α-decay half-lives: Empirical relations

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Sets of simple relations for evaluation of the half-lives of α transitions between the ground states of parent and daughter nuclei are presented. Experimental data for half-lives in 344 α emitters are used for obtaining the sets of equations. The sets of simple expressions are found for the whole data set as well as for heavy and light subsets of nuclei. Terms related to the orbital moment and parity of α transition are introduced for the case of α decay in even-odd, odd-even, and odd-odd nuclei. The electron screening effect is taken into account.

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I. INTRODUCTION

Since the work of Gamow [1] and Condon and Gurney [2], who formulated the α-decay theory in 1928, α-decay has been an important and hot topic of nuclear physics. It is very important to have simple and accurate expressions for the evaluation of α-decay half-lives. The first empirical formula for α-decay half-lives was presented by Geiger and Nuttall in 1911 [3]. Since then, many other empirical relationships have been proposed by various authors; see, for example, Refs. [4–12] and references cited therein. Some empirical relationships [4,5,8,10] use one set of parameters for all sets of nuclei, while other ones are more detailed and take into account differences between even-even (e-e), even-odd (e-o), odd-even (o-e), and odd-odd (o-o) nuclei [7,9,11,12].

In general, experimentalists would like to evaluate expected half-life values during experiment design. This is especially important for α-decay studies of superheavy elements [13–16] or nuclei, which are very far from the stability line [17–20], because such processes are very rare and difficult to observe. That is why simple and accurate empirical relationships are still claimed. As a consequence, many empirical expressions have appeared during the last several decades [4–12].

As a rule the empirical expressions for α-decay half-lives depend on proton number Z, the number of nucleons in nucleus A, and reaction Q value. The ground state spins and parities of parent and daughter nuclei are ignored usually. However if the spin and parity values of parent and daughter nuclei are different, then the emitted α particle carries out nonzero angular momentum. Because of this the orbital moment of emitted α particle should be taken into account in an accurate approach for α decay. Such approaches are related to the semi-microscopic cluster or microscopic considerations of α decay (see Refs. [21–24] and references cited therein).

We discuss the empirical expressions for α-decay half-lives between the ground states of parent and daughter nuclei. Note that the ground-state-to-ground-state α transition is partial α decay of the parent nucleus. Because of this we select well-defined experimental data for the ground-state-to-ground-state α transitions with the help of the branching ratio. By using this data set we found simple phenomenological expressions for the half-lives. In contrast to this some other empirical expressions have been obtained by using the total α-decay half-lives and not the partial ones corresponding to the ground-state-to-ground-state transition.

Here we present a set of empirical relationships for α-decay half-lives that well describe selected experimental values for 344 α transitions between the ground states of nuclei in Sec. II. The orbital momentum of emitted α particle is taken into account in our empirical relationships. According to the current trend we present four empirical equations for e-e, e-o, o-e, and o-o nuclei. Moreover, the empirical relationships in Refs. [8] and [12] are especially designed for heavy nuclei with $A - Z > 126$ and $Z > 82$. Therefore, we also find two additional sets of empirical α-decay half-life relationships for heavy (with $A - Z > 126$ and $Z > 82$) and light (rest part of nuclei from the full set) nuclei. Such empirical relations are very accurate in dedicated ranges of nuclei.

II. RESULTS AND DISCUSSION

A. Input experimental data

We find expressions for the α-decay half-lives by fitting the well-defined experimental data for ground-state-to-ground-state transitions for e-e, e-o, o-e, and o-o nuclei. Note that we use the same data set as in our previous work [21]. This data set is considered in detail in Ref. [21]; however, we repeat here some important issues.

The data for α-decay half-lives presented in various compilations (see, for example, Ref. [25]) contain the total α-decay half-lives. It is necessary to take into account experimental values of the branching ratios for α transitions between the ground state of parent nuclei and various states of daughter nuclei [26] for correct extracting of the half-lives for the ground-state-to-ground-state α decay. The branching ratio correction is very important, because it significantly changes the values of the half-lives. Thus the branching ratio correction for the nuclei ^{181}Hg, ^{206}At, ^{241}Am, and ^{237}Np enlarges the half-lives for the ground-state-to-ground-state α-decay values by approximately two orders in comparison to the total α-decay half-lives. Our data set contains 344 nuclei and a correction induced by the branching ratio applies for 161 nuclei. Moreover, α decay of the parent nuclei ^{172}Ir, ^{196}Bi, and ^{210}Bi goes into excited states of corresponding daughter nuclei only.

