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Partial alpha-decay half-lives for alpha-emitting Osmium isotopes: accurate determinations by a semi-empirical model

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ABSTRACT

Partial alpha-decay half-life-values for twenty-four cases of alpha-decaying Osmium isotopes ($^{161-174,\,184,\,186-188}$Os) have been obtained in the framework of a semi-empirical, one-parameter model based on the quantum mechanical tunneling mechanism through a potential barrier. Here the Coulomb, centrifugal and overlapping contributions to the barrier have been considered within the spherical nucleus approximation. The calculation method enabled to reproduce, within a factor 2, the measured half-lives for ground-state to ground-state (gs-gs) α-transitions of twelve artificially produced Osmium isotopes ($^{162-172,\,174}$Os) and of two naturally occurring isotopes ($^{184,\,186}$Os). In addition, a half-life prediction of $T_{½} = (2.0 \pm 0.1) \times 10^{16}$ a has been found for the gs-gs α-transition of naturally occurring ^{187}Os isotope. Two cases of gamma quanta accompanying α-decay possible of being accessed experimentally have been predicted: ^{184}Os decaying to the first level of ^{180}W, with $T_{½} = (0.73 \pm 0.04) \times 10^{15}$ a, and ^{186}Os decaying to the first level of ^{182}W, with $T_{½} = (3.9 \pm 0.2) \times 10^{16}$ a. New α-decay schemes for ^{184}Os, ^{186}Os, ^{187}Os isotopes have been anticipated, and estimated $T_{½}$-values for rarer cases of α-transitions of Osmium isotopes have been reported.

1. Introduction

Significant advances in the investigation of α-decay processes, in particular the achievement of methodologies for a precise long term half-life evaluations, play nowadays a leading role in projecting fundamental research into applied technologies. Crossing the gap between different disciplines, the α-decay studies are opening new horizons in highly impacting areas, encompassing nuclear physics and Cosmo-chronology.

As regards the field of nuclear physics, the process of α-particle emission from nuclei is a fundamental tool to investigate the nuclear structure. The relationship established for the first time by Geiger and Nuttall (1911), and recently updated by Sahu and Bhoi (2016), between the total α-disintegration energy (the Q_α-value) and half-life, $T_{½}$, of the disintegration process, makes the precise determination of α-decay constant, λ_α, a fundamental step to confirm the predictions from the theoretical models (Denisov and Khudenko, 2009; Denisov and Khudenko, 2009a).

The studies of α-emitting nuclides not only help in checking the basic statements of nuclear theories, projecting the present nuclear technology towards the future scenario of an enlarged Table of Elements (Eichler, 2019), but also open somewhat unexpected scenarios towards the past. The second relevant output produced by the α-decay investigations is indeed the chance to look back through time, giving a glimpse at the history of the early solar system and of the Universe.

Beyond supplying valuable time traces and evidences in Geo- and Cosmo-chronology (an application started by *sir* Ernest Rutherford in 1929), the knowledge of the decay properties of naturally occurring long-lived isotopes provides hints also to the exciting fields of nucleosynthesis, astrochemistry and astrophysics (Clayton, 2011). The abundance and the decay rate of some α-emitting nuclides found on the earth, in meteorites or in interstellar medium represent indeed a fundamental input to formulate and prove chronological theories.

In this regard, starting from 1964, the ^{190}Pt-^{186}Os and ^{187}Re-^{187}Os decay systems have been widely used as chronometers for the dating of terrestrial magmatic ores and iron stony meteorites. Moreover, earth/planetary science takes advantages of the ^{186}Os/^{188}Os isotope-amount ratio, detected in terrestrial sediments, meteorites and dust, to understand the Earth evolution over geological times (Morgan and Lovering, 1964; Walker *et al.*, 1994; Walker *et al.*, 1997; Morgan *et al.*, 2002; Cook *et al.* 2004). Hence, $^{186-188}$Os isotopes play a key role in Geo- and Cosmo-chronology, but the achievement of reliable results depends on the accuracy with which the decay constant of the radiogenic transitions are known (Begeman *et al*., 2001).

Alpha activities lower than a few units of disintegration per minute and per milligram of a pure α-emitting nuclide make very difficult the experimental determination of the decay constant of the process by physical methods, therefore hampering the identification of other possible naturally occurring α-radioactive isotopes. This is the main reason for which up to now only the α-decay of ^{186}Os isotope was experimentally investigated (Viola, Jr., *et al*., 1975), and the half-life obtained in 1975 ($(2.0 \pm 1.1) \times 10^{15}$ a) is still the only value reported in nuclear data compilations (Singh, 2015; Audi *et al*., 2017; Holden *et al*., 2019).

The experimental difficulties also faced in the case of ^{184}Os isotope, for which a half-life of 2.6×10^{13} a had been predicted in 2006 (Medeiros *et al*. 2006), were overcome eight years later by Peters *et al*. (2014). By using a combined ^{184}Os-^{180}W isochron dating for iron meteorites and chondrites, a half-life-value of $(1.12 \pm 0.23) \times 10^{13}$ a has been found. Such experimental value is in quite good agreement with two other estimates, *viz*., 1.3×10^{13} a (Gangopadhyay, 2009) and 1.5×10^{13} a (Denisov *et al*., 2015).

Beyond the need to validate the gs-gs α-decay half-life data for the ^{184,186}Os isotopes, the interest in extending the investigation to naturally occurring ^{187,188}Os isotopes was raised by the observation that the Q_α-values for these two Osmium isotopes (~2.75 MeV and ~2.17 MeV, respectively) differ little from that for ^{184}Os (~3.0 MeV) and ^{186}Os (~2.85 MeV).

Moreover, from the physical point of view, it is also important to investigate on the possible existence of α-transitions that eventually could populate states of W daughters (then) decaying by gamma quantum emissions. In this context, the development of closed formulae based on physical models can be viewed as an outstanding tool for confirming and/or predicting a radioactive behavior, otherwise very difficult to detect.

Fifteen years ago, aiming to determine the partial α-decay half-lives of bismuth isotopes, we developed a semi-empirical, one-parameter, calculation model. Such a model was able to reproduce, within a factor ~2, the known half-lives of $^{191,193,195,\ 211-214}$Bi isotopes (Tavares *et al*., 2005). In particular, the calculation model provided a half-life value $(1.0 \pm 0.3) \times 10^{19}$ a for the unique naturally occurring ^{209}Bi isotope, considered for its extremely low α-activity a stable nuclear species until 2003, when a measured value of (1.9 ± 0.2)×10^{19} a has been reported (de Marcillac *et al.*, 2003).

