Theoretical study of evaporation cross sections in the synthesis of very neutron-deficient nuclei

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The synthesis of rare-earth neutron-deficient nuclei with large Z/N ratio ≈ 0.88 is studied within the framework of the standard statistical model. The fusion cross sections are calculated on the basis of the nuclear reaction video model. The deexcitation process is calculated with the help of the statistical code ALICE. It is found that the excitation functions can be predicted using a few exited experimental data by carefully choosing the input parameters in the statistical model. The results obtained show that a satisfactory description of the experimental evaporation cross sections requires a great reduction in the theoretical fission barriers.

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I. INTRODUCTION

An explosive nuclear synthesis near the drip line produces proton-rich unstable nuclei, which can be used to study physics under extreme conditions. This represents one of the most active areas of research in modern nuclear physics. The nuclei near the proton drip line were used to examine the correlations among nuclear deformation, pairing effects, and exotic decays [1–4]. The production of these nuclei can be achieved using both radioactive nuclei and stable nuclei. The difference between these two methods is the loosely bound structure of the radioactive nuclei that are located near the drip line [5,6].

The experimental research of the very neutron-deficient rare-earth nuclei via fusion evaporation reaction between stable nuclei was undertaken recently. The evaporation cross sections of the reactions ^{32}S $+^{92}$ Mo, ^{32}S $+^{106}$ Cd [4], ^{36}Ar $+^{92}$ Mo, ^{36}Ar $+^{96}$ Ru, ^{36}Ar $+^{106}$ Cd [7], ^{40}Ca $+^{97}$ Mo [8], ^{40}Ca $+^{106}$ Cd [9], and ^{40}Ca $+^{112}$ Sn [10] were measured at one or several energy points. However, since the products of these reactions are nuclei near the proton drip line, this was difficult and it still has not been fully investigated. In addition to experimental efforts, theoretical calculations are helpful to provide support for experimental investigations. Comparing the experimental yield with calculated cross sections allows us to obtain new information about the level density and macroscopic component of the fission barrier and provides further insight into the reaction mechanism.

The goal of the present work is to use the standard statistical model (SSM) to provide exploratory calculations for evaporation cross sections at energies below and above fusion barriers and to generally discuss the relevant ingredients of the reaction processes. The method of analysis is summarized in Sec. II. The calculated results and discussion are presented in Sec. III, and concluding remarks are made in Sec. IV.

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II. THEORETICAL PROCESS

In fusion-evaporation reactions, fusion occurs when the projectile overcomes the fusion barrier. In term of the energies above the fusion barriers, a one-dimensional barrier penetration model is known to work well for most complete fusion reactions above the fusion barrier. On the other hand, it underestimates the subbarrier fusion cross sections, and this is attributed to the coupling of the relative motion and the nuclear structure degrees of projectile and target [11]. Some theoretical methods were developed to resolve this phenomenon, such as the barrier fluctuation (BF) model [12–14], coupled-channel calculations (code CCFULL) [15], and the empirical fusion code of Nuclear Reactions Video (NRV) [16]. The BF model involves barrier fluctuations with amplitude correlated with the collective surface properties of the colliding nuclei. The code CCFULL takes account of the effects of nonlinear couplings to all orders, and the empirical code of NRV is based on the multidimensional barrier and the idea of a "barrier distribution function." All three methods were successfully applied in heavy-ion induced fusion reactions [17–24].

In our calculations, the NRV model is applied to calculate the fusion cross sections because it has few free parameters and is easy to use. In the standard statistical model, the fusion cross section was usually decomposed over partial waves as follows:

$$\sigma_{\text{fus}}(E) = \frac{\pi}{k^2}\sum_{l=0}^{\infty}(2l+1)T(E,l), \tag{1}$$

where $T(E,l)$ represents the probability that the projectile will overcome the entrance channel potential barrier in order to fuse. In the NRV model, the entrance channel potential is approximated by a multidimensional nuclear potential [23,25]

$$\begin{aligned} V_C(r,\beta_1,\beta_2,\theta_1,\theta_2) = {} & V_C(r,\beta_1,\beta_2,\theta_1,\theta_2) \\ & + V_{\text{prox}}(r,\beta_1,\beta_2,\theta_1,\theta_2) \\ & + \tfrac{1}{2}C_1\left(\beta_1-\beta_1^0\right)^2 + \tfrac{1}{2}C_2\left(\beta_2-\beta_2^0\right)^2, \end{aligned} \tag{2}$$

where the surface oscillations or rotation are taken into account. The quantum penetrability $T(E,l)$ is defined with the help of the Hill-Wheeler approximation and semiphenomenological barrier distribution function method

$$T(E,l) = \int f(B) \frac{1}{1+\exp\left\{\frac{2\pi}{\hbar\omega(l)}\left[B+\frac{\hbar^2}{2\mu R_B^2(l)}l(l+1)-E\right]\right\}} dB. \quad (3)$$