Note that 136 even-even, 84 even-odd, 76 odd-even, and 48 odd-odd α emitters are included in the data set. Among the 344 nuclei there are 200 light and 144 heavy nuclei (with $A - Z > 126$ and $Z > 82$).

B. Spin and parity selection rule

The α-particle emission from nuclei obeys the spin-parity selection rule [21]

$$\ell_{\min} = \begin{cases} \Delta_j & \text{for even } \Delta_j \text{ and } \pi_p = \pi_d, \\ \Delta_j + 1 & \text{for odd } \Delta_j \text{ and } \pi_p = \pi_d, \\ \Delta_j & \text{for odd } \Delta_j \text{ and } \pi_p \neq \pi_d, \\ \Delta_j + 1 & \text{for even } \Delta_j \text{ and } \pi_p \neq \pi_d, \end{cases} \tag{1}$$

where $\Delta_j = |j_p - j_d|$, j_p, π_p, j_d, π_d are spin and parity values of the parent and daughter nuclei, respectively.

Note that the α particle has zero value for spin and positive parity. The value of α-particle angular momentum ℓ can be larger than $\ell_{\min}$ because of both α-particle formation in parent nuclei and the intrinsic structure of the single-particle levels around proton and neutron Fermi levels in parent and daughter nuclei.

For the sake of simplicity, in our calculations we suppose that the angular momentum of α transition between ground states $\ell = \ell_{\min}$. As a result, $\ell_{\min} = 0$ for all even-even nuclei. The centrifugal contribution to the α-nucleus potential is very important for α emission from e-o, o-e, and o-o nuclei [21], therefore below we add terms into the simple analytical expressions for the α-decay half-lives. These additional terms lead to spectacular improvement of the data descriptions in e-o, o-e, and o-o nuclei as we see below.

Our data set contains 81 α transitions between ground states of nuclei with $\ell_{\min} \neq 0$. The values of spins and parities of parent and daughter nuclei as well as the values of $\ell_{\min}$ for our data set are tabulated in Ref. [21]. Note that the values of spins and parities of parent and daughter nuclei in Ref. [21] are taken from experimental data or data evaluation compilations.

C. Energy of α decay

In the fitting procedure we use the reaction energy values (Q) calculated by using mass excess experimental data [25]. We take into account the electron screening effect [21] on the reaction energy values,

$$Q = \Delta M_p - (\Delta M_d + \Delta M_\alpha) + k\left(Z_p^\epsilon - Z_d^\epsilon\right), \tag{2}$$

where ΔM_p, ΔM_d, and ΔM_α are, correspondingly, the mass-excess of parent and daughter nuclei and α particle [25]. The last term $kZ^\epsilon_{p(d)}$ represents the total binding energy of $Z_{p(d)}$ electrons in the parent (daughter) atom, where $k = 8.7$ eV, $\epsilon = 2.517$ for nuclei with $Z \geqslant 60$ and $k = 13.6$ eV, $\epsilon = 2.408$ for nuclei with $Z < 60$ [27].

D. Relationships for full data set

Fitting the total experimental data set for ground-state-to-ground-state α-decay half-lives, we obtain Set I of empirical equations for the evaluation of α-decay half-lives in e-e, e-o, o-e, and o-o nuclei:

$$\log_{10}\left(T_{1/2}^{\text{e-e}}\right) = -26.1779 - 1.1521\frac{A^{1/6}Z^{1/2}}{\mu} + \frac{1.6068Z}{\sqrt{Q}},$$

$$\log_{10}\left(T_{1/2}^{\text{e-o}}\right) = -30.3391 - 1.0785\frac{A^{1/6}Z^{1/2}}{\mu} + \frac{1.6979Z}{\sqrt{Q}} + \frac{0.2688\sqrt{\ell(\ell+1)}}{QA^{-1/6}} - 0.6784((-1)^\ell - 1),$$

$$\log_{10}\left(T_{1/2}^{\text{o-e}}\right) = -30.2138 - 1.0841\frac{A^{1/6}Z^{1/2}}{\mu} + \frac{1.6949Z}{\sqrt{Q}} + \frac{0.1302\sqrt{\ell(\ell+1)}}{QA^{-1/6}} - 0.5972((-1)^\ell - 1),$$

$$\log_{10}\left(T_{1/2}^{\text{o-o}}\right) = -30.3526 - 1.0149\frac{A^{1/6}Z^{1/2}}{\mu} + \frac{1.6609Z}{\sqrt{Q}} + \frac{0.2762\sqrt{\ell(\ell+1)}}{QA^{-1/6}} - 0.2209((-1)^\ell - 1).$$

Here A and Z are the mass number and charge of parent nucleus, respectively, ℓ is the orbital moment of emitted α particle, and $\mu = (A/(A-4))^{1/6}$. The value of $T_{1/2}$ is given in seconds, the reaction energy Q is defined by Eq. (2), and $\ell = \ell_{\min}$ [see Eq. (1)].

