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α-decay half-lives of neutron-deficient nuclei

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Abstract

The α-decay half-lives of neutron-deficient nuclei with $Z = 80 - 118$ are studied by employing the effective liquid drop model (ELDM), generalized liquid drop model (GLDM) with the fission-like mode and the cluster-like mode, Royer formula, and Denisov formula. By comparison between the calculated half-lives and the experimental ones, it is shown that the accuracy by the GLDM with the cluster-like mode is higher than those by other models and formulas. In addition, the α-decay half-lives of the unmeasured neutron-deficient nuclei with $Z = 80 - 120$ are predicted using the GLDM with the cluster-like mode by inputting the Weizsäcker-Skyrme-4 (WS4) Q_α values. These predictions are helpful for future measurements.

Keywords: α-Decay; Neutron-deficient nuclei

1. Introduction

α-decay was firstly observed by Rutherford and Geiger at the beginning of the last century [1]. For unstable nuclei, α-decay is a dominant radioactive decay mode and it has been a powerful tool to identify the new elements or new isotopes [2–11]. Meanwhile, via the observation of the α radioactivity, rich nuclear structure information can be obtained, such as the half-lives, decay energies, spin-parity, radii, and shell effects [2–5]. On the aspect of the theoretical study, the α radioactivity was explained successfully as a typical quantum tunneling effect by Gamov [12]

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and by Condon and Gurney [13] in 1928. Since then, various theoretical models and empirical formulas were proposed to calculate the α-decay half-lives [14–43]. The experimental α-decay half-lives can be reproduced more or less satisfactorily by these theoretical models and formulas [14–43].

Recent years, the synthesis of superheavy nuclei (SHN) has been a hot subject in modern nuclear physics. So far, many SHN have been produced by cold and hot fusion reactions [3–11]. But these synthesized nuclei are neutron-deficient ones. Meanwhile, the heavy nuclei in the upper left part of the nuclear chart have been paid attention by many researchers [44–50]. Owing to the application of digital data acquisition and the exploration on multi-nucleon transfer reactions, some new heavy neutron-deficient nuclei have been produced, such as ^{215,216,221}U [44–46], ^{219,223,224}Np [47–49], and ^{220}Pa [50]. The α radioactivity of these nuclei is helpful for understanding the nuclear structure and predicting the limit of existence. On the other hand, these experimental data can provide a ground for testing the extant α-decay models. We know that the ELDM [32–36] and GLDM [39] are successful models to estimate the α-decay half-lives. In addition, some empirical formulas, such as the Royer formula [40,41], the Denisov formula [42, 43], are usually used to calculate the α-decay half-lives. So in this article we will extend them to investigate the α radioactivity of the neutron-deficient nuclei. This article is organized in the following way. Sec. 2 gives the theoretical approaches. In Sec. 3 numerical results and discussions are performed. In the last section, some conclusions are drawn.

2. Theoretical methods

2.1. ELDM

The ELDM is a successful phenomenological model, which was proposed by Goncalves and Duarte in 1993 [32]. It is assumed as a super-asymmetric fission model to study the α-decay, the proton emission, the cluster radioactivity, and the cold fission in a unified framework. The details of the ELDM can be seen from Refs. [32–36]. In the framework of the ELDM, the decay constant is defined as

$$\lambda = \nu_0 P, \tag{1}$$

where ν_0 is the assault frequency of α particle on the barrier of the parent nucleus. For the varying mass asymmetry shape (VMAS) description, the ν_0 value is taken as 1.8×10^{22} s^{-1}. P is the Gamow penetrability factor through the barrier, which is calculated by

$$P = \exp\left[-\frac{2}{\hbar}\int_{\zeta_0}^{\zeta_c}\sqrt{2\mu_{WW}^{VMAS}[V(\zeta) - Q_\alpha]}d\zeta\right]. \tag{2}$$

Here, the limits ζ_0 and ζ_c of the integral are the inner and outer turning points, respectively. μ_{WW}^{VMAS} is the inertial coefficient obtained by using the Werner-Wheeler approximation [51] within the VMAS description. $V(\zeta)$ is the one-dimensional total potential energy which consists of Coulomb energy, effective surface energy, and the centrifugal potential energy [32]. Q_α denotes the energy released in α-decay process. Then the α-decay half-life is calculated by

$$T_{1/2} = \frac{\ln 2}{\lambda}. \tag{3}$$

2.2. GLDM

In GLDM, the process of the shape evolution from one body to two separated fragments can be described in a unified way. Its details can be found in Refs. [29,39].

The decay constant λ can be obtained by the fission-like mode and cluster-like mode, respectively. To discuss conveniently in the next section, the GLDM with the fission-like mode and the GLDM with the cluster-like mode are represented by GLDM1 and GLDM2, respectively. For GLDM1 [52], the λ is defined by Eq. (1) and ν_0 is taken as $1.0 \times 10^{19} s^{-1}$. For GLDM2, λ is defined as [53]

$$\lambda = S_\alpha \nu_0 P, \tag{4}$$

where S_α denotes the preformation factor of the α cluster in the parent nucleus. The S_α value can be extracted from the following expression [54]

$$\log S_\alpha = a + b(Z - Z_1)(Z_2 - Z) + c(N - N_1)(N_2 - N) + dA, \tag{5}$$

where the coefficients of a, b, c, d, Z, N, A, Z_1, Z_2, N_1, and N_2 can be found in Ref. [54]. ν_0 is estimated by the classical method

$$\nu_0 = \frac{1}{2R}\sqrt{\frac{2E_\alpha}{M_\alpha}}, \tag{6}$$

where R is the radius of the parent nucleus. E_α and M_α represent the kinetic energy and the mass of the emitted α particle, respectively.

The penetrability factor P is calculated by the WKB approximation, which is expressed as

$$P = \exp\left[-\frac{2}{\hbar} \int_{R_{\mathrm{in}}}^{R_{\mathrm{out}}} \sqrt{2B(r)[E(r) - E_{sph}]}\mathrm{d}r \right], \tag{7}$$

where R_{in} and R_{out} are the two turning points of the WKB action integral, respectively. Here, the approximation is used: $B(r) = \mu$, which stands for the reduced mass of the α particle and the residual daughter nucleus. The macroscopic energy $E(r)$ is written as

$$E(r) = E_V + E_S + E_C + E_{\mathrm{Prox}} + E_{\mathrm{cen}}(r), \tag{8}$$

where $E(r)$ contains the volume, surface, Coulomb, proximity, and the centrifugal potential energy [55], respectively. Then by combining Eq. (3), the α-decay half-lives can be estimated.