Subsequently, the proposed model has also been successfully applied not only to a large number of alpha radioactive decay cases (Tavares *et al.*, 2006; Medeiros *et al.*, 2006; Tavares and Medeiros, 2011; Tavares and Terranova, 2018), but also to cases of one- and two-proton radioactivity (Medeiros *et al.*, 2007; Tavares and Medeiros, 2010; Tavares and Medeiros, 2018), and to the spontaneous emission of heavy clusters from nuclei (the so-called exotic decays) (Tavares *et al.*, 2007; Tavares and Medeiros, 2012).

The quite satisfactory agreement found between the results of the numerical treatment and the available experimental data for a number of cases and modes of heavy-particle radioactivity, has led us to apply the model mentioned above to a systematic investigation of the artificially produced Osmium isotopes ($^{161-174}$Os) that exhibit alpha emission. Moreover the study has been extended to naturally occurring isotopes ($^{184,186-188}$Os) that could possibly exhibit a radioactive decay by alpha emission. For Osmium isotopes of mass number $A > 188$ the Q_α-values are less than ~ 2 MeV, making therefore the α-emission mode very difficult to occur, or even not possible of being detected.

We believe the present investigation can be useful in different areas of research such as nuclear physics and chemistry, astrophysics, meteoritics, and geochronological and cosmochronological applications as well.

2. Semi-empirical, one-parameter, calculation model to systematize alpha-decay half-lives

The routine calculation used in the present determination of partial alpha-decay half-lives of Osmium isotopes is based on the quantum mechanical tunneling mechanism first introduced by Gamow (1928) and Gurney and Condon (1928, 1929). The model has been described in details in our previous publications (see, for instance, Tavares *et al.*, 2005; Tavares and Medeiros, 2011; Tavares and Medeiros, 2012). Some key points of the method are briefly highlighted here.

Firstly, the semi-empirical character of the calculation model is due to the presence of a unique adjustable parameter, $0 < g \leq 2/3$, that strongly depends upon the adopted values for two fundamental physical quantities involved in the calculation, namely the nuclear (rather than atomic) mass, *m*, and the nuclear radius, *R*, of the nuclides involved in the decay process. Accordingly, the sources of the basic data for the alpha-decaying nuclides must be specified. Once a mass table and/or a nuclear radius parametrization were chosen, subsequent half-life evaluations should be done using these same sources for mass- and radius-values, as well as for the physical constants from which the *g*-value was obtained.

In the present analysis we choose the AME2016 mass tables by Wang *et al.* (2017) in order to evaluate the Q_α-values and the effective reduced mass, μ_0, of the disintegrating system. These quantities are given by

$$Q_\alpha = m_P - (m_D + m_\alpha), \quad \mu_0^{-1} = m_D^{-1} + m_\alpha^{-1}, \tag{1}$$

where the *m*'s are calculated by the usual way, namely,

$$m_i = A_i - Z_i \cdot m_e + (\Delta M_i + kZ_i^\beta)/F, \quad i = \text{P (parent), D (daughter)}. \tag{2}$$

Here, $m_e = 0.54857990907\times10^{-3}$ u is the electron rest mass, $m_\alpha = 4.001506179127$ u is the alpha particle mass, ΔM_i's are the atomic mass-excess values (expressed in MeV) as tabulated in (Wang *et al.*, 2017), kZ_i^β represents the total binding energy of the *Z* electrons in the atom, and $F = 931.4940038$ MeV/u is the mass-energy conversion factor. The *k*- and β-values come from an analysis of calculated data for electron binding energies of neutral atoms by Huang *et al.* (1976). From the analysis it is obtained

$$k = 8.7\times10^{-6} \text{ MeV} \quad \text{and } \beta = 2.517, \quad \text{for nuclei of } Z \geq 60. \tag{3}$$

The Q_α-values for the partial α-decaying Osmium isotopes ($Z_P = 76$, $Z_D = 74$) are therefore given by

$$Q_\alpha = \Delta M_P - \Delta M_D - 2.39438 \quad \text{MeV}, \tag{4}$$

where the numerical term contains the effect of the screening of the nucleus due to the surrounding electrons (order of ~ 30 keV). Subscripts P and D indicate the parent Osmium isotope and daughter Tungsten isotope, respectively.

The nuclear radius values for the parent, R_P, and daughter, R_D, have been evaluated following the finite range droplet model of atomic nuclei as is described by Möller *et al*. (1995), where the spherical approximation of the nuclear volume has been adopted (see also (Myers, 1977)). This nuclear radius parametrization has been updated recently by Möller *et al*. (2016). The new radius data have been obtained from a significantly improved treatment, that took into account more accurate experimental ground-state nuclear mass data. The expressions that enable to calculate the average equivalent root-mean-square radius of the proton and neutron density distributions are now read as

$$R_i \equiv \langle Q_{Z,A} \rangle = (Z/A)Q_p + (1 - Z/A)Q_n, \quad i = P, D, \tag{5}$$

where the equivalent radii, Q_j (j = p, n), are obtained from

$$Q_j = R_j \cdot [1 + 5/(2R_j^2)] \,, \tag{6}$$

in which R_j represents the sharp radii for the proton and neutron density distributions (j = p, n, respectively), the values of which are given by

$$R_p = r_0(1 + \langle\varepsilon\rangle)\cdot[1 - (2/3)\cdot(1 - Z/A)\cdot(1 - 2Z/A - \langle\delta\rangle)]\cdot A^{1/3}, \tag{7}$$

$$R_n = r_0(1 + \langle\varepsilon\rangle)\cdot[1 + (2/3)\cdot(Z/A)\cdot(1 - 2Z/A - \langle\delta\rangle)]\cdot A^{1/3} \;. \tag{8}$$

Here, r_0 = 1.16 fm, and the values for the quantities $\langle\delta\rangle$ and $\langle\varepsilon\rangle$ are given by (Möller *et al*., 2016)

$$\langle\delta\rangle = (1 - 2Z/A + 0.0048626\cdot Z/A^{2/3})/(1 + 2.5304666/A^{1/3}), \tag{9}$$

$$\langle\varepsilon\rangle = 0.854167\cdot\exp(-0.988\cdot A^{1/3}) - 0.1896936/A^{1/3} + 0.2229167\cdot\langle\delta\rangle^2 + 0.0031034Z^2/A^{4/3}. \tag{10}$$

The evaluated reduced radius, $r_{ld} = \langle Q_{Z,A}\rangle/A^{1/3}$, for the Osmium and Tungsten isotopes of interest to the present analysis, are plotted in Fig. 1 as a function of mass number A.