It should be noted that the fusion probability $P_{\rm fus}$ is assumed to be unity in our calculations. This means that the quasifission (QF) process in which the system may evolve directly into the fission channel without the compound nucleus formation is ignored. The influence of this assumption is discussed in Sec. III.

For the deexcitation stage, the statistical model was implemented in the HIVAP [26], PACE [27], and ALICE [28] codes. In practice, the most relevant ingredients in these codes are particle transmission coefficients, level densities, fission barriers, and Q values. Because these parameters are estimated or extracted from different phenomenological models in different codes, care should be taken when dealing with them.

The code ALICE is used in our calculations. In this code, the level density parameter a, ratio of the level density parameter for the fission and the neutron-emission channels, a_f/a_n, and the scaling factor of the fission barrier, k_f, should be determined to obtain the evaporation cross sections. For the level density, the famous Fermi gas model is implemented as

$$\rho \propto U^{-2}\exp[2(aU)^{1/2}], \quad (4)$$

where U is the excitation energy and a is the level density parameter. More complex formulas have been developed to give a better description of the nuclear levels, such as the Ignatyuk procedure [29], the Reisdorf expression [26], and the Bethe formula [30]. However, the simple Fermi gas model gives a good description of the nuclei level density in the $A <\approx 200$ mass region [17,31,32]. In particular, in our investigated mass region $120 < A < 160$, the Fermi gas model with $a = 8$ supports the experimental level density quite satisfactorily [33]. Hence, $a = 8$ is used in all our calculations. It should also be noted that our calculations suggest that a small change in the level density parameter has little influence on the position and width of the excitation function peak, thus making it possible to predict evaporation cross sections with only the parameter k_f. The energy dependence of the level density is not taken into account in our study since the calculations show that this changes slowly with energy and becomes almost constant at higher excitation energies [34]. We set the value $a_f/a_n = 1.1$ for the ratio of level density according to the work of Reisdorf [26] for nuclei in this mass region. Its small fluctuation is ignored because the theoretical calculations show that a slight change of a_f/a_n influences the fission probability to be within experimental uncertainties [32].

In this way, the scaling factor k_f of the rotating liquid drop (LD) fission barrier in the expression $B_f(L) = k_f B_f^{\rm LD}(L) - \triangle W_{\rm g.s.}$ is left as the only free parameter to fit the experimental data, as has been done in previous works [14,35]. The fission barrier $B_f^{\rm LD}$ is obtained from the rotating liquid drop (RLD) model [36], and $W_{\rm g.s.}$ is the shell correction.

III. CALCULATION OF CROSS SECTIONS

Before making our analysis, we checked the consistency between the ALICE and HIVAP codes. We calculated the evaporation cross sections of the reaction $^{52}{\rm Cr} + {}^{142}{\rm Nd} \rightarrow {}^{194}{\rm Po}^*$, which were studied with the code HIVAP in previous work [35]. The results indicated that these two different codes showed a satisfactory consistency in both the peak position and the maximum value of excitation functions within the discrepancy caused by the input parameters such as particle transmission coefficients, the level density formula, etc. This compatibility was also confirmed for the reaction $^{31}{\rm P} + {}^{169}{\rm Tm} \rightarrow {}^{200}{\rm Po}^*$ [14], and this gave us more confidence to investigate the fusion-evaporation cross sections with ALICE for the nuclei in these mass regions with few experimental points.

