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The experimental α decay energies and half-lives are investigated systematically to extract the α particle preformation in heavy nuclei. Formulas for the preformation factors are proposed. They can be used to guide the 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 (SHN).

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The α radioactivity, firstly observed in the beginning of the last century, has been explained successfully as a typical quantum mechanical tunnelling effect. The quantitative investigations on the α decay half-lives must be pursued for the following reasons. Firstly, recently a set of superheavy nuclei beyond Rutherfordium [1–9] have been synthesized and detected via their α decay and predictions are needed for future experimental assignment and identification. Secondly, new facilities and experiments are mainly focused on new nuclei far away from the β stability line and detailed researches on α decay will shed new lights on the structure of these nuclei. Thirdly, it is interesting to reach an unified understanding of the proton emission, the α decay and cluster decay and the nuclear fission. Some first works have been accomplished within a macroscopic-microscopic approach, the generalized liquid drop model (GLDM) [10–14]. The microscopic structures which plays the key role has 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 is to provide expressions given analytically the α particle preformation in heavy nuclei.

The experimental nuclear data are taken from Refs. [16, 17] in adding more recent experimental data particularly on superheavy nuclei. In Fig.1(a) to (c) the α decay energies (upper panel) and half-lives (lower panel) are shown as functions of the neutron, proton and mass numbers N, Z, 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 gives the vague signal for an island of stability of superheavy nuclei.

Another information 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 little stability excess stability appears from the half-live curve, which tell us that the proton magic number Z=82 has smaller effects for the α decay properties than the neutron number N=126. The lines both for Q value and half-live show the same trend after Z=92 as in the Fig.1(a) after N=142.

From Fig.1(a) to (c), it can be deduced that the most stable nuclei against the α decay stay at the beginning of the curve, these nuclei having small Q values and very long half-lives. Besides there exists stable nuclei against α emissions at mass number around 240 (the Q values being about 5 MeV and the half-lives 100 seconds approximately) (see Fig.1(c)). The Q values exceed 10 MeV and the half-lives are about 1 second or even shorter in the end of the curve, implying by extension whether the island of stability of superheavy nuclei really exists, half-lives of several or several tens seconds. When the rich neutron projectiles and sufficient rich neutron targets will be available in the future it should be possible to identify these nuclei due to the relatively long half-lives against α decay, but the study on fission properties is still a challenge 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 from tunnelling through GLDM potential barriers and the decay constant λ can be obtained from the experimental half-lives $\lambda = \frac{ln2}{T_{expt.}}$. Then the preformation factor can been extracted from experimental α decay energies and half-lives.

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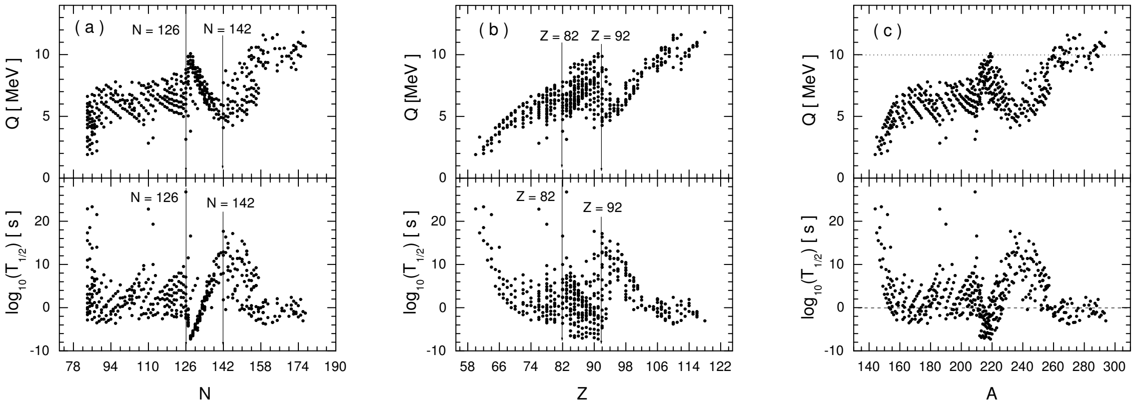

FIG. 1: Experimental α decay energies (upper panel) and α decay half lives (lower panel) as a function of neutron number N, proton number Z, mass number A from left to right are differed with (a), (b), (c) respectively.