2.3. Royer and Denisov formulas

The Royer formula [41] and Denisov formula [42,43] were proposed to calculate the α-decay half-lives by fitting 344 experimental data from ground state to ground state. The two formulas are dependent on the orbital angular momentum (l) carried by the α-particle, which are listed as follows

$$\log_{10} T_{1/2}(Royer) = a + bA^{1/6}\sqrt{Z} + c\frac{Z}{\sqrt{Q_\alpha}} + \frac{dANZ[l(l+1)]^{1/4}}{Q_\alpha} + eA[1 - (-1)^l], \tag{9}$$

$$\log_{10} T_{1/2}(Denisov) = a + b\frac{A^{1/6}Z^{1/2}}{\mu} + c\frac{Z}{\sqrt{Q_\alpha}} + d\frac{\sqrt{l(l+1)}}{Q_\alpha A^{-1/6}} + e[(-1)^l - 1], \tag{10}$$

where A, N, and Z are the mass number, neutron number, and charge number of the parent nucleus, respectively. In the Denisov formula, $\mu = [A/(A-4)]^{1/6}$. The values of the parameters a, b, c, d, and e can be found in Refs. [41–43].

3. Results and discussions

We have performed calculations on the α-decay half-lives of the ground state to ground state for 120 neutron-deficient nuclei with $Z = 80 - 118$ by the ELDM, GLDM1, GLDM2, Royer formula, and Denisov formula by inputting the experimental Q_α values. The calculated results are listed in Table 1. The first column of Table 1 denotes the parent nuclei. In column 2 the experimental Q_α values are shown. The third column represents the minimal orbital angular momenta carried by α particles, which are determined by the spin-parity selection rule. For SHN with $Z = 104 - 118$, the orbital angular momenta carried by α particles are selected as 0. The experimental half-lives are listed in columns 4. The calculated half-lives by the ELDM, GLDM1, and GLDM2 are listed in the 5th-7th columns. The half-lives by the Royer formula and Denisov formula are listed in the last two columns. To test the agreement between the experimental half-lives and the calculated ones, the average deviation $\overline{\sigma}$ and the standard deviation $\sqrt{\overline{\sigma^2}}$ are calculated, which are written as

$$\overline{\sigma} = \frac{1}{n}\sum_{i=1}^{n}\left|\log_{10} T_{1/2}^{\exp.i} - \log_{10} T_{1/2}^{cal.i}\right|, \tag{11}$$

$$\sqrt{\overline{\sigma^2}} = \left[\frac{1}{n}\sum_{i=1}^{n}(\log_{10} T_{1/2}^{\exp.i} - \log_{10} T_{1/2}^{cal.i})^2\right]^{1/2}. \tag{12}$$

By using Eqs. (11) and (12) the $\overline{\sigma}$ and $\sqrt{\overline{\sigma^2}}$ for the 120 neutron-deficient nuclei from the above mentioned models (formulas) can be obtained, whose values are listed in Table 2. As can be seen from Table 2, the GLDM2 generates the smallest $\overline{\sigma}$ and $\sqrt{\overline{\sigma^2}}$ values by comparison with those of other models (formulas), which are 0.407 and 0.512, respectively. This means that the average deviation between the experimental half-lives and the calculated ones is about 3 times. This indicates that the GLDM2 is the most accurate one to reproduce the experimental half-lives of the neutron-deficient nuclei among these models (formulas).

We know that the ELDM is assumed as a super-asymmetric fission model. In the frameworks of the ELDM and the GLDM1, the assaulting frequencies ν_0 of the α particles on potential barrier are selected as constants (1.8×10^{22} s^{-1} and 1.0×10^{19} s^{-1}, respectively), which is too rough. For the Royer and Denisov formulas, only some simple nuclear structure information, such as A, Z, Q_α, and l, is included. So the extracted half-lives by the ELDM, the GLDM1, and the two formulas have some deviation from the experimental ones. However, in GLDM2 more physical information is considered. On the one hand, the ν_0 is not a simple constant, which is correlated with the kinetic energies of the α particles. On the other hand, the preformation factor S_α in the parent nucleus plays an important role in the α-decay process. In the S_α expression (Eq. (5)), more microscopic nuclear structure information is taken into account, such as the shell effect, odd-even effect, and isospin effect. Thus the GLDM2 can reproduce the experimental half-lives better than other models (formulas). Similar conclusion can be found in our previous work [29]. However, from the 7th column of Table 1 we find that the each ratio between the calculated half-life and the experimental one of six isotopes (^{187}Bi, ^{232}Am, ^{243}Es, ^{258}Db, ^{260}Bh, and ^{272}Rg)

Table 1
The experimental and calculated α-decay half-lives of 120 neutron-deficient nuclei with $Z = 80 - 118$. The experimental half-lives and Q_α values are taken from Refs. [38,44–50,56–58].