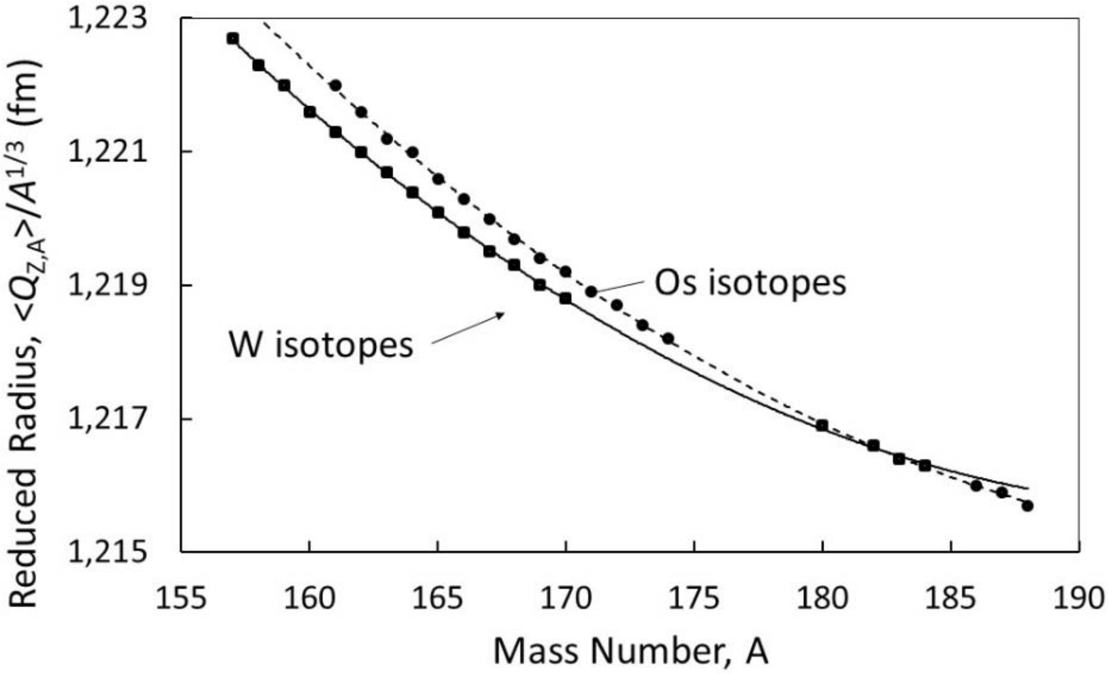

Fig.1. Reduced, equivalent liquid drop nuclear radius ($<Q_{Z,A}>/A^{1/3}$) for Osmium (filled circles) and Tungsten (filled squares) isotopes *vs* mass number *A*. $<Q_{Z,A}>$ is the average equivalent rms radius of the proton and neutron density distributions as given by Eqs. (5–10).

It is remarked that the reduced, average equivalent liquid drop nuclear radius, $r_{\rm ld}$, reveals a small, but important, decrease when one passes from intermediate-mass nuclei ($r_{\rm ld} \approx 1.223$ fm) to heaviest ones ($r_{\rm ld} \approx 1.216$ fm). Such a trend indicates a clear degree of nuclear compressibility, making, therefore, the simple expression $R_i = <r_{\rm ld}>\cdot A_i^{1/3}$ (i = P, D) not valid in estimating nuclear radii in the whole range of mass number.

Concerning the alpha-particle radius, it has been adopted the value $R_\alpha = (1.62 \pm 0.01)$ fm, in accordance to the α-radius value derived from the charge density distribution measured by Sick *et al*. (1976) in electron scattering experiments on ^{4}He target. Excellent reproducibility of alpha-decay data was attained using the above mentioned R_α-value coupled with a simple Gamow's-like model applied to a large number (more than three hundred cases) of measured alpha-decay half-lives covering the mass-number interval $106 \leq A \leq 264$ (Medeiros *et al*., 2006).

3. Half-life determination of α-radioactivity of Osmium isotopes

Once the main nuclear quantities (radius, ground-state mass and total disintegration energy of the decay process) have been defined, we will present below the routine calculation we have developed to evaluate the partial α-decay half-lives for eighteen Osmium isotopes mentioned in Section 1. The general expressions which can be used in all modes and cases of heavy-particle radioactivity are reported in (Tavares and Medeiros, 2012) together with details of the calculation model.

By expressing lengths in fm (1fm = 10^{-13} cm), masses in u (1 u = 1.660539040 × 10^{-24} g), energies in MeV (1 MeV = 1.602176565 erg), and time in annum (1 a = 3.1557×10^{7} s), the half-life $T_{1/2}$ is obtained from

$$\log_{10}T_{1/2} = \tau = \tau_{fa} + \tau_{ov} + \tau_{se} \,, \qquad (11)$$

where τ_{fa} is the term related to the frequency of assaults of the α-particle on the potential barrier, τ_{ov} is the contribution due to the overlapping barrier region, and τ_{se} is the one corresponding to the external, separation barrier region. It resulted that

$$\tau_{fa} = -29.5 + \log_{10}[a\cdot(\mu_0/Q_\alpha)^{1/2}] \,;\ \tau_{ov} = g\cdot\tau_1,\ \text{and}\ \tau_{se} = \tau_2^{cou} + \tau_2^{cen} \,. \qquad (12)$$

Here, $\tau_1 = 0.19\cdot(c-a)\cdot(\mu_0\cdot Q_\alpha)^{1/2}\cdot H(x, y)$, (13)

g is the adjustable parameter of the model, and

$$\tau_2^{cou} = C\cdot z \quad \text{and} \quad \tau_2^{cen} = \tau_2^{cou}\cdot[F(x, y)/F(0, y) - 1] \,, \qquad (14)$$

with C = 40.48984 and $z = (\mu_0/Q_\alpha)^{1/2}\cdot F(0, y)$. (15)

The length $c - a$ gives the width of the overlapping barrier region that extends from $a = R_P - R_\alpha$ up to $c = R_D + R_\alpha$, where the contact configuration of the preformed fragments is reached. In this way,

$$c - a = 2R_\alpha - (R_P - R_D) \approx 3.2 \text{ fm}. \qquad (16)$$

The quantity τ_{ov} is related to preformation probability or the “arrival” of the α-particle to the nuclear surface just at the contact with the daughter nucleus.

