Analytic expressions for α particle preformation in heavy nuclei

H. F. Zhang,[1,*] G. Royer,[2,†] Y. J. Wang,[1] J. M. Dong,[1] W. Zuo,[1,3] and J. Q. Li[1,3]
[1] *School of Nuclear Science and Technology, Lanzhou University, Lanzhou 730000, People's Republic of China*
[2] *Laboratoire Subatech, UMR IN2P3/CNRS Université Ecole des Mines, Nantes 44, France*
[3] *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China*

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Experimental α decay energies and half-lives are investigated systematically to extract α particle preformation in heavy nuclei. Formulas for the preformation factors are proposed that can be used to guide microscopic studies on preformation factors and perform accurate calculations of the α decay half-lives. There is little evidence for the existence of an island of long stability of superheavy nuclei.

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The α radioactivity, first observed in the beginning of the last century, has been explained successfully as a typical quantum mechanical tunneling effect. Quantitative investigations of the α decay half-lives must be pursued for the following reasons. First, recently, a set of superheavy nuclei beyond rutherfordium [1–9] has been synthesized and detected via the set's α decay, and predictions are needed for future experimental assignment and identification. Second, new facilities and experiments are mainly focused on new nuclei far from the β stability line, and detailed research on α decay will shed new light on the structure of these nuclei. Third, it would be interesting to reach a unified understanding of proton emission, α decay, cluster decay, and nuclear fission. Some first works have been accomplished with a macroscopic-microscopic approach: the generalized liquid drop model (GLDM) [10–14]. The microscopic structures that play a key role have been extracted from the experimental α decay energies and half-lives for even-even nuclei [15]. In this study, all the nuclei are taken into account, and the purpose of the study is to provide analytical expressions for α particle preformation in heavy nuclei.

The experimental nuclear data are taken from Refs. [16,17], which add more recent experimental data, particularly on superheavy nuclei. In Fig. 1, the α decay energies (top) and half-lives (bottom) are shown as functions of the neutron, proton, and mass numbers N, Z, and A, from left to right. Before $N = 126$, the α decay energy generally increases slowly with increasing neutron number N, and the half-life presents vibrations with neutron number. The α decay energy Q decreases sharply and the half-life increases rapidly between $N = 126$ and $N = 142$. Then the value of Q increases again, and the half-life decreases, when the neutron number increases. Up to superheavy region N, beyond about 160, the trend of the curve presents a flatness, which may be a vague signal suggesting an island of stability of superheavy nuclei.

Another important factor is that the nuclei with $Z = 82$, which is a well-known magic number, do not have a visible stability excess from the Q value. Such a small stability excess appears from the half-life curve, which tells us that the proton magic number $Z = 82$ has smaller effects than the neutron number $N = 126$ for the α decay properties. The lines for both the Q value and half-life show the same trend after $Z = 92$ after $N = 142$, as shown in Fig. 1(a).

From Fig. 1, it can be deduced that the most stable nuclei against α decay stay at the beginning of the curve; these nuclei have small Q values and very long half-lives. In addition, there exist stable nuclei against α emissions at a mass number of around 240 (the Q values being about 5 MeV and the half-lives being approximately 100 shalf-lives being approximately 100 s) [see Fig. 1(c)]. The Q values exceed 10 MeV, and the half-lives are about 1 s, or even shorter, at the end of the curve, implying by extension whether the island of stability of superheavy nuclei really exists, with half-lives of several or several tens of seconds. In the future, at a time when the rich neutron projectiles and sufficient rich neutron targets are available, it should be possible to identify these nuclei because of their relatively long half-lives against α decay, but a study on fission properties is still challenging for these nuclei.

The calculational details for the preformation factors are described in a recent work [15]. The α decay constant is defined as

$$\lambda = P_0 \nu_0 P. \tag{1}$$

The assault frequency ν_0 is estimated using classical methods, the penetration probability P is estimated from tunneling GLDM potential barriers, and the decay constant λ can be obtained from the experimental half-lives $\lambda = \ln 2/T_{\rm expt}$. Then the preformation factor can been extracted from experimental α decay energies and half-lives.

The 445 nuclei from Audi *et al.*'s recent data [16,17], together with the results of the newly observed superheavy nuclei [5–9], are considered. The extracted preformation factors are shown in Fig. 2 (black circles).