Nuclei	Q_α (MeV)	l	$T_{1/2}^{\mathrm{Exp.}}$ (s)	$T_{1/2}^{\mathrm{ELDM}}$ (s)	$T_{1/2}^{\mathrm{GLDM1}}$ (s)	$T_{1/2}^{\mathrm{GLDM2}}$ (s)	$T_{1/2}^{\mathrm{Royer}}$ (s)	$T_{1/2}^{\mathrm{Denisov}}$ (s)
^{171}Hg	7.668	0	7.00×10^{-5}	2.56×10^{-4}	9.07×10^{-4}	1.90×10^{-4}	1.25×10^{-4}	1.27×10^{-4}
^{172}Hg	7.524	0	2.31×10^{-4}	6.61×10^{-4}	2.35×10^{-3}	2.80×10^{-4}	2.90×10^{-4}	3.05×10^{-4}
^{173}Hg	7.373	0	7.00×10^{-4}	1.84×10^{-3}	6.59×10^{-3}	1.20×10^{-3}	9.69×10^{-4}	1.06×10^{-3}
^{174}Hg	7.233	0	1.91×10^{-3}	4.93×10^{-3}	1.78×10^{-2}	2.00×10^{-3}	2.27×10^{-3}	2.34×10^{-3}
^{177}Tl	7.067	0	2.47×10^{-2}	4.11×10^{-2}	1.47×10^{-1}	2.96×10^{-2}	2.37×10^{-2}	2.69×10^{-2}
^{178}Tl	7.020	0	4.79×10^{-1}	5.68×10^{-2}	1.89×10^{-1}	1.00×10^{-1}	6.85×10^{-2}	7.23×10^{-2}
^{179}Tl	6.718	0	2.30×10^{-1}	6.45×10^{-1}	2.17×10^{0}	4.33×10^{-1}	4.17×10^{-1}	5.10×10^{-1}
^{178}Pb	7.790	0	1.20×10^{-4}	5.22×10^{-4}	1.69×10^{-3}	3.32×10^{-4}	2.57×10^{-4}	2.42×10^{-4}
^{179}Pb	7.598	2	3.50×10^{-3}	3.07×10^{-3}	1.05×10^{-2}	1.39×10^{-2}	3.45×10^{-3}	4.44×10^{-3}
^{180}Pb	7.419	0	4.10×10^{-3}	6.58×10^{-3}	2.17×10^{-2}	4.13×10^{-3}	3.46×10^{-3}	3.19×10^{-3}
^{185}Bi	8.140	0	5.80×10^{-4}	9.41×10^{-5}	2.93×10^{-4}	2.02×10^{-4}	4.16×10^{-5}	4.33×10^{-5}
^{186}Bi	7.423	4	1.02×10^{-2}	6.32×10^{-2}	3.95×10^{-2}	1.10×10^{-1}	9.34×10^{-2}	1.30×10^{-1}
^{187}Bi	7.778	5	4.22×10^{-1}	1.01×10^{-2}	3.81×10^{-2}	2.36×10^{-2}	1.14×10^{-2}	2.63×10^{-2}
^{186}Po	8.503	0	2.80×10^{-5}	2.25×10^{-5}	6.53×10^{-5}	8.10×10^{-6}	1.13×10^{-5}	9.43×10^{-6}
^{188}Po	8.083	0	3.50×10^{-4}	2.94×10^{-4}	8.77×10^{-4}	1.13×10^{-4}	1.60×10^{-4}	1.31×10^{-4}
^{189}Po	7.695	0	4.38×10^{-2}	4.02×10^{-3}	1.21×10^{-2}	6.13×10^{-3}	2.46×10^{-3}	3.19×10^{-3}
^{191}At	7.822	0	1.70×10^{-3}	3.80×10^{-3}	1.12×10^{-2}	4.64×10^{-3}	2.20×10^{-3}	2.67×10^{-3}
^{192}At	7.696	0	1.15×10^{-2}	8.94×10^{-3}	2.66×10^{-2}	1.80×10^{-2}	1.16×10^{-2}	1.52×10^{-2}
^{193}At	7.572	0	2.90×10^{-2}	2.12×10^{-2}	5.98×10^{-2}	2.35×10^{-2}	1.32×10^{-2}	1.68×10^{-2}
^{194}At	7.454	0	2.86×10^{-1}	4.93×10^{-2}	1.41×10^{-1}	7.96×10^{-2}	6.47×10^{-2}	9.13×10^{-2}
^{193}Rn	8.042	0	4.42×10^{-3}	1.91×10^{-3}	5.24×10^{-3}	1.77×10^{-3}	1.23×10^{-3}	1.65×10^{-3}
^{194}Rn	7.862	0	7.80×10^{-4}	6.37×10^{-3}	1.77×10^{-2}	1.87×10^{-3}	4.27×10^{-3}	3.11×10^{-3}