If s represents the distance between the centers of the separating nuclei (α-particle and daughter, product nucleus), the separation barrier region extends from c up to the point where the total potential energy, *i. e.*, the $1/s$-Coulomb plus $1/s^2$-centrifugal potentials, equals to Q_α.

Finally, the functions $H(x, y)$ and $F(x, y)$ contain the dependence upon mutual angular momentum, l (if any), which comes from the nuclear spin ($\boldsymbol{J}$) and parity (π) conservation laws ($\boldsymbol{J}_P = \boldsymbol{J}_D + \boldsymbol{J}_\alpha + l$, $\pi_P = \pi_D \cdot \pi_\alpha \cdot (-1)^l$) to the decay process. These functions are written as

$$H(x, y) = (x + 2y - 1)^{1/2}, \quad (17)$$

$$F(x, y) = x^{1/2}/(2y)\cdot \ln\{[x^{1/2}\cdot H(x, y) + x + y]/(x + y^2)^{1/2}\} + \arccos\{[1 - (y - 1)/(x + y^2)^{1/2}]/2\}^{1/2} - H(x, y)/(2y), \quad (18)$$

where the quantities x and y are defined as

$$x = 20.9008\cdot l(l + 1)/(\mu_0\cdot c^2\cdot Q_\alpha), \quad y = 106.55737/(c\cdot Q_\alpha), \quad (19)$$

and l is mutual angular momentum of the decaying system.

Expressions (17) and (18) are valid for all values of $x \geq 0$ and $y > 1/2$.

In cases for which $l = 0$ it results $x = 0$, $\tau_2^{cen} = 0$, and, in addition,

$$H(0, y) = (u^{-1} - 1)^{1/2}, \quad F(0, y) = \arccos u^{1/2} - [u\cdot(1 - u)]^{1/2}, \quad u^{-1} = 2y. \quad (20)$$

3.1. Semi-empirical determination of parameter g

In the present analysis it has been assumed that a unique value of parameter-g is applicable (or valid) to all the α-transitions that occur in Osmium isotopes.

Table: 1

Input data for determination of parameter g in ground-state to ground (gs-gs) α-transitions of Os isotopes[1,2,3].

A_P	$T^t_{1/2} \pm \delta T^t_{1/2}$	$b^+_\alpha(\%)$	$\tau^{e\sharp}$	A_D	$Q_\alpha(MeV)^\ddagger$	$g \pm \delta g(2\sigma)$
161	$(640\pm60)\mu$s	94.1^a	-10.666	157	7.0956	0.194±0.016
162	(2.1 ± 0.1)ms	100^b	-10.177	158	6.7956	0.104±0.008
163	(5.5 ± 0.6)ms	100	-9.759	159	6.7156	0.135±0.018
164	(21 ± 1)ms	98	-9.168	160	6.5156	0.117±0.008
165	(71 ± 3)ms	90	-8.602	161	6.3656	0.123±0.007
166	(213 ± 5)ms	72	-8.028	162	6.1726	0.095±0.004
167	(839 ± 5)ms	51	-7.283	163	6.0156	0.120±0.001
168	(2.1 ± 0.1)s	43	-6.810	164	5.8466	0.080±0.008
169	(3.46 ± 0.11)s	13.7	-6.097	165	5.7436	0.133±0.006
170	(7.37 ± 0.18)s	9.5	-5.609	166	5.5676	0.079±0.004
171	(8.3 ± 0.2)s	1.68^c	-4.805	167	5.4016	0.085±0.004
172	(19.2 ± 0.9)s	1.1	-4.257	168	5.2546	0.056±0.008
173	(22.4 ± 0.9)s	0.021^d	-2.471	169	5.0856	0.228±0.006
174	(44 ± 4)s	0.02^e	-2.157	170	4.9016	0.103±0.014
184	$(1.12\pm0.23)10^{13}$a^f	100^f	13.049	180	2.98922	0.056±0.032
186	$(2.0\pm1.1)10^{15}$a^g	100^g	15.301	182	2.85182	0.158±0.084

[1] Unless otherwise specified, values for $T^t_{1/2}$ and b_α have been taken from (Audi *et al.*, 2017).
[2] A_P and A_D are mass number of parent Os and daughter W isotopes.
[3] In all cases, the mutual angular momentum is $l = 0$
[+] This is the branching ratio for gs-gs α-transitions.
[♯] $\tau^e = \log_{10} T^e_{1/2}[a] = \log_{10}\left(T^t_{1/2}[a]/b_a\right)$.
[‡] See Eq. (4).
[a] (Nica, 2016)
[b] (Nica, 2017)
[c] (Baglin, 2000)
[d] (Baglin, 2008)
[e] (Baglin, *et al.*, 2018)
[f] (Peters *et al.*, 2014)
[g] (Viola, Jr. *et al.*, 1975)

Two procedures have been used to obtain the value for the adjustable, semi-empirical parameter of the present model. First, we solve Eq. (11) for g, and using the experimental data in Table 1 we calculate the corresponding g-values for all the sixteen cases under investigation:

$$g = [\tau^e - (\tau_{fa} + \tau_2^{cou})]/\tau_1, \quad \delta g = 0.4343\cdot\delta T^t_{1/2}/(\tau_1\cdot T^t_{1/2}). \qquad (21)$$

Here, τ^e stands for the decimal logarithm of the experimental α-half-life, δg is the uncertainty associated to each g-value, and $T^t_{1/2}$ is the total half-life of the nuclide. Results are also listed in Table 1(last column). Next, by calculating the unweighted average of the sixteen g-values, $\bar{g}$, and applying the criterion $|\ g - \bar{g}\ | > 2\sigma$ for data rejection (σ is the standard deviation relative to $\bar{g}$), we have found the value $\bar{g}$ = 0.103. Only two cases, *viz.*,

^{161}Os and ^{173}Os, have been removed in two runs from the initial data set. An uncertainty $\delta\bar{g} = 0.015$, which results from the average of the uncertainty-values (two standard deviation) associated to the fourteen remaining data, has been attributed to $\bar{g}$-value.