As a first step in our analysis, we calculated the evaporation residual cross section of the reaction $^{40}{\rm Ca} + {}^{97}{\rm Mo} \rightarrow {}^{137}{\rm Sm}$. Its xn and pxn evaporation cross sections (from $4n$ to $5p6n$) were measured at the Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research (JINR) [8], at a projectile energy of ∼200 MeV. We calculated the evaporation cross sections with $k_f = 1.0$, 0.50, and 0.34, respectively, to study the influence of k_f on the evaporation cross sections. A comparison between the experimental data and our results is shown in Table I, and it can be seen that decreasing the scaling factor k_f obviously improves the theoretical representation of the experimental data. To estimate the accuracy of different k_f values, we used a simple deviation factor defined as

$$H = \left|\frac{\sigma^{\rm expt} - \sigma^{\rm cal}}{\sigma^{\rm expt}}\right|, \quad (5)$$

where $\sigma_{\rm cal}$ and $\sigma_{\rm expt}$ are the calculated cross section and the measured cross section. Figure 1 illustrates the global success or failure of the different k_f values of the calculations. The best reproduction of the experimental data is observed to be reducing the fission barrier scaling factor k_f to 0.34. It can also be concluded from Fig. 1 that the fission barrier scaling factor k_f is inclined to influence the exit channel with fewer neutrons and proton numbers.

The influence of the fission barrier scaling factor k_f on the excitation function was then considered in detail. We performed our analysis on the reaction $^{36}{\rm Ar} + {}^{96}{\rm Ru}$, for which $3n$ and $1p3n$ evaporation residual cross sections were measured to be 0.2 and 0.8 μb at projectile energies 165 and 174 MeV, respectively [7]. The evaporation residual cross sections were calculated using $k_f = 1.0$, $k_f = 0.5$, and $k_f = 0.3$. The comparison of the calculated results and the experimental data is shown in Fig. 2. It can be seen from Fig. 2 that the scaling factor of the fission barrier influences not only the absolute value of the cross sections but also the shape of the excitation functions. Reducing k_f decreases more of the cross sections at higher excitation energies because the fission cross section is a larger proportion of the total reaction cross sections at higher energies, and the smaller k_f increases the fission cross sections. This suggests that it is possible to fit the

TABLE I. Comparison of the calculated evaporation cross sections using different fission barrier scaling factors with experimental data taken from Ref. [8].

	Theoretical results with different k_f			
Evaporated particle	$k_f = 1$	$k_f = 0.5$	$k_f = 0.34$	σ_{expt} (mb)
$5n$	1.62	0.586	0.02	<0.2
$4n$	1.48	0.04	4×10^{-4}	<0.2
$p4n$	6.44	1.23	0.03	<0.1
$p3n$	12.6	0.167	0.002	<0.1
$2p3n$	140	32.0	2.07	2.2
$2p4n$	37.1	26.3	4.02	2.8
$3p2n$	7.69	2.88	0.274	3.1
$3p3n$	78.2	50.4	7.09	3.5
$3p4n$	13.5	6.36	1.24	8.0
$4p2n$	6.43	4.77	0.98	1.8
$4p3n$	39.6	19.2	3.92	1.1
$4p4n$	39.0	19.2	2.96	0.6
$5p2n$	0.02	0.016	4.85×10^{-3}	1.6
$5p3n$	3.35	1.62	0.225	3.7
$5p4n$	1.32	1.15	0.341	1.4
$5p5n$	9.36	6.61	1.77	0.8
$5p6n$	1.51	1.05	0.233	0.5

excitation functions with few experimental data far above the Bass barrier.

It should be noted that the value of $B_f = 0.3$ can reproduce both the xn and pxn experimental results at the same time. The $2n$ channel has the maximum evaporation cross sections near the Bass barrier for xn evaporation. For the pxn evaporation, the $p2n$ channel has the maximum peak cross section. As shown in the figure, the pxn evaporation cross section is much larger than the xn channel, which is because the binding energy of protons is smaller than that of the neutrons for the neutron-deficient nuclei.

After confirming that the reducing fission barrier scaling factor can describe the excitation functions satisfactorily with global success, we carried out an analysis similar to that for the ^{32}S-, ^{36}Ar-, and ^{40}Ca-induced reactions mentioned earlier, which led to the synthesis of very neutron-deficient nuclei. The obtained fission barrier scaling factors k_f and the corresponding fitted fission barriers are listed in Table II together with the rotating finite liquid drop (RFLD) model results [37].