In a first step, a simple formula, given the preformation factor as a function of the charge number Z, the mass number A of the parent nucleus, and the isospin-dependent term $(N - Z)$, is proposed:

$$\log P_0 = 2.465075 - 0.068113Z - 0.002325A + 0.004857(N - Z). \tag{2}$$

*zhanghongfei@lzu.edu.cn
†Royer@subatech.in2p3.fr

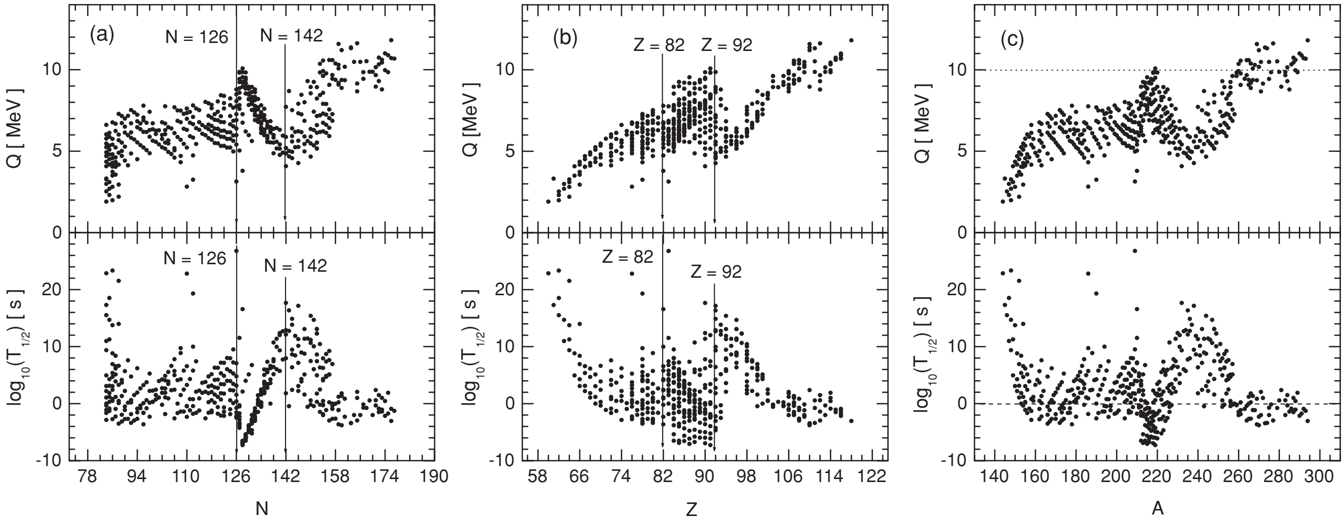

FIG. 1. Experimental α decay energies (top) and α decay half-lives (bottom) as a function of (a) neutron number N, (b) proton number Z, and (c) mass number A.

To measure the agreement of the theoretical half-lives with the experimental data, the standard deviation is defined as

$$\sqrt{\sigma^2} = \sqrt{\sum_{i=1}^{n} \frac{\left(\log P_0^{\text{expt},i} - \log P_0^{\text{fit},i}\right)^2}{N}}. \quad (3)$$

The standard deviation obtained from Eq. (2) is only 1.5571, implying that the average deviation between the theoretical estimates and experimental data for the α decay half-lives will be $e^{1.5571} = 4.74$. This approximation can be accepted for α decay half-life calculations. The preformation factors calculated by Eq. (2) are shown in Fig. 2 (left) (open triangles). It is clear that Eq. (2) can give the general trend of the preformation factors but cannot provide an elaborated description; therefore this formula can be used only for rough estimates of the preformation factors.

It has been previously shown that shell closure effects play a key role in α preformation [15]. The closer the nucleon number is to the magic numbers, the more the formation of an α cluster is difficult inside the mother nucleus. The penetration probability determines mainly the α decay half-life, whereas the preformation factor allows us to obtain information on the nuclear structure. Therefore a more sophisticated formula is proposed for the preformation factor because of the nuclear shell structure:

$$\log P_0 = a + b(Z - Z_1)(Z_2 - Z) + c(N - N_1)(N_2 - N) + dA, \quad (4)$$

where Z, N, and A are the charge number, neutron number, and mass number of the parent nucleus, respectively. Z_1 and Z_2 are the proton magic numbers around Z ($Z_1 < Z \leqslant Z_2$), and N_1 and N_2 are the neutron magic numbers around N ($N_1 < N \leqslant N_2$). The parameters a, b, c, and d are different because of the microscopic nuclear structure, and the corresponding deviations are presented in Table I. The accuracy is better for the even-even nuclei than for the other nuclei, probably