An alternative way to reach a $\bar{g}$-value is by minimizing the root-mean-square of the differences between calculated, τ^c, and experimental, τ^e, half-life-values, *i. e.*,

$$[\sum(\tau^c - \tau^e)^2/N]^{1/2} = \text{minimum}, \quad (22)$$

where τ^c is given by Eq. (11), and N is the number of cases (subscripts have been omitted). This leads to the expression

$$\bar{g} = [\sum\tau^e\cdot\tau_1 - (\sum\tau_{fa}\cdot\tau_1 + \sum \tau_2^{cou}\cdot\tau_1)]/\sum \tau_1^2. \quad (23)$$

Note that in all cases $\tau_2^{cen} = 0$, because $l = 0$. Disregarding the data for ^{161}Os and ^{173}Os isotopes we found again

$$\bar{g} = 0.103 \pm 0.015. \quad (24)$$

The above $\bar{g}$-value is much the same the one previously obtained in an analysis of Platinum isotopes ($\bar{g} = 0.105$) (Tavares and Medeiros, 2011), and compares well with the result of a systematic study performed over 320 cases of α-emitting nuclides along the Periodic Table ($\bar{g} = 0.122$) (Medeiros *et al.*, 2006).

3.2 Calculated α-decay half-life and comparison with experimental data

The semi-empirical determination of the unique parameter of the present calculation model ($\bar{g} = 0.103 \pm 0.015$) is now inserted back into Eqs. (11) and (12) to evaluate the half-life-values. Table 2 summarizes the results for the sixteen cases of gs-gs α-transitions analyzed here.

Table 2

Comparison between calculated and experimental half-live-values of grand-state to ground-state α-transitions of Osmium isotopes.

A_P^a	IA[b]	J_P^π	J_D^π	ℓ	$Q_\alpha(MeV)^+$	Half-life-values, $T_{1/2}[a]$			Calculated $T_{1/2}$-values by other authors		
						Experimental[c], $T^e_{1/2}$	Calculated, $T^c_{1/2}$ (This work)	Ratio[d], r	(Penaru *et al.* 1986)	(Denisov and Khudenko, 2009)	(Denisov *et al.*, 2015)
161	-	$7/2^-$	$7/2^-$	0	7.0956	$(2.15\pm0.20)10^{-11}$	$(0.72\pm0.04)10^{-11}$	3.0	-	-	$0.54+10^{-11}$
162	-	0^+	0^+	0	6.7956	$(0.66\pm0.03)10^{-10}$	$(0.66\pm0.04)10^{-10}$	1.0	-	0.35×10^{-10}	0.70×10^{-10}
163	-	$7/2^-$	$7/2^-$	0	6.7156	$(1.7\pm0.2)10^{-10}$	$(1.18\pm0,06)10^{-10}$	1.4	0.6×10^{-10}*	4.3×10^{-10}	1.1×10^{-10}
164	-	0^+	0^+	0	6.5156	$(0.68\pm0.03)10^{-9}$	$(0.57\pm0.03)10^{-9}$	1.2	0.5×10^{-9}*	0.56×10^{-9}	0.67×10^{-9}
165	-	$7/2^-$	$7/2^-$	0	6.3656	$(2.5\pm0.1)10^{-9}$	$(2.0\pm0.1)10-9$	1.3	1.0×10^{-9}*	1.3×10^{-7}	2.1×10^{-9}
166	-	0^+	0^+	0	6.1726	$(0.937\pm0.022)10^{-8}$	$(1.03\pm0.06)10^{-8}$	1.1	1.0×10^{-8}*	1.0×10^{-7}	1.1×10^{-8}
167	-	$7/2^-$	$7/2^-$	0	6.0156	$(5.21\pm0.03)10^{-8}$	$(4.2\pm0,2)10^{-8}$	1.2	1.9×10^{-8}	1.7×10^{-7}	0.61×10^{07}
168	-	0^+	0^+	0	5.8466	$(1.54\pm0.07)10^{-7}$	$(2.1\pm0.1)10^{-7}$	1.4	1.6×10^{-7}*	1.9×10^{-7}	2.3×10^{-7}
169	-	$5/2^-$	$5/2^-$	0	5.7436	$(0.800\pm0.025)10^{-6}$	$(0.55\pm0.03)10^{-6}$	1.4	1.0×10^{-7}	2.1×10^{-6}	0.90×10^{-6}
170	-	0^+	0^+	0	5.5676	$(2.46\pm0.06)10^{-6}$	$(3.3\pm0.2)10^{-6}$	1.3	3.2×10^{-6}	3.0×10^{-6}	3.8×10^{-6}
171	-	$5/2^-$	$5/2^-$	0	5.4016	$(1.56\pm0.04)10^{-5}$	$(2.0\pm0.1)10^{-5}$	1.3	1.6×10^{-5}	0.93×10^{-4}	3.9×10^{-5}
172	-	0^+	0^+	0	5.2546	$(0.55\pm0.03)10^{-4}$	$(1.00\pm0.06)10^{-4}$	1.8	2.0×10^{-4}	0.76×10^{-4}	1.1×10^{-4}
173	-	$5/2^-$	$5/2^-$	0	5.0856	$(3.38\pm0.14)10^{-3}$	$(0.70\pm0.04)10^{-3}$	4.8	2.5×10^{-3}	2.7×10^{-3}	1.7×10^{-3}
174	-	0^+	0^+	0	4.9016	$(0.70\pm0.06)10^{-2}$	$(0.69\pm0.04)10^{-2}$	1.0	0.6×10^{-2}	0.59×10^{-2}	0.78×10^{-2}
184	0.017	0^+	0^+	0	2.98922	$(1.12\pm0.23)10^{13}$	$(2.05\pm0.12)10^{13}$	1.8	5.0×10^{13}	3.6×10^{13}	1.5×10^{13}
186	1.59	0^+	0^+	0	2.85182	$(2.0\pm1.1)10^{15}$	$(1.0\pm0.1)10^{15}$	2.0	2.0×10^{15}	1.9×10^{15}	0.63×10^{15}

[a] Mass number of parent Os isotopes (Z=76).