It was found that reproducing the measurements at energies much larger than the Bass barrier should greatly reduce the fission barrier scaling factors. As a result, the obtained macroscopic components of the fission barrier are also very much smaller than the theoretical predictions of the RLD and

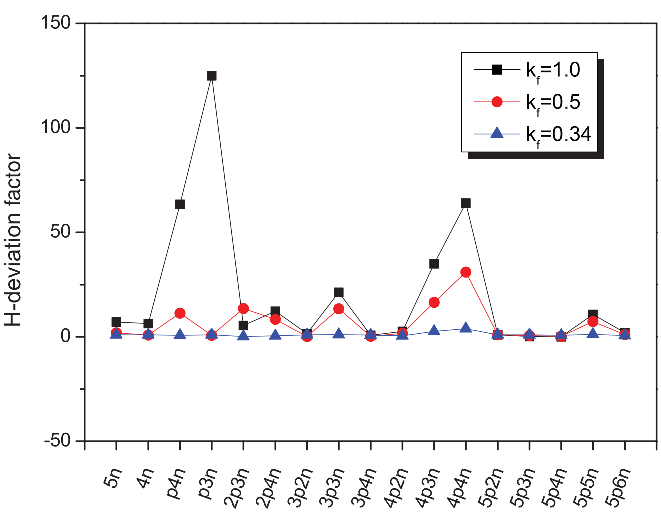

FIG. 1. (Color online) The H-deviation factor as a function of exit channel calculated with different fission barrier scaling factor k_f.

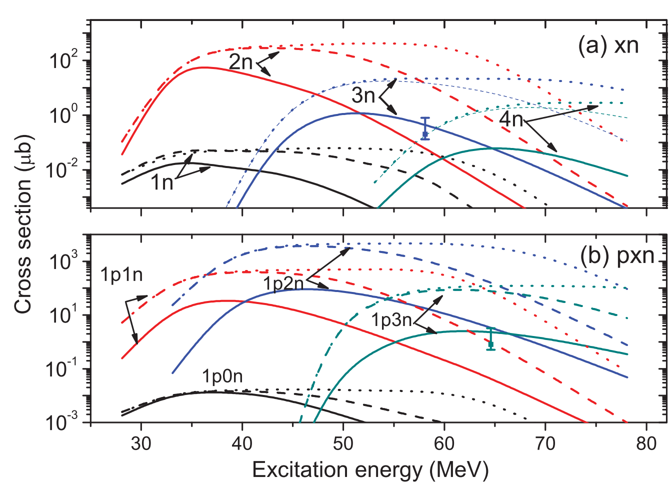

FIG. 2. (Color online) The comparison of experimental data and calculated cross sections using different fission barrier scaling factor k_f for the reaction $^{36}\mathrm{Ar} + {}^{96}\mathrm{Ru} \rightarrow {}^{132}\mathrm{Sm}^*$: (a) xn channel and (b) pxn channel. Experimental data are taken from Ref. [7]. The dotted, dashed, and solid lines represent the theoretical results with $k_f = 1.0$, $k_f = 0.5$, and $k_f = 0.3$, respectively.

TABLE II. The obtained fission barrier scale parameter k_f for the very neuron-deficient nuclei investigated in this work. The corresponding fitted fission barriers are compared with those of the RFLD model [37].

Reaction	Bass barrier (MeV)	$E_{c.m.}$ (MeV)	Exit channel	σ_{expt} (μb)	k_f	B_f^{fit} (MeV)	B_f^{RFLD} (MeV)
$^{32}S + ^{92}Mo \rightarrow ^{124}Ce^*$	85	112	$3n$	2.1	0.22	7.84	28.82
$^{36}Ar + ^{92}Mo \rightarrow ^{128}Nd^*$	95	121	$3n$	1.6	0.32	8.26	26.87
$^{36}Ar + ^{96}Ru \rightarrow ^{132}Sm^*$	99	120	$3n$	0.2	0.30	9.08	24.80
$^{36}Ar + ^{96}Ru \rightarrow ^{132}Sm^*$	99	127	$1p3n$	0.8	0.30	9.08	24.80
$^{40}Ca + ^{97}Mo \rightarrow ^{137}Sm^*$	103	142			0.34	11.4	27.81
$^{32}S + ^{106}Cd \rightarrow ^{138}Gd^*$	96	116	$3n$	0.6	0.35	10.1	23.91
$^{36}Ar + ^{106}Cd \rightarrow ^{142}Dy^*$	107	131	$3n$	1.5	0.42	10.9	21.65
$^{40}Ca + ^{106}Cd \rightarrow ^{146}Er^*$	117	147	$1p3n$	1.2	0.45	10.3	19.36
$^{40}Ca + ^{112}Sn \rightarrow ^{152}Yb^*$	121	136	$3n$	3.3	0.53	11.1	18.14

RFLD models. Another phenomenon we can see form Table II is that the fission barrier scaling factor k_f increases with the compound nuclei number.