^{195}Rn	7.694	0	6.02×10^{-3}	2.05×10^{-2}	5.77×10^{-2}	1.90×10^{-2}	1.43×10^{-2}	2.10×10^{-2}
^{196}Rn	7.617	0	4.41×10^{-3}	3.44×10^{-2}	9.58×10^{-2}	1.12×10^{-2}	2.39×10^{-2}	1.71×10^{-2}
^{197}Fr	7.900	3	2.33×10^{-3}	2.71×10^{-2}	2.92×10^{-2}	8.04×10^{-3}	1.72×10^{-1}	3.23×10^{-1}
^{198}Fr	7.869	0	1.50×10^{-2}	1.29×10^{-2}	3.52×10^{-2}	8.98×10^{-3}	1.78×10^{-2}	2.70×10^{-2}
^{199}Fr	7.817	0	6.60×10^{-3}	1.80×10^{-2}	4.94×10^{-2}	1.36×10^{-2}	1.19×10^{-2}	1.60×10^{-2}
^{200}Fr	7.623	0	4.90×10^{-2}	7.18×10^{-2}	2.01×10^{-1}	5.32×10^{-2}	1.00×10^{-1}	1.64×10^{-1}
^{201}Ra	8.002	0	2.00×10^{-2}	1.11×10^{-2}	2.84×10^{-2}	6.74×10^{-3}	8.17×10^{-3}	1.25×10^{-2}
^{202}Ra	7.880	0	1.60×10^{-2}	2.55×10^{-2}	6.44×10^{-2}	6.94×10^{-3}	1.99×10^{-2}	1.28×10^{-2}
^{203}Ra	7.742	0	3.10×10^{-2}	6.73×10^{-2}	1.71×10^{-1}	4.31×10^{-2}	5.25×10^{-2}	8.59×10^{-2}
^{204}Ra	7.636	0	5.70×10^{-2}	1.43×10^{-1}	3.67×10^{-1}	4.71×10^{-2}	1.16×10^{-1}	7.29×10^{-2}
^{205}Ac	8.090	0	2.00×10^{-2}	1.27×10^{-2}	3.15×10^{-2}	6.92×10^{-3}	8.79×10^{-3}	1.24×10^{-2}
^{206}Ac	7.944	0	2.20×10^{-2}	3.42×10^{-2}	8.65×10^{-2}	1.62×10^{-2}	4.99×10^{-2}	9.08×10^{-2}
^{207}Ac	7.840	0	2.70×10^{-2}	7.03×10^{-2}	1.80×10^{-1}	4.41×10^{-2}	5.25×10^{-2}	7.79×10^{-2}
^{208}Ac	7.720	0	9.60×10^{-2}	1.65×10^{-1}	4.22×10^{-1}	1.13×10^{-1}	2.41×10^{-1}	4.72×10^{-1}
^{208}Th	8.200	0	2.40×10^{-3}	1.28×10^{-2}	3.13×10^{-2}	3.40×10^{-3}	1.12×10^{-2}	6.43×10^{-3}
^{210}Th	8.053	0	9.00×10^{-3}	3.34×10^{-2}	7.69×10^{-2}	1.04×10^{-2}	2.96×10^{-2}	1.68×10^{-2}
^{211}Th	7.942	0	3.70×10^{-2}	7.14×10^{-2}	1.67×10^{-1}	4.26×10^{-2}	5.93×10^{-2}	1.04×10^{-1}
^{212}Pa	8.429	0	5.10×10^{-3}	5.58×10^{-3}	1.26×10^{-2}	2.55×10^{-3}	8.35×10^{-3}	1.62×10^{-2}
^{213}Pa	8.390	0	5.30×10^{-3}	6.97×10^{-3}	1.59×10^{-2}	3.70×10^{-3}	4.96×10^{-3}	7.37×10^{-3}
^{215}Pa	8.240	0	1.40×10^{-2}	1.80×10^{-2}	4.13×10^{-2}	1.17×10^{-2}	1.33×10^{-2}	2.04×10^{-2}
^{216}Pa	8.098	0	3.55×10^{-1}	4.73×10^{-2}	1.09×10^{-1}	7.62×10^{-2}	7.15×10^{-2}	1.54×10^{-1}
^{215}U	8.588	0	7.30×10^{-4}	4.13×10^{-3}	8.96×10^{-3}	1.94×10^{-3}	3.30×10^{-3}	5.61×10^{-3}
^{216}U	8.542	0	4.72×10^{-3}	5.37×10^{-3}	1.17×10^{-2}	1.82×10^{-3}	5.13×10^{-3}	2.63×10^{-3}
^{217}U	8.169	0	1.60×10^{-2}	6.80×10^{-2}	1.54×10^{-1}	4.20×10^{-2}	6.05×10^{-2}	1.13×10^{-1}
^{218}U	8.775	0	5.10×10^{-4}	1.09×10^{-3}	2.25×10^{-3}	1.29×10^{-3}	9.89×10^{-4}	5.02×10^{-4}