[b] Isotopic abundance expressed as percent of atoms in naturally occurring Osmium as reported in (Zhu *et al.*, 2018).

[c] Values deduced from data listed in Table 1.

[d] This is given by $r = 10^{|\tau^c-\tau^e|}$, where $\tau^c = \log_{10} T^c_{1/2}$[a], and $\tau^e = \log_{10} T^e_{1/2}[a]$.

[+] Values are those listed in Table 1, where the electron screening effect is taken into account.

[*] Values taken from (Poenaru *et. al.*, 1991).

The ninth column shows that, in general, the agreement between experimental and calculated $T_{½}$-values is very satisfactory, except for the parent ^{161}Os and ^{173}Os isotopes. The measured $T_{½}$-values for naturally occurring ^{184}Os and ^{186}Os isotopes have been reproduced within a factor 2. The standard ratio of the present estimates to those by Denisov *et al*. (2015) is only 1.47 for all cases listed in Table 2, and still drops to a factor 1.29 when the data for ^{161}Os and ^{173}Os isotopes are disregarded. These results demonstrate that the present methodology can provide reliable half-life estimates for a number of yet unmeasured cases of nuclei for which Q_{α}-data indicate a possible radioactive decay by α-emission.

3.3 Half-life predictions for possible, new α-transitions in Osmium isotope

The Q_{α}-value for gs-gs α-transitions of ^{187}Os isotope (2.75232 MeV) makes this isotope a good candidate to access experimentally its α-radioactivity. The corresponding predicted half-life are: $(2.0 \pm 0.1) \times 10^{16}$ a (this work), 2.7×10^{16} a (Denisov and Khudenko, 2009), and 3.3×10^{17} a (Denisov *et al*., 2015). Starting from a sample of pure natural Osmium, and using the calculated half-life data of the present work, it is found that the estimated α-activities for $^{184,\ 186,\ 187}$Os isotopes are ~ 18, ~ 35, and ~ 1.7 disintegrations per milligram and per annum, respectively. Being the estimated ^{187}Os α-activity one tenth and about 5% of that of ^{184}Os and ^{186}Os, respectively, α-emission from ^{187}Os isotope could also be observed, although not so easily. Differently, the same cannot be expected from ^{188}Os isotope in view of its extremely long half-life, estimated as $(2–18) \times 10^{25}$ a (see Table 3).

The present calculation model can be applied to investigate, beyond the gs-gs transitions, also other α-transitions that may have a chance of being detected. In fact, gamma quantum emissions can accompany the α-emissions from the first excited level of ^{180}W ($J^{\pi} = 2^{+}$, $E_{\gamma} = 103.56$ keV), of ^{182}W ($J^{\pi} = 2^{+}$, $E_{\gamma} = 100.106$ keV), and of the first ($J^{\pi} = 3/2^{-}$, $E_{\gamma} = 46.48$ keV) and second ($J^{\pi} = 5/2^{-}$, $E_{\gamma} = 99.08$ keV) excited levels of ^{183}W (see Table 3) originated from the respective parent $^{184,\ 186,\ 187}$Os isotopes. The quite low energies of the excited states of daughter W isotopes indicate energies available for α-transitions to these levels not much lower than those to the gs of W isotopes.

In this context, the present half-life calculation routine has been applied as before, this time by introducing the appropriate Q_α-values ($Q_\alpha^* = Q_\alpha^{gs} - E_\gamma$) and the mutual angular momentum $l = 2$ or 4 (see Table 3). The second excited level of W isotopes has also been considered in the calculations, and the results can be appreciated in Table 3. It can be seen that α-transitions to the first excited levels have good chances of being detected in the cases of parent $^{184,\,186}$Os isotopes. Moreover, decays to both the first and second excited levels of ^{183}W could most likely be observed. Other estimated half-life-data of $^{184,\,186,\,187\text{-}190,\,192}$Os isotopes for both gs-gs and gs-es (excited states) α-transitions have been also reported by Belli *et al.* (2019) in Tables 1 and 4 of their review paper on rare alpha and beta decays.

Table: 3

Partial half-life predictions for yet unobserved α-transitions

A_P^a	IA^b	J_P^π	Level of daughter W isotope J_D	E_γ(keV)	ℓ	Q_α(MeV)$^+$	Half-life predictions, $T_{1/2}^c$[a] This work	(Denisov *et al.*, 2015)	(Denisov and Khudenko, 2009)
184	0.017	0^+	2^+	103.56	2	2.88566	$(0.73\pm0.04)\cdot10^{15}$	2.7×10^{14}	-
			4^+	337.56	4	2.65166	$(4.6\pm0.3).10^{18}$	3.5×10^{17}	-
186	1.59	0^+	2^+	100.106	2	2.75171	$(3.9\pm0.2)\cdot10^{16}$	1.3×10^{16}	-
			4^+	329.43	4	2.52239	$(3.7\pm0.2).10^{20}$	2.4×10^{19}	-
187	1.54	$1/2^-$	$1/2^-$	0	0	2.75232	$(2.0\pm0.1)\cdot10^{16}$	3.3×10^{17}	2.7×10^{16}
			$3/2^-$	46.48	2	2.70584	$(1.62\pm0.09)\cdot10^{17}$	1.8×10^{20}	-
			$5/2^-$	99.08	2	2.65324	$(0.91\pm0.05)\cdot10^{18}$	1.2×10^{21}	-
188	13.28	0^+	0^+	0	0	2.17322	$(5.2\pm0.3)\cdot10^{25}$	1.9×10^{25}	1.8×10^{26}

[a] Mass number of parent Os isotopes (Z=76).
[b] Isotopic abundance (atoms percent) as reported in (Zhu *et al.*, 2018).
[+] These are obtained by subtracting the quantity E_γ from the usual. Q_α-value calculated according to Eq. (4).

The data of partial half-life obtained according to the present model and listed in Table 3 have been used to predict schemes of α-decay for the $^{184,\,186,\,187}$Os isotopes (see Fig. 2). Inspection on Fig. 2 reveals that the percentages of α-transitions to excited states of W isotopes are small, but non-negligible.