Note that the first and third terms of the empirical equations were first discussed in Ref. [3] and after that have been used in various phenomenological expressions for the α-decay half-lives. The second term is similar to the corresponding one in Ref. [7], but we have introduced additional dependence related to the reduced mass ($\mathcal{M} \propto 4(A-4)/A$) into this term, because the α-decay half-life evaluated in the WKB approximation depends on the reduced mass (for details, see Ref. [21].

The centrifugal potential $\frac{\hbar^2}{2\mathcal{M}}\ell(\ell+1)$ distinctly contributes to the total α-nucleus potential at small distances between daughter nucleus and α particle at $\ell \neq 0$ [21]. The α-decay half-life depends exponentially on the action, which is very sensitive to the α-nucleus potential. Therefore, accurate consideration of the α transitions should take into account the spins and parities of parent and daughter nuclei and angular momentum of the emitted α particle [21]. We introduce into the empirical relationships for α-decay half-lives in e-o, o-e, and o-o nuclei two terms (see corresponding Eqs. of Set I) that depend on ℓ. The term proportional to $\sqrt{\ell(\ell+1)}$ simulates the influence of the centrifugal potential, which is proportional to $\ell(\ell+1)$. The term proportional to $((-1)^\ell - 1)$ is phenomenological correction, which takes into account hindrance of α-particle emission with odd values of ℓ.

The root-mean-square (rms) errors of the decimal logarithm of the α-decay half-lives,

$$\delta = \frac{1}{N}\sum_{i=1}^{N}\left[\log_{10}\left(T_{1/2\,i}^{\text{theor}}\right) - \log_{10}\left(T_{1/2\,i}^{\exp}\right)\right]^2, \tag{3}$$

evaluated for the total data set as well as for e-e, e-o, o-e, and o-o subsets of the total data set in our empirical approach (Set I) and in the unified model for α decay and α capture [21] are presented in Table I. N in Eq. (3) is the number

TABLE I. The rms errors of the decimal logarithm of the α-decay half-lives calculated for the full data set as well as for e-e, e-o, o-e, and o-o subsets of the full data set. The last column contains the references for corresponding approaches.

Total ($N = 344$)	e-e ($N = 136$)	e-o ($N = 84$)	o-e ($N = 76$)	o-o ($N = 48$)	
0.5484	0.3314	0.6237	0.6768	0.6792	Set I
0.6248	0.3088	0.7816	0.7621	0.7546	[21]
1.0113	0.4164	1.3548	1.2572	1.0965	[9]
1.0185	0.5165	1.1611	1.3348	1.2568	[11]
1.1130	0.3837	1.4762	1.3688	1.3340	[7]
1.1285	0.3712	1.5425	1.3541	1.3307	[10]
1.3813	1.2928	1.4300	1.5607	1.2751	[6]

of nuclei used for evaluation of the rms errors. The values of N used are given in the tables. The unified model for α decay and α capture is based on cluster representation of the α-decay process and takes into account Coulomb, nuclear, and centrifugal interactions between the daughter nucleus and the α particle. Similar rms errors obtained by using empirical relations from Ref. [9] (universal curves) [6,7,10,11] for our data set are also given in Table I. Note that we use the same values of parameters in the formulas from Refs. [6,7,9–11] as those recommended in the cited articles. Only the α-decay energy is evaluated according to Eq. (2). We stress that we use the half-life data for the ground-state-to-ground-state α transitions for evaluating our empirical formulas. In contrast to this some other empirical relations are obtained by using data for the total half-lives.

We introduce 18 fitting parameters into our empirical relations. The number of parameters in other empirical relations mentioned in Table I is 7 in Refs. [6] and [9], 12 in Refs. [7] and [11], 1 in Ref. [10], and 22 in Ref. [21]. The number of nuclei involved in the fitting procedure in Refs. [7,9,10], and [11], is, respectively, 373, 286, 336, and 77. The expression obtained in Ref. [5] with additional terms for e-o, o-e, and o-o nuclei is used in the analysis in Ref. [6]. (Note that only even-even nuclei are considered in Ref. [5].) Our empirical relations (Set I) have the lowest values of the rms errors for total data set and for any subset considered in Table I in comparison with other empirical relations.