(*continued on next page*)

Table 1 (*continued*)

Nuclei	Q_α (MeV)	l	$T_{1/2}^{\text{Exp.}}$ (s)	$T_{1/2}^{\text{ELDM}}$ (s)	$T_{1/2}^{\text{GLDM1}}$ (s)	$T_{1/2}^{\text{GLDM2}}$ (s)	$T_{1/2}^{\text{Royer}}$ (s)	$T_{1/2}^{\text{Denisov}}$ (s)
^{219}Np	9.207	0	1.50×10^{-4}	1.68×10^{-4}	3.33×10^{-4}	6.29×10^{-4}	1.04×10^{-4}	1.49×10^{-4}
^{223}Np	9.650	0	2.15×10^{-6}	1.13×10^{-5}	2.19×10^{-5}	9.15×10^{-6}	5.74×10^{-6}	7.75×10^{-6}
^{225}Np	8.790	0	3.60×10^{-3}	1.77×10^{-3}	3.63×10^{-3}	9.67×10^{-4}	1.21×10^{-3}	1.87×10^{-3}
^{226}Np	8.200	0	3.50×10^{-2}	9.42×10^{-2}	2.06×10^{-1}	4.86×10^{-2}	1.49×10^{-1}	3.84×10^{-1}
^{228}Pu	7.940	0	1.10×10^{0}	1.50×10^{0}	3.01×10^{0}	3.60×10^{-1}	4.68×10^{-1}	7.99×10^{-1}
^{229}Pu	7.590	0	9.00×10^{1}	2.31×10^{1}	4.67×10^{1}	8.05×10^{0}	2.64×10^{1}	6.51×10^{1}
^{230}Pu	7.182	0	1.26×10^{2}	7.39×10^{2}	1.51×10^{3}	1.44×10^{2}	2.13×10^{2}	4.20×10^{2}
^{231}Pu	6.839	0	5.16×10^{3}	1.74×10^{4}	3.61×10^{4}	6.01×10^{3}	2.35×10^{4}	7.26×10^{4}
^{232}Am	7.300	0	2.63×10^{3}	6.47×10^{2}	1.32×10^{3}	1.63×10^{2}	1.15×10^{3}	4.75×10^{3}
^{233}Am	7.060	0	4.27×10^{3}	5.49×10^{3}	1.15×10^{4}	1.78×10^{3}	7.72×10^{3}	1.84×10^{4}
^{233}Cm	7.470	0	1.35×10^{2}	3.77×10^{2}	7.59×10^{2}	1.05×10^{2}	5.08×10^{2}	1.46×10^{3}
^{234}Cm	7.365	0	1.28×10^{2}	9.07×10^{2}	1.86×10^{3}	1.71×10^{2}	2.88×10^{2}	5.35×10^{2}
^{236}Cm	7.067	0	2.27×10^{3}	1.27×10^{4}	2.32×10^{4}	1.88×10^{3}	3.82×10^{3}	7.51×10^{3}
^{237}Cf	8.220	0	1.14×10^{0}	4.96×10^{0}	8.57×10^{0}	1.06×10^{0}	6.36×10^{0}	1.68×10^{1}
^{240}Cf	7.719	0	9.76×10^{1}	2.41×10^{2}	4.35×10^{2}	3.82×10^{1}	8.53×10^{1}	1.43×10^{2}
^{223}Np	9.650	0	2.15×10^{-6}	1.13×10^{-5}	2.19×10^{-5}	9.15×10^{-6}	5.74×10^{-6}	7.75×10^{-6}
^{225}Np	8.790	0	3.60×10^{-3}	1.77×10^{-3}	3.63×10^{-3}	9.67×10^{-4}	1.21×10^{-3}	1.87×10^{-3}
^{226}Np	8.200	0	3.50×10^{-2}	9.42×10^{-2}	2.06×10^{-1}	4.86×10^{-2}	1.49×10^{-1}	3.84×10^{-1}
^{228}Pu	7.940	0	1.10×10^{0}	1.50×10^{0}	3.01×10^{0}	3.60×10^{-1}	4.68×10^{-1}	7.99×10^{-1}
^{229}Pu	7.590	0	9.00×10^{1}	2.31×10^{1}	4.67×10^{1}	8.05×10^{0}	2.64×10^{1}	6.51×10^{1}
^{230}Pu	7.182	0	1.26×10^{2}	7.39×10^{2}	1.51×10^{3}	1.44×10^{2}	2.13×10^{2}	4.20×10^{2}
^{231}Pu	6.839	0	5.16×10^{3}	1.74×10^{4}	3.61×10^{4}	6.01×10^{3}	2.35×10^{4}	7.26×10^{4}
^{232}Am	7.300	0	2.63×10^{3}	6.47×10^{2}	1.32×10^{3}	1.63×10^{2}	1.15×10^{3}	4.75×10^{3}
^{233}Am	7.060	0	4.27×10^{3}	5.49×10^{3}	1.15×10^{4}	1.78×10^{3}	7.72×10^{3}	1.84×10^{4}
^{233}Cm	7.470	0	1.35×10^{2}	3.77×10^{2}	7.59×10^{2}	1.05×10^{2}	5.08×10^{2}	1.46×10^{3}
^{234}Cm	7.365	0	1.28×10^{2}	9.07×10^{2}	1.86×10^{3}	1.71×10^{2}	2.88×10^{2}	5.35×10^{2}
^{236}Cm	7.067	0	2.27×10^{3}	1.27×10^{4}	2.32×10^{4}	1.88×10^{3}	3.82×10^{3}	7.51×10^{3}
^{237}Cf	8.220	0	1.14×10^{0}	4.96×10^{0}	8.57×10^{0}	1.06×10^{0}	6.36×10^{0}	1.68×10^{1}
^{240}Cf	7.719	0	9.76×10^{1}	2.41×10^{2}	4.35×10^{2}	3.82×10^{1}	8.53×10^{1}	1.43×10^{2}
^{242}Es	8.160	0	3.12×10^{1}	1.62×10^{1}	2.90×10^{1}	4.96×10^{0}	3.23×10^{1}	1.48×10^{2}
^{243}Es	8.072	0	3.29×10^{2}	3.11×10^{1}	5.51×10^{1}	1.59×10^{1}	4.19×10^{1}	9.80×10^{1}
^{243}Fm	8.690	0	2.54×10^{-1}	7.52×10^{-1}	1.25×10^{0}	2.49×10^{-1}	9.67×10^{-1}	2.55×10^{0}
^{246}Md	8.890	0	9.20×10^{-1}	3.95×10^{-1}	5.98×10^{-1}	1.51×10^{-1}	8.11×10^{-1}	3.63×10^{0}
^{247}Md	8.764	1	1.20×10^{0}	1.05×10^{0}	1.42×10^{0}	6.51×10^{-1}	5.53×10^{1}	6.20×10^{1}
^{251}No	8.752	0	9.64×10^{-1}	2.06×10^{0}	3.14×10^{0}	4.83×10^{0}	2.93×10^{0}	8.55×10^{0}
^{253}Lr	8.918	0	7.02×10^{-1}	1.40×10^{0}	2.09×10^{0}	4.93×10^{0}	1.91×10^{0}	4.62×10^{0}
^{254}Lr	8.816	0	2.38×10^{1}	2.79×10^{0}	3.88×10^{0}	3.14×10^{1}	6.14×10^{0}	3.40×10^{1}
^{255}Rf	9.055	1	3.46×10^{0}	1.35×10^{0}	1.61×10^{0}	6.09×10^{0}	2.62×10^{2}	2.57×10^{2}
^{256}Rf	8.923	0	2.08×10^{0}	2.87×10^{0}	3.98×10^{0}	1.72×10^{0}	1.40×10^{0}	1.74×10^{0}
^{256}Db	9.340	0	2.84×10^{0}	3.82×10^{-1}	5.09×10^{-1}	2.63×10^{0}	8.87×10^{-1}	5.05×10^{0}
^{257}Db	9.206	0	2.45×10^{0}	9.08×10^{-1}	1.20×10^{0}	5.00×10^{0}	1.31×10^{0}	3.30×10^{0}
^{258}Db	9.500	0	5.58×10^{0}	1.24×10^{-1}	1.60×10^{-1}	2.71×10^{-1}	2.80×10^{-1}	1.54×10^{0}
^{259}Sg	9.804	0	3.11×10^{-1}	3.90×10^{-2}	4.72×10^{-2}	2.05×10^{-1}	5.54×10^{-2}	1.59×10^{-1}
^{260}Sg	9.901	0	1.24×10^{-2}	2.07×10^{-2}	2.49×10^{-2}	1.33×10^{-2}	1.12×10^{-2}	1.15×10^{-2}
^{261}Sg	9.714	0	1.87×10^{-1}	6.38×10^{-2}	7.95×10^{-2}	2.85×10^{-1}	9.17×10^{-2}	2.69×10^{-1}
^{260}Bh	10.400	0	3.50×10^{-2}	2.35×10^{-3}	2.64×10^{-3}	2.87×10^{-3}	5.29×10^{-3}	2.77×10^{-2}
^{261}Bh	10.500	0	1.18×10^{-2}	1.28×10^{-3}	1.47×10^{-3}	6.64×10^{-3}	1.39×10^{-3}	3.14×10^{-3}
^{264}Hs	10.591	0	1.60×10^{-3}	1.48×10^{-3}	1.53×10^{-3}	1.04×10^{-3}	8.64×10^{-4}	7.87×10^{-4}

Table 1 (*continued*)