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

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

$$logP_0 = 2.465075 - 0.068113Z - 0.002325A + 0.004857(N - Z). \tag{2}$$

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

$$\sqrt{\sigma^2} = \sqrt{\sum_{i=1}^{n} \frac{[logP_0^{expt,i} - logP_0^{fit,i}]^2}{N}}. \tag{3}$$

The standard deviation obtained from the 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 times. This approximation can be accepted for α decay half-live calculations. The preformation factors calculated by the Eq. (2) are shown in Fig. 2(a) by the triangles. It is clear that the Eq. (2) can give the general trend of the preformation factors, but not provide an elaborated description. So this formula can be used only for rough estimates of the preformation factors.

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

$$logP_0 = a + b(Z - Z_1)(Z_2 - Z) + c(N - N_1)(N_2 - N) + dA, \tag{4}$$

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 ($Z_1 < Z \leq Z_2$) and N_1 and N_2 the neutron magic numbers around N ($N_1 < N \leq N_2$). The parameters a, b, c, d are different due to the microscopic nuclear structure, and the corresponding deviations are presented in Tab. 1. The accuracy is better for the even-even nuclei than for the other ones, probably 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. The Eq. 4 can give a satisfied estimate for the preformation factors.

In order to make a more explicit comparison, the preformation factors extracted from the experimental data, calculated by the Eq. 2 and Eq. 4 are drawn in Fig. 3 using respectively the black dots, triangles and circles for the Po isotopes. The preformation factors calculated from the 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 to give a rough estimate for the preformation factors. These results indicate that when the

TABLE I: Parameters for the Eq. (4).

		even-even nucleus		
Parameters	$50 < Z < 82$ $82 < N < 126$	$82 < Z$ $82 < N < 126$	$82 < Z$ $126 < N < 152$	$82 < Z$ $152 < N$
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

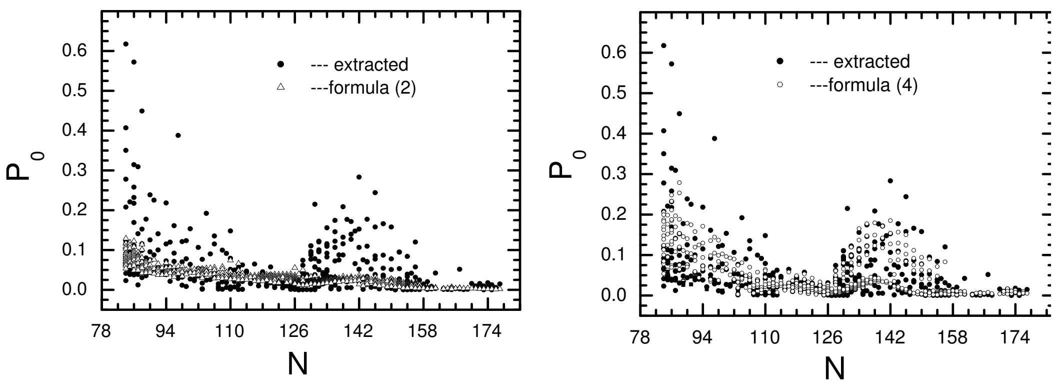

FIG. 2: Extracted and fitted preformation factors from formulas (2) and (4) respectively.

preformation factors are calculated by the Eq. 4 in the framework of the GLDM, the known experimental α decay half-lives can be reproduced accurately. It is interesting to provide the bulk predictions for unobserved heavy and superheavy nuclei, which should be the next work.

As a conclusion the experimental α decay energies and half-lives have been investigated systematically. The microscopic nuclear structure play the key role on the α decay properties, the neutron magic number N=126 being crucial for the 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 seconds or minutes in the case where this island of stability exists. A formula for the preformation factors is proposed which can be used to provide general guidance for the microscopic study on preformation factor and nuclear structure and also to allow accurate calculations for α decay half-lives in the future.

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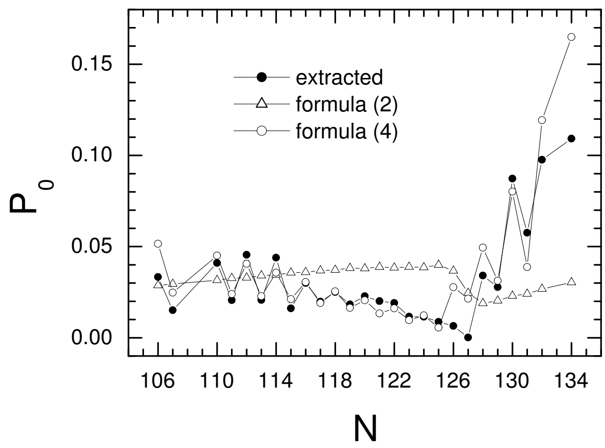

FIG. 3: Extracted and fitted preformation factors (from formulas (2) and (4)) for Po isotopes.

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