We introduce into the empirical relationships for α-decay half-lives in e-o, o-e, and o-o nuclei two ℓ-dependent terms that relate to angular momentum and parity corrections. Note that the empirical relations obtained in Refs. [6,7,9–11] have not taken into account any angular momentum and/or parity corrections. Because of this the rms errors obtained by using a unified model for α decay and α capture [21] and the equations of Set I are the lowest for α transitions in e-o, o-e, and o-o nuclei (see Table I).

We can evaluate the rms errors for the α-decay half-lives when we substitute the experimental values for the ground-state-to-ground-state α-decay half-lives for our total set of nuclei by experimental values for the total α-decay half-lives. The values of the rms errors evaluated in such a way for other approaches [6,7,9–11] are strongly reduced for e-o, o-e, and o-o nuclei and become closer to the corresponding ones given in the original articles. Taking into account this fact and analysis of experimental values of α-decay half-lives considered in other works, we may conclude that the other empirical relationships are established for the total α-decay half-lives.

E. Relationships for light and heavy nuclei subsets

We find two additional sets of empirical relationships for α-decay half-lives for heavy (with $A - Z > 126$ and $Z > 82$) and light (rest part of nuclei from the full data set) nuclei too. The fitting procedure and all definitions are the same as before.

As a result, we find Set II of the empirical relations by fitting $T_{1/2}$ in light nuclei:

$$\begin{aligned}
\log_{10}\left(T_{1/2}^{\text{e-e}}\right) &= -29.2230 - 1.0347\frac{A^{1/6}Z^{1/2}}{\mu} + \frac{1.6290Z}{\sqrt{Q}},\\
\log_{10}\left(T_{1/2}^{\text{e-o}}\right) &= -29.3760 - 1.0835\frac{A^{1/6}Z^{1/2}}{\mu} + \frac{1.6711Z}{\sqrt{Q}}\\
&\quad + \frac{0.3324\sqrt{\ell(\ell+1)}}{QA^{-1/6}} - 6.2873((-1)^{\ell} - 1),\\
\log_{10}\left(T_{1/2}^{\text{o-e}}\right) &= -28.7300 - 1.1068\frac{A^{1/6}Z^{1/2}}{\mu} + \frac{1.6652Z}{\sqrt{Q}}\\
&\quad + \frac{0.1377\sqrt{\ell(\ell+1)}}{QA^{-1/6}} - 0.6153((-1)^{\ell} - 1),\\
\log_{10}\left(T_{1/2}^{\text{o-o}}\right) &= -31.5090 - 1.0626\frac{A^{1/6}Z^{1/2}}{\mu} + \frac{1.7298Z}{\sqrt{Q}}\\
&\quad + \frac{0.1675\sqrt{\ell(\ell+1)}}{QA^{-1/6}} + 0.1080((-1)^{\ell} - 1).
\end{aligned}$$

For heavy nuclei only, we search out Set III of the empirical relations:

$$\begin{aligned}
\log_{10}\left(T_{1/2}^{\text{e-e}}\right) &= -27.9238 - 1.0521\frac{A^{1/6}Z^{1/2}}{\mu} + \frac{1.5847Z}{\sqrt{Q}},\\
\log_{10}\left(T_{1/2}^{\text{e-o}}\right) &= -34.9988 - 0.8552\frac{A^{1/6}Z^{1/2}}{\mu} + \frac{1.6822Z}{\sqrt{Q}}\\
&\quad + \frac{0.2278\sqrt{\ell(\ell+1)}}{QA^{-1/6}} - 0.6763((-1)^{\ell} - 1),\\
\log_{10}\left(T_{1/2}^{\text{o-e}}\right) &= -33.5438 - 0.9627\frac{A^{1/6}Z^{1/2}}{\mu} + \frac{1.7077Z}{\sqrt{Q}}\\
&\quad + \frac{0.1538\sqrt{\ell(\ell+1)}}{QA^{-1/6}} - 0.5200((-1)^{\ell} - 1),\\
\log_{10}\left(T_{1/2}^{\text{o-o}}\right) &= -38.8157 - 0.5200\frac{A^{1/6}Z^{1/2}}{\mu} + \frac{1.5645Z}{\sqrt{Q}}\\
&\quad + \frac{0.5175\sqrt{\ell(\ell+1)}}{QA^{-1/6}} + 0.0287((-1)^{\ell} - 1).
\end{aligned}$$

Using our empirical relations, Set II and Set III, we evaluate the rms errors of α-decay half-lives for light and heavy data subsets (see Tables II and III, respectively). Similar rms

TABLE II. The rms errors of the decimal logarithm of the α-decay half-lives calculated for the total light data subset as well as for e-e, e-o, o-e, and o-o subsets of the light data subset. The last column contains the references for corresponding approaches.

