (fission), it reads
\[
E_r(J) = J(J + 1) \hbar^2 / 2\theta,
\]
in which \(\theta\) is the moment of inertia. The fission barrier is defined by including the liquid drop component \((B_f^{LD})\) and the shell component \((B_f^{\text{shell}})\), scaled by a coefficient \(C\), i.e.,
\[
B_f = C(B_f^{LD} + B_f^{\text{shell}}),
\]
in equilibrium configuration.

HIVAP takes into account the competition of \(\gamma\)-ray, neutron, proton and \(\alpha\)-particle emission with fission using angular-momentum and shape-dependent level densities and angular-momentum-dependent fission barriers.

The level densities have been calculated using the well known Fermi gas model. The same level density parameters have been used for the fission and neutron emission channels \((a_f/a_n = 1\). The arguments in support of this value were discussed in Ref. [21]. A phenomenological way of the introduction of shell effects into the level density calculation according to Ignatyuk [21], have been used in the evaporation channels. The shell damping energy \(E_d\) is 18.5 MeV. The liquid-drop fission barrier \((B_f^{LD})\) has been calculated according to the rotating charged liquid drop model of Cohen-Plasil-Swiatecki [22]. The shell component \((B_f^{\text{shell}})\) of the fission barrier is equal to the difference between the liquid-drop model [22] and experimental [21] masses of the nucleus. Light-particle transmission coefficients are obtained using WKB approximation. The shell corrections are added at the saddle point.

In Fig.1 we use HIVAP model to calculate the fusion cross sections for the reaction of \(^{18}\text{O} + ^{248}\text{Cm}\). The cross sections for the channels with 3n to 7n emission are shown. Generally the energy corresponding to the peak of the cross section for a given xn channel increases with the number of emitted neutrons, which is consistent with the excitation extent of the reaction with the more neutron emission. In all channels, the maximum cross section can be reached for 5n channels. Since \(^{18}\text{O} + ^{248}\text{Cm}\) is a hot fusion reaction, we take the maximum value of cross section at 5n channel to compare with the experimental data [26,27,30]. Fig. 2 shows the comparison. An overall satisfied overlap of the calculations with the data was obtained. We listed the experiment data in Table I. From the comparison, it looks that this model has a good agreement with the data for these reactions.

So far, we used the HIVAP to fit the experimental data very well. Based on this achievement, we would like to make some predictions for the synthesizing the elements of \(Z = 109\). With all the same parameters in the model calculation, we calculated some channels for producing \(Z = 109\) elements and listed the results is in Table II. From this table, we found that the channels of \(^{30}\text{Si} + ^{243}\text{Am} \rightarrow ^{270}\text{Mt} + 3n\) at \(E = 151\) MeV or \(^{30}\text{Si} + ^{243}\text{Am} \rightarrow ^{269}\text{Mt} + 4n\) at \(E=161\) MeV have a larger cross sections for synthesizing the new isotopes of element 109. The cross section can reach to \(\simeq 21\) pb.

From the calculation results listed in Table 1 we can see the maximum error of our calculations is within 5 times comparing with the experimental data, so it seems that our estimation for cross section should be reasonable. Element 109 was produced firstly in cold fusion by physicists of the Heavy Ion Research Laboratory, Darmstadt, West Germany using \(^{58}\text{Fe}\) ion bombarding on \(^{209}\text{Bi}\).
The results from the different works which have been already listed the experimental data (symbols). The different symbols present the results from the different works which have been already listed in Table I.

| Channel | $E_{lab}$ (MeV) | Cross section (pb) |
|---------|----------------|-------------------|
| $^{214}\text{Es}$ ($^{22}\text{Ne},4n$) $^{272}\text{Mt}$ | 115 | 8 |
| $^{214}\text{Es}$ ($^{22}\text{Ne},5n$) $^{271}\text{Mt}$ | 124 | 5 |
| $^{214}\text{Es}$ ($^{20}\text{Ne},4n$) $^{270}\text{Mt}$ | 114 | 3 |
| $^{223}\text{Bk}$ ($^{26}\text{Mg},4n$) $^{271}\text{Mt}$ | 137 | 9.5 |
| $^{223}\text{Bk}$ ($^{26}\text{Mg},5n$) $^{270}\text{Mt}$ | 148 | 5 |
| $^{224}\text{Am}$ ($^{28}\text{Si},4n$) $^{267}\text{Mt}$ | 155 | 3 |
| $^{224}\text{Am}$ ($^{30}\text{Si},4n$) $^{269}\text{Mt}$ | 161.3 | 13 |
| $^{224}\text{Am}$ ($^{30}\text{Si},3n$) $^{270}\text{Mt}$ | 151 | 21.6 |

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