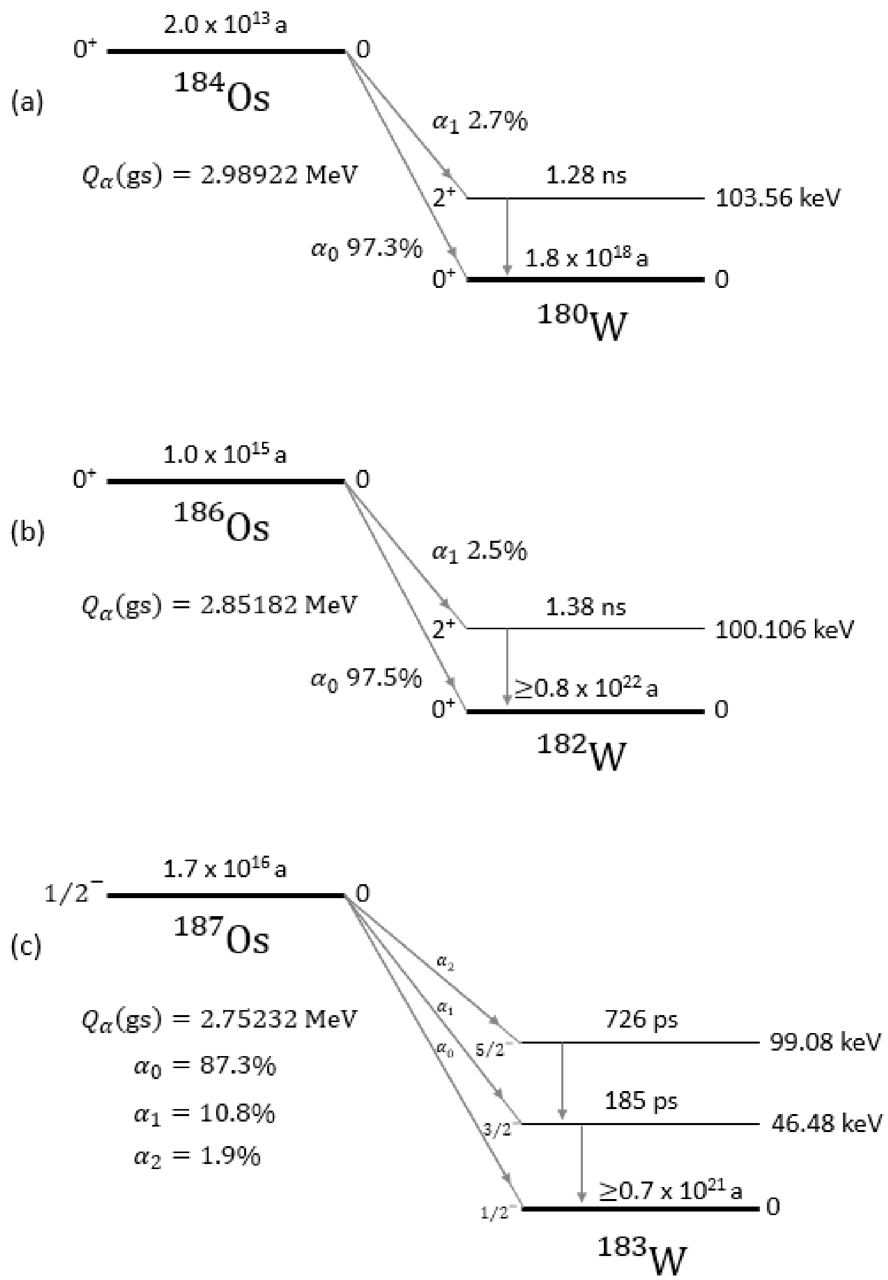

Fig.2. Schemes proposed for α-decay of: ^{184}Os (a); ^{186}Os (b); ^{187}Os (c). Values reported for half-life and α-branching of parent Osmium isotopes have been obtained from the present α-decay methodology. Nuclear data of the levels and gamma quantum emissions of daughter W isotopes are taken from (McCutchan, 2015), (Singh, 2015), and (Baglin, 2016), respectively

3.4 Global systematization of the data

All the results presented in the precedent sections can be organized in a graphical form that allows one to appreciate more easily a global description of the half-life data.

Starting from Eqs. (11) and (12), we define the "reduced", calculated half-life, τ_r^c, by subtracting from the calculated one, τ^c, all contributions other than the Coulomb, *i. e.*,

$$\tau_r^c = \tau^c - (\tau_{fa} + \bar{g}\cdot\tau_1 + \tau_2^{cen}) = \tau_2^{cou} = C\cdot z \,, \qquad (25)$$

where the constant C and the variable z are given by formulas (15) and (20), respectively.

This makes $\tau_r^c = \tau_2^{cou} = C\cdot z$ proportional to the Coulomb parameter z, defined in (15). Therefore, the quantity τ_r^c does not depend upon angular momentum, l. On the other hand, the corresponding "reduced", experimental half-life is

$$\tau_r^e = \tau^e - (\tau_{fa} + \bar{g}\cdot\tau_1 + \tau_2^{cen}) \qquad (26)$$

in such a way that $\Delta\tau = \tau_r^c - \tau_r^e = \tau^c - \tau^e$.

Incidentally, $l = 0$ for all measured cases analyzed in the present research, and so $\tau_2^{cen} = 0$. However, the method remains valid for any value of l.

Figure 3 displays all the α-decay half-life data that have been obtained following the present methodology for the twenty-four cases of α-transitions of Osmium isotopes. As one can see, the measured, reduced half-life-data, indicated by full circles, are located closely to the straight line which represents the calculate values.