Total ($N = 200$)	e-e ($N = 77$)	e-o ($N = 51$)	o-e ($N = 42$)	o-o ($N = 30$)	
0.4960	0.2692	0.5733	0.5869	0.6667	Set II
0.5336	0.3747	0.5811	0.5947	0.7094	Set I
0.5509	0.3071	0.6588	0.6192	0.7381	[21]
0.7699	0.3744	0.8375	1.0579	0.9532	[10]
0.7817	0.4463	0.8563	0.9544	1.0580	[9]
0.8034	0.4738	0.8334	1.1064	0.9552	[7]
0.8138	0.6001	0.6952	1.1971	0.8607	[11]
1.4822	1.7049	1.1484	1.6447	1.1659	[6]

TABLE III. The rms errors of the decimal logarithm of the α-decay half-lives calculated for the total heavy data subset as well as for e-e, e-o, o-e, and o-o subsets of the heavy data subset. The last column contains the references for corresponding approaches.

Total ($N = 144$)	e-e ($N = 59$)	e-o ($N = 33$)	o-e ($N = 34$)	o-o ($N = 18$)	
0.5369	0.1905	0.6739	0.7632	0.5620	Set III
0.5702	0.2677	0.6937	0.7757	0.6457	Set I
0.7170	0.3135	0.9520	0.9184	0.8032	[21]
1.2326	0.2854	1.8008	1.4748	1.4753	[6]
1.2516	0.3861	1.6558	1.5062	1.7615	[11]
1.2543	0.2686	1.9013	1.5686	1.1856	[9]
1.3410	0.3067	2.0223	1.6186	1.4219	[12]
1.4399	0.2202	2.1371	1.6545	1.8339	[7]
1.4933	0.3701	2.2528	1.6663	1.8292	[10]
1.6926	0.2187	2.5050	1.9202	2.2285	[8]

errors obtained with the help of empirical relations from Refs. [6–12,21] for these data subsets are also presented in Tables II and III. In the same manner as before, we use the same values of parameters in the formulas from Refs. [6–12,21] as recommended in the cited articles. The number of nuclei involved in the fitting procedure in Refs. [12] and [8] is, respectively, 201 and 65. Moreover only even-even nuclei are used in Ref. [8]. The number of fitting parameters of empirical relations introduced in Refs. [12] and [8] is 5 and 4, respectively.

F. Discussion

Comparing the rms errors in Tables I–III, we can conclude that

(i) empirical relations obtained for light and heavy subsets describe better the dedicated region;
(ii) the values of errors for the e-e subsets are the lowest; and
(iii) spin-parity corrections, which are taken into account in Sets I–III and in Ref. [21], lead to spectacular reduction of the rms errors for e-o, o-e, and o-o nuclei.

Note that the values of rms errors for some relationships presented in Tables I–III are different from the corresponding values given in the original articles. There may be several reasons for this difference.

(i) Different data sets of nuclei are considered in different articles.
(ii) Different experimental data for α-decay half-lives and/or Q_α are used in different works. Note that the experimental data are permanently improved and extended.
(iii) We include in our data set the α-decay half-lives for the ground-state-to-ground-state transitions only. We take into account the branching ratio of α transitions systematically and use both the α-decay half-lives and the energies of α transitions for the ground-state-to-ground-state transitions. Therefore, our data set contains consistent data. In contrast to this the energies of α transitions are evaluated by using an atomic mass evaluation table and, therefore, are related to the ground-state-to-ground-state transitions, whereas the total α-decay half-lives are used in the evaluation of the corresponding relationships in some other works. The data sets obtained in such a manner are inconsistent and, as a result, the values of rms errors are high.
(iv) To consider accurately the nuclear effects in α decay, we evaluate the energy of α transition taking into account the effect of the binding energy of electrons in the atom (see Eq. (2) and Ref. [21]). However, the energy of α transition is obtained by various methods in other works.

In summary, to find the simple empirical relationships for α-decay half-lives we fitted the data set of experimental values for 344 nuclei. The analysis was performed for the total set of nuclei and separately for heavy/light nuclei. We compared the rms errors for our calculations with the rms errors of other approaches (in the framework of our data set), which resulted in an improved description of α-decay half-lives in our work in comparison with earlier works.

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