The suppression of the evaporation cross sections, corresponding to an unexpected low macroscopic components of the fission barrier, can be attributed to the entrance-channel effect or the decay-channel effect. Two independent ingredients, collection enhancement in the level density (CELD) and the QF effect, are considered responsible for the large reduction of the evaporation cross sections as discussed in Ref. [35]. The CELD effect is the influence of collective excitations in terms of a reduced collective contribution to the level density in spherical nuclei [35,38]. The compound nuclei in our study are all deformed, and consequently the CELD effect would not be responsible for the evaporation cross-section suppression. This conclusion is confirmed by our calculations with the decay code of NRV in which the CELD effect is implemented.

The QF process takes charge of the inhibition of fusion cross sections for many heavy-ion-induced reactions. It achieves this by reducing the complete fusion cross section. It was observed in a rather asymmetric reaction and in a reaction leading to less-fissile compound nuclei than previously thought [39–41]. It was also found in fusion reactions with $Z_1Z_2 < 1000$ [40,42,43] and is preferred to happen in reactions with deformed target nuclei [44,45]. For all the systems we study here, however, the mass number of the compound nuclei is no more than 160 and $Z_1Z_2 \leqslant 1000$. No QF effect has been discovered in such a light system up to now. So we can cautiously argue that the obtained small barrier reduction coefficients cannot be understood by the QF process.

The other input parameters in the calculation of the decay process are also the ingredients that can cause the reduction of the k_f value. We compared the theoretical evaporation cross sections of the reaction $^{52}Cr + ^{142}Nd \rightarrow ^{194}Po^*$ calculated with the different codes HIVAP and ALICE in detail. The results show that the uncertainty of the k_f value caused by other input parameters is within 0.1. Therefore, we do not think that the discrepancy of the other input parameters in the code can bear out the great k_f value suppression.

Although the fission barriers we obtained here cannot be considered "experimental barriers" because of approximations in the statistical model [35], they still can be thought of as representing the trend for the very neutron-deficient nuclei. This is in agreement with previous work [14,35], in which a satisfactory description of the SSM involving the experimental data of Po and Bi isotope synthesis was found needing to reduce the fission barrier under RFLD results. Together with these theoretical predictions, we think the trend naturally reflects the fact that, in this mass region, the fission barriers are lower than those from the RLD model. Of course, more cross-section measurements for both fusion evaporation and fission are needed to fully understand this interesting behavior, in particular for very neutron-deficient nuclei.

Additionally, it should be noted that the nonreduced RLD model fission barrier underestimates the fission cross sections of the reaction $^{64}Ni + ^{100}Mo$ more than the dynamical cluster-decay (DCM) model [46]. In the DCM, the effects of deformations and orientations of nuclei are included in the fission cross-section calculations. This indicates that the dynamical process may be partly responsible for this phenomenon.

IV. CONCLUSIONS AND REMARKS

In this paper, we calculated the fusion-evaporation cross sections with the statistical model for the reaction of nuclei synthesis near the proton drip line. The results are compared to the experimental data.

For the fusion process, we obtained the fusion cross sections with the NRV model to enhance the subbarrier fusion cross sections which were underestimated by the single-barrier penetration model. In the deexcitation stage, the evaporation cross sections are calculated with statistical model ALICE. The input parameters a and a_f/a_n were carefully chosen according to the experimental data and other theoretical calculations. The fission barrier scaling factor k_f was left as the only free parameter in our study. This process is extensively used and has been proved to describe the experimental data successfully.

We found that the fission barrier scaling factor should be greatly reduced to reproduce the experimental data and the scaling factors obtained increase with the compound nuclei mass number. This phenomenon is attributed to the decay-channel effect according to our discussions, and our results are consistent with the previous findings.

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