Nuclei	Q_α (MeV)	l	$T_{1/2}^{\mathrm{Exp.}}$ (s)	$T_{1/2}^{\mathrm{ELDM}}$ (s)	$T_{1/2}^{\mathrm{GLDM1}}$ (s)	$T_{1/2}^{\mathrm{GLDM2}}$ (s)	$T_{1/2}^{\mathrm{Royer}}$ (s)	$T_{1/2}^{\mathrm{Denisov}}$ (s)
^{265}Hs	10.470	0	1.96×10^{-3}	2.83×10^{-3}	2.96×10^{-3}	1.18×10^{-2}	3.80×10^{-3}	1.06×10^{-2}
^{266}Hs	10.346	0	2.30×10^{-3}	5.58×10^{-3}	5.94×10^{-3}	3.47×10^{-3}	3.27×10^{-3}	3.06×10^{-3}
^{267}Ds	11.780	0	1.00×10^{-5}	1.17×10^{-5}	1.21×10^{-5}	6.41×10^{-5}	1.25×10^{-5}	3.05×10^{-5}
^{269}Ds	11.509	0	1.79×10^{-4}	4.13×10^{-5}	4.29×10^{-5}	1.89×10^{-4}	4.73×10^{-5}	1.21×10^{-4}
^{270}Ds	11.117	0	2.05×10^{-4}	3.01×10^{-4}	3.05×10^{-4}	2.24×10^{-4}	1.88×10^{-4}	1.54×10^{-4}
^{271}Ds	10.870	0	1.63×10^{-3}	1.10×10^{-3}	1.12×10^{-3}	4.16×10^{-3}	1.50×10^{-3}	4.32×10^{-3}
^{272}Rg	11.197	0	3.80×10^{-3}	3.81×10^{-4}	3.73×10^{-4}	3.13×10^{-4}	9.05×10^{-4}	5.66×10^{-3}
^{278}Rg	10.850	0	4.20×10^{-3}	2.03×10^{-3}	1.88×10^{-3}	2.48×10^{-3}	4.89×10^{-3}	3.37×10^{-2}
^{279}Rg	10.520	0	1.70×10^{-1}	1.29×10^{-2}	1.24×10^{-2}	2.79×10^{-2}	1.77×10^{-2}	4.78×10^{-2}
^{280}Rg	9.891	0	3.53×10^{0}	5.96×10^{-1}	6.00×10^{-1}	9.60×10^{-1}	1.59×10^{0}	1.38×10^{1}
^{281}Rg	9.414	0	1.70×10^{2}	1.42×10^{1}	1.50×10^{1}	2.93×10^{1}	2.77×10^{1}	8.95×10^{1}
^{282}Rg	9.084	0	1.86×10^{2}	1.47×10^{2}	1.61×10^{2}	3.11×10^{2}	4.13×10^{2}	4.49×10^{3}
^{277}Cn	11.620	0	6.90×10^{-4}	7.42×10^{-5}	6.87×10^{-5}	2.34×10^{-4}	9.26×10^{-5}	2.58×10^{-4}
^{281}Cn	10.460	0	1.30×10^{-1}	3.70×10^{-2}	3.37×10^{-2}	8.17×10^{-2}	6.31×10^{-2}	2.19×10^{-1}
^{283}Cn	9.670	0	3.80×10^{0}	5.21×10^{0}	4.92×10^{0}	1.02×10^{1}	1.09×10^{1}	4.48×10^{1}
^{284}Cn	9.301	0	9.81×10^{0}	6.61×10^{1}	6.42×10^{1}	3.03×10^{1}	4.42×10^{1}	4.45×10^{1}
^{285}Cn	9.320	0	3.20×10^{1}	5.57×10^{1}	5.47×10^{1}	9.47×10^{1}	1.25×10^{2}	5.62×10^{2}
^{278}Nh	11.850	0	2.40×10^{-4}	4.61×10^{-5}	4.19×10^{-5}	3.06×10^{-5}	1.07×10^{-4}	6.98×10^{-4}
^{282}Nh	10.780	0	7.00×10^{-2}	1.18×10^{-2}	1.02×10^{-2}	1.05×10^{-2}	3.15×10^{-2}	2.60×10^{-1}
^{283}Nh	10.265	0	1.02×10^{-1}	2.47×10^{-1}	2.15×10^{-1}	5.66×10^{-1}	4.29×10^{-1}	1.31×10^{0}
^{284}Nh	10.112	0	9.43×10^{-1}	6.22×10^{-1}	5.56×10^{-1}	6.81×10^{-1}	1.78×10^{0}	1.73×10^{1}
^{285}Nh	9.840	0	3.22×10^{0}	3.52×10^{0}	3.25×10^{0}	7.17×10^{0}	6.95×10^{0}	2.28×10^{1}
^{286}Nh	9.432	0	2.00×10^{1}	5.61×10^{1}	5.38×10^{1}	7.90×10^{1}	1.67×10^{2}	1.96×10^{3}
^{285}Fl	10.540	0	4.70×10^{-1}	9.36×10^{-2}	7.74×10^{-2}	2.16×10^{-1}	1.79×10^{-1}	6.80×10^{-1}
^{286}Fl	10.370	0	3.50×10^{-1}	2.54×10^{-1}	2.19×10^{-1}	1.50×10^{-1}	1.91×10^{-1}	1.60×10^{-1}
^{287}Fl	10.160	0	5.20×10^{-1}	9.15×10^{-1}	8.01×10^{-1}	1.87×10^{0}	1.92×10^{0}	7.90×10^{0}
^{288}Fl	10.072	0	7.50×10^{-1}	1.55×10^{0}	1.36×10^{0}	8.06×10^{-1}	1.16×10^{0}	1.01×10^{0}
^{289}Fl	9.970	0	2.40×10^{0}	2.92×10^{0}	2.59×10^{0}	5.01×10^{0}	6.36×10^{0}	2.74×10^{1}
^{287}Mc	10.740	0	1.20×10^{-1}	5.72×10^{-2}	4.52×10^{-2}	1.34×10^{-1}	9.85×10^{-2}	3.06×10^{-1}
^{288}Mc	10.630	0	1.90×10^{-1}	1.06×10^{-1}	8.40×10^{-2}	7.77×10^{-2}	3.12×10^{-1}	3.17×10^{0}
^{289}Mc	10.489	0	2.00×10^{-1}	2.40×10^{-1}	1.93×10^{-1}	4.77×10^{-1}	4.44×10^{-1}	1.44×10^{0}
^{290}Mc	10.450	0	1.30×10^{0}	2.95×10^{-1}	2.38×10^{-1}	2.57×10^{-1}	8.74×10^{-1}	9.35×10^{0}
^{290}Lv	10.990	0	8.00×10^{-3}	2.57×10^{-2}	1.92×10^{-2}	1.67×10^{-2}	2.10×10^{-2}	1.56×10^{-2}
^{291}Lv	10.890	0	2.80×10^{-2}	4.41×10^{-2}	3.31×10^{-2}	8.62×10^{-2}	8.72×10^{-2}	3.43×10^{-1}
^{292}Lv	10.774	0	2.40×10^{-2}	8.41×10^{-2}	6.41×10^{-2}	4.80×10^{-2}	6.86×10^{-2}	5.23×10^{-2}
^{293}Lv	10.680	0	8.00×10^{-2}	1.42×10^{-1}	1.11×10^{-1}	2.40×10^{-1}	2.94×10^{-1}	1.21×10^{0}
^{293}Ts	11.180	0	1.46×10^{-2}	1.66×10^{-2}	1.15×10^{-2}	3.18×10^{-2}	2.83×10^{-2}	9.00×10^{-2}
^{294}Ts	11.200	0	5.10×10^{-2}	1.43×10^{-2}	9.94×10^{-3}	8.02×10^{-3}	4.24×10^{-2}	4.51×10^{-1}
^{294}Og	11.810	0	1.40×10^{-3}	1.10×10^{-3}	7.44×10^{-4}	8.14×10^{-4}	9.52×10^{-4}	6.20×10^{-4}