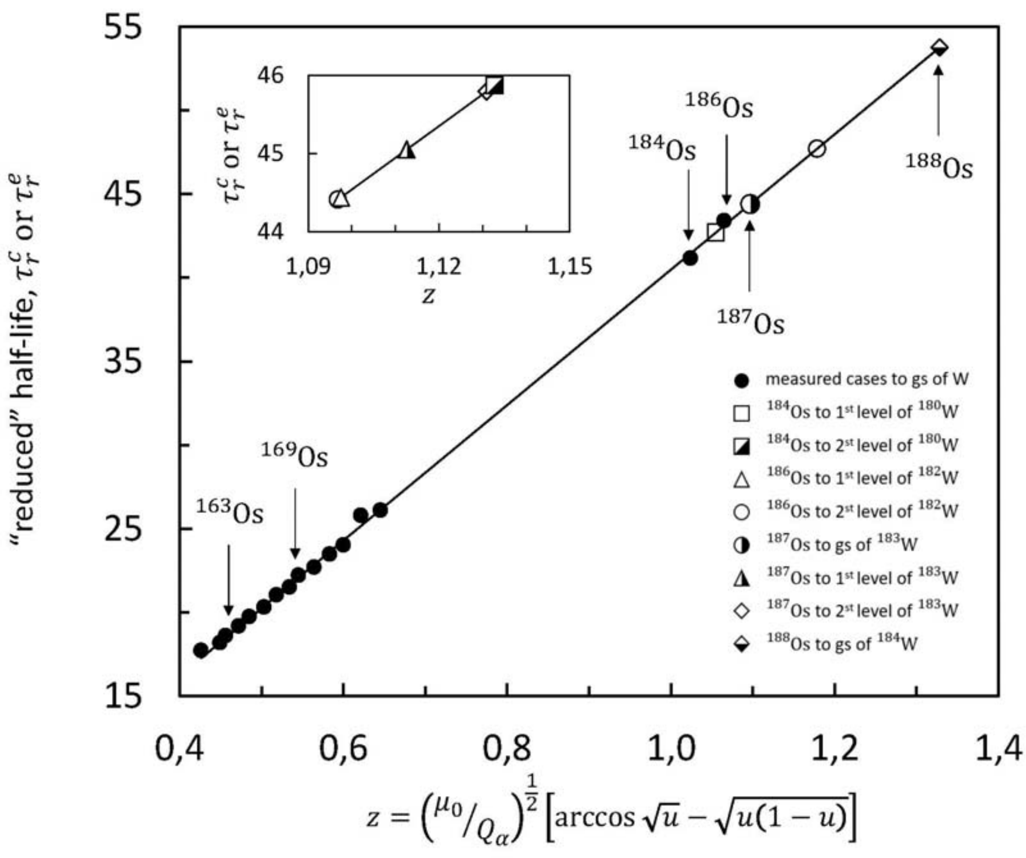

Fig.3. Reduced half-life, $\tau_r = \tau_2^{cou}$ (Eqs. (25), (26)), plotted against z for all cases of α-transitions of Osmium isotopes. Calculated values are represented by the straight line $\tau_r^c = 40.48984 \cdot z$. Full circles: experimental τ_r^e-values for all sixteen observed cases of gs-gs α-transitions; open and semi-open symbols (see inserted caption): yet unobserved gs-gs α-decays for $^{187,\ 188}$Os isotopes and six cases to excited levels of daughter W isotopes which could emit γ quanta accompanying the α emission. Five of these last cases are represented in the inserted graph: the corresponding, predicted $T_{1/2}$-values are listed in Table 3.

4. Final comments and conclusion

Among the gs-gs α-decay cases analyzed for the sixteen Osmium isotopes according to the present calculation model, only two cases show a ratio of experimental to calculated half-life-values somewhat greater than 1, *viz.*, a factor 3 for ^{161}Os and ~ 5 for ^{173}Os parent isotopes (see Table 2). It is not easy to identify a reason (or reasons) that can clearly explain such differences. These could be ascribed, among others, to uncertainties associated to input data of gs-gs Q_α-value and associated α-branching ratio, or even to efficiencies in the experimental methods of α-particle detection.

As regard the naturally occurring Osmium isotopes, new experimental results on α-decay half-life for α-transitions to both ground-state and excited levels of daughter Tungsten isotopes are being awaited (Belli *et al.*, 2019). The availability of a further data set to be compared with the predictions of the present calculation model will provide the possibility to further check the validity of the model.

^{187}Os isotope, descendent from ^{187}Re through β^- decay with $T_{1/2}$ = (41.53 ± 0.08) Ga (Selby *et al.*, 2007), is an important isotope, widely used for dating of terrestrial and meteoritic rocks (Dabek and Halas, 2007). The ^{187}Re→^{187}Os decaying system is one of the cosmological "clocks" that have been proposed to establish a lower limit for the age of the Universe.

Additionally, ^{187}Os isotope comes into play on both the ^{187}Os/^{186}Os and ^{187}Os/^{188}Os isotopic ratios, that represent a fundamental tracer of magma migrations and meteorite impacts over geological times. The variations of such ratios enable also to estimate the diameter of impacting meteorites across the late Eocene (Paquay *et al.*, 2008). Moreover, such isotopic ratios find a relevant application in mineral industry, useful in determining the origin of various metals inside conglomerates (Kirk *et al.*, 2002). Even if for geo-related applications the ^{187}Os/^{186}Os and ^{187}Os/^{188}Os ratios appear rather unaffected by the radiogenic behavior of the involved isotopes, the knowledge of the α-decay properties of such nuclides can conversely play a role in an extraterrestrial context. Therefore, theoretical predictions of half-life for long-term decaying nuclides, such as $^{186-188}$Os isotopes, for which there is still lack of experimental proofs, can help in addressing some big questions regarding cosmochemistry, nucleosynthesis and the Universe chronology.

In this regard, it is to be noted that the lowest natural alpha activity ever observed, equivalent to 1.71 ± 0.05 α's/(g·a) (Münster *et al.*, 2014), which is due to 0.12% of ^{180}W isotope in natural Tungsten, was predicted by the present approach as 2.72 α's/(g·a) (Medeiros *et al.*, 2006), *i. e.*, only ~ 60% higher than the measured value.

The feasibility of the presently adopted methodology to predict with a reasonably good accuracy the feature of the α-decay process means that the physical model based on the quantum mechanical tunneling through the described potential barrier in the precedent sections is a valid representation of the mechanism acting for the spontaneous heavy-particle (such α-particles) emission from nuclei. In this view, the present approach can be employed to reach results even more exciting that the evaluation of unmeasured decay constant, or serve as inspiration for further experiments.

This model can indeed give a clue to predict and identify α-decay chains that compete with the spontaneous fission process in the decay of artificially produced super-heavy nuclides (Z > 103), applied to other sequences of α-emitting radioisotopes or to other modes of heavy-particle radioactivity. To conclude, the investigation of the α-radioactive decay process is expected to provide new opportunities and open somewhat unexpected scenarios in several research fields at the crossroads of past and future.

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