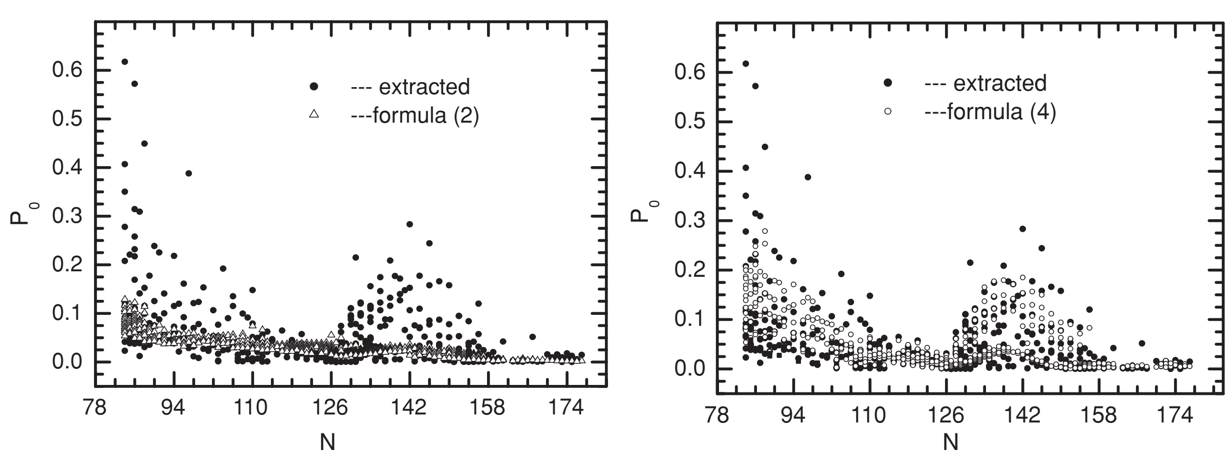

FIG. 2. Extracted and fitted preformation factors from (left) Eq. (2) and (right) Eq. (4), respectively.

TABLE I. Parameters for Eq. (4).

	$50 < Z < 82$ $82 < N < 126$	$82 < Z$ $82 < N < 126$	$82 < Z$ $126 < N < 152$	$82 < Z$ $152 < N$
		Even-even nucleus		
a	5.229272	−2.597503	−18.98287	892.7088
b	0.004801	0.169926	−0.172610	3.600399
c	0.004473	0.003017	0.008532	3.893642
d	−0.057485	−0.011362	0.074752	−3.812500
$\sqrt{\sigma^2}$	0.499	0.333	0.411	0.346
		Odd-A nucleus		
a	6.194819	−17.70253	9.584417	−1196.707
b	0.005354	0.091751	0.147407	−5.273438
c	0.006363	0.004019	0.020438	−5.003726
d	−0.069859	0.059800	−0.076871	5.103626
$\sqrt{\sigma^2}$	0.670	0.850	1.608	1.601
		Odd-odd nucleus		
a	12.18941	−50.85612	22.07726	−9157.626
b	−0.006942	0.136975	0.357635	−38.89009
c	−0.002655	0.013371	0.027708	−39.16380
d	−0.084889	0.205916	−0.146806	39.09218
$\sqrt{\sigma^2}$	0.696	0.811	1.876	1.409

because the angular momentum dependence is not taken into account.

The calculated preformation factors for the 445 heavy and superheavy nuclei are presented in Fig. 2. Equation (4) can give a satisfying estimate for the preformation factors.

To make a more explicit comparison, the preformation factors extracted from the experimental data, calculated by Eqs. (2) and (4), are drawn in Fig. 3 using black dots, triangles, and circles for the Po isotopes, respectively. The preformation factors calculated from Eq. (4) are very close to the extracted data. The nuclear microscopic properties, such as the neutron magic number $N = 126$ and the odd-even effect, are correctly reflected, and Eq. (2) is convenient for giving a rough estimate for the preformation factors. These results indicate that when the preformation factors are calculated by Eq. (4) in the framework of the GLDM, the known experimental

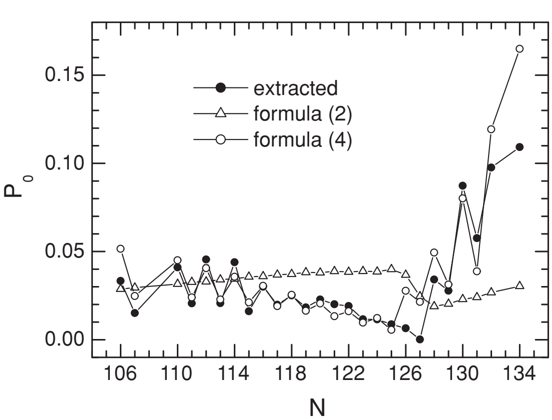

FIG. 3. Extracted and fitted preformation factors [from Eqs. (2) and (4)] for Po isotopes.

α decay half-lives can be reproduced accurately. It would be interesting to provide bulk predictions for unobserved heavy and superheavy nuclei, which will be the subject of a following study.

We have noticed very recently a formula for the formation probability of all clusters that is, evidently, not dependent on the structure of the nucleus [18]. We would also like to point out that Gangopadhyay [19] also proposed an α preformation formula showing a simple dependence on the mass number and the product of valence protons and neutrons, which actually shares the same idea as Eq. (4), including the shell effects of the parent nucleus, in this Brief Report.

In conclusion, the experimental α decay energies and half-lives have been investigated systematically. The microscopic nuclear structure plays a key role in α decay properties, the neutron magic number $N = 126$ being crucial for long α decay half-lives. There is little evidence for the existence of an island of stability of superheavy nuclei with half-lives as long as the half-lives of elements observed in nature. The half-lives should be several or several tens of seconds or minutes in the case in which this island of stability exists. A formula for the preformation factors is proposed, which can be used to provide general guidance for microscopic study on preformation factors and nuclear structure and also to allow accurate calculations for α decay half-lives in the future.

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