is not within the factor of 0.1. To explain the reason, the extracted S_α values from Eq. (5) and the experimental S_α values are given in Table 3. From Table 3, we see the S_α values from Eq. (5) deviate largely from the experimental ones. As a result, the estimated α-decay half-lives are not in agreement with the experimental data. But as a whole, the GLDM2 is a successful model to calculate the α-decay half-lives.

Encouraged by the good agreement with the GLDM2, the α-decay half-lives of the neutron-deficient nuclei where the experimental data are not available are predicted by it. We know that

Table 2
The $\overline{\sigma}$ and the $\sqrt{\overline{\sigma^2}}$ values between the experimental and calculated α-decay half-lives for the 120 neutron-deficient nuclei using different models (formulas).

Models (Formulas)	$\overline{\sigma}$	$\sqrt{\overline{\sigma^2}}$
ELDM [32–36]	0.465	0.576
GLDM1 [52]	0.577	0.677
GLDM2 [53]	0.407	0.512
Royer [41]	0.445	0.577
Denisov [42,43]	0.563	0.713

Table 3
The experimental and theoretical S_α values. The experimental S_α values are extracted by the method of Ref. [54]. The theoretical S_α values are calculated by Eq. (5).

Nuclei	S_α (Expt.)	S_α (Theo.)
^{187}Bi	6.31×10^{-4}	1.13×10^{-2}
^{232}Am	3.90×10^{-3}	6.33×10^{-2}
^{243}Es	1.26×10^{-3}	2.61×10^{-2}
^{258}Db	2.03×10^{-4}	4.17×10^{-3}
^{260}Bh	5.12×10^{-4}	6.25×10^{-3}
^{272}Rg	6.52×10^{-4}	7.91×10^{-3}

the Q_α value plays an important role in the α-decay half-life. Its value is usually derived by the relationship between the Q_α value and the nuclear mass excesses *M(Z,N)*

$$Q_\alpha(Z,N) = M(Z,N) - M(Z-2,N-2) - M(2,2). \tag{13}$$

Nowadays, many nuclear mass models with different accuracies have been developed [59–66]. Among these mass models, the rms deviation of the WS4 mass model with respect to the 2353 known masses fall to 0.298 MeV [66]. Moreover, recent studies indicate that the WS4 mass model is more accurate than the other mass models by systematic analysis [14,67]. So in present work, we select the WS4 mass model to get the Q_α values. By inputting the WS4 Q_α values the predicted α-decay half-lives with $Z = 80 - 120$ of the unmeasured neutron-deficient nuclei within the GLDM2 are listed in Table 4. We hope it may be useful for future experiments.

4. Conclusions

In this article, the α-decay half-lives of 120 neutron-deficient nuclei with $Z = 80 - 118$ have been studied by the ELDM, GLDM1, GLDM2, Royer formula, and Denisov formula. According to the comparison between the calculated half-lives and the experimental ones, it is found that the GLDM2 is the most accurate model to reproduce the experimental data among those models (formulas) because more nuclear structure information is taken into account in it. Additionally, by inputting the WS4 Q_α values the α-decay half-lives of some unmeasured neutron-deficient nuclei with $Z = 80 - 120$ are predicted by GLDM2. These predictions are helpful for future measurements.

Table 4
The predicted half-lives of neutron-deficient nuclei with $Z = 80 - 120$ using the GLDM2 by inputting the Q_α values extracted from the WS4 mass model.

Nuclei	Q_α^{WS4} (MeV)	$T_{1/2}^{\mathrm{GLDM2}}$ (s)
^{169}Hg	7.887	6.28×10^{-5}
^{170}Hg	7.849	3.95×10^{-5}
^{174}Tl	7.569	1.19×10^{-3}
^{175}Tl	7.468	1.68×10^{-3}
^{176}Pb	7.873	2.35×10^{-4}
^{177}Pb	7.688	6.31×10^{-3}
^{182}Bi	8.345	7.62×10^{-4}
^{183}Bi	8.058	4.46×10^{-4}
^{184}Po	9.151	2.24×10^{-7}
^{185}Po	8.966	2.98×10^{-6}
^{189}At	8.456	7.88×10^{-5}
^{190}At	8.153	1.06×10^{-3}
^{191}Rn	8.493	1.09×10^{-4}
^{192}Rn	8.225	1.60×10^{-4}
^{195}Fr	8.319	5.09×10^{-4}
^{196}Fr	8.212	9.54×10^{-4}
^{199}Ra	8.195	1.93×10^{-3}
^{200}Ra	8.032	2.36×10^{-3}
^{203}Ac	8.513	3.87×10^{-4}
^{204}Ac	8.361	7.31×10^{-4}
^{206}Th	8.577	2.32×10^{2}
^{207}Th	8.366	2.03×10^{-3}
^{209}Pa	8.597	7.93×10^{-4}
^{210}Pa	8.359	2.82×10^{-3}
^{213}U	8.822	3.79×10^{-4}
^{214}U	9.157	3.01×10^{-5}
^{221}Np	10.551	1.94×10^{-7}
^{222}Np	10.077	1.61×10^{-6}
^{226}Pu	8.792	1.29×10^{-3}
^{227}Pu	8.518	9.84×10^{-3}
^{228}Am	8.707	4.36×10^{-3}
^{229}Am	8.321	6.98×10^{-2}
^{231}Cm	8.160	4.41×10^{-1}
^{232}Cm	7.995	1.15×10^{0}
^{232}Bk	8.620	1.92×10^{-2}
^{233}Bk	8.467	8.95×10^{-2}
^{235}Cf	8.803	1.52×10^{-2}
^{236}Cf	8.637	4.32×10^{-2}
^{238}Es	8.871	1.04×10^{-2}
^{239}Es	8.666	9.05×10^{-2}
^{239}Fm	9.318	2.04×10^{-3}
^{240}Fm	9.113	8.01×10^{-3}
^{243}Md	9.194	1.27×10^{-2}
^{244}Md	9.285	4.87×10^{-3}
^{246}No	10.002	1.23×10^{-4}
^{247}No	9.841	7.82×10^{-4}

(*continued on next page*)

Table 4 (*continued*)

Nuclei	Q_α^{WS4} (MeV)	$T_{1/2}^{\mathrm{GLDM2}}$ (s)
^{249}Lr	9.893	1.53×10^{-3}
^{250}Lr	9.598	1.09×10^{-2}
^{251}Rf	9.824	6.26×10^{-3}
^{252}Rf	9.556	1.07×10^{-2}
^{253}Db	9.804	2.07×10^{-2}
^{254}Db	9.595	1.10×10^{-1}
^{256}Sg	9.747	1.91×10^{-2}
^{257}Sg	9.711	2.91×10^{-1}
^{258}Bh	10.205	2.87×10^{-2}
^{259}Bh	10.243	3.77×10^{-2}
^{261}Hs	10.956	1.45×10^{-3}
^{262}Hs	11.017	1.39×10^{-4}
^{263}Mt	11.721	5.84×10^{-5}
^{264}Mt	11.669	9.68×10^{-6}
^{261}Ds	12.147	6.75×10^{-6}
^{262}Ds	12.224	2.96×10^{-6}
^{263}Ds	12.337	9.14×10^{-6}
^{264}Ds	12.387	1.05×10^{-6}
^{265}Ds	12.334	6.87×10^{-6}
^{266}Ds	12.172	2.07×10^{-6}
^{266}Rg	12.728	1.92×10^{-7}
^{267}Rg	12.545	5.24×10^{-6}
^{268}Rg	12.240	1.72×10^{-6}
^{269}Rg	11.925	6.63×10^{-5}
^{270}Rg	11.637	3.13×10^{-5}
^{271}Rg	11.373	7.66×10^{-4}
^{270}Cn	12.285	5.28×10^{-6}
^{271}Cn	12.061	6.96×10^{-5}
^{272}Cn	11.862	3.04×10^{-5}
^{273}Cn	11.640	3.50×10^{-4}
^{274}Cn	11.548	9.89×10^{-5}
^{275}Cn	11.741	1.65×10^{-4}
^{272}Nh	12.512	1.31×10^{-6}
^{273}Nh	12.325	3.48×10^{-5}
^{274}Nh	12.084	8.33×10^{-6}
^{275}Nh	11.934	1.63×10^{-4}
^{276}Nh	12.064	1.02×10^{-5}
^{277}Nh	12.201	3.73×10^{-5}
^{278}Fl	12.519	4.47×10^{-6}
^{279}Fl	12.430	2.56×10^{-5}
^{280}Fl	12.226	1.34×10^{-5}
^{281}Fl	11.816	3.42×10^{-4}
^{282}Fl	11.378	7.05×10^{-4}
^{283}Fl	10.879	3.68×10^{-2}
^{281}Mc	12.203	1.37×10^{-4}
^{282}Mc	11.777	1.15×10^{-4}
^{283}Mc	11.324	8.03×10^{-3}
^{284}Mc	10.933	1.08×10^{-2}
^{285}Mc	10.730	1.87×10^{-1}

Table 4 (*continued*)

Nuclei	Q_α^{WS4} (MeV)	$T_{1/2}^{\mathrm{GLDM2}}$ (s)
^{286}Mc	10.501	1.61×10^{-1}
^{283}Lv	12.107	3.76×10^{-4}
^{284}Lv	11.832	3.52×10^{-4}
^{285}Lv	11.549	4.80×10^{-3}
^{286}Lv	11.312	4.38×10^{-3}
^{287}Lv	11.284	1.60×10^{-2}
^{288}Lv	11.290	3.83×10^{-3}
^{285}Ts	12.445	1.53×10^{-4}
^{286}Ts	12.267	2.52×10^{-5}
^{287}Ts	12.052	7.56×10^{-4}
^{288}Ts	11.982	1.03×10^{-4}
^{289}Ts	11.987	7.80×10^{-4}
^{290}Ts	11.839	2.33×10^{-4}
^{288}Og	12.616	3.47×10^{-5}
^{289}Og	12.592	1.10×10^{-4}
^{290}Og	12.601	2.98×10^{-5}
^{291}Og	12.420	1.91×10^{-4}
^{292}Og	12.240	1.32×10^{-4}
^{293}Og	12.242	3.53×10^{-4}
^{289}119	13.175	2.16×10^{-5}
^{290}119	13.067	1.66×10^{-6}
^{291}119	13.048	2.90×10^{-5}
^{292}119	12.902	3.76×10^{-6}
^{293}119	12.715	9.87×10^{-5}
^{294}119	12.726	7.97×10^{-6}
^{291}120	13.509	1.03×10^{-5}
^{292}120	13.468	3.74×10^{-6}
^{293}120	13.400	1.26×10^{-5}
^{294}120	13.242	6.73×10^{-6}
^{295}120	13.272	1.48×10^{-5}
^{296}120	13.343	3.46×10^{-6}

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