Romanian Reports in Physics, Vol. 59, No. 2, P. 667–674, 2007

Dedicated to Prof. Dorin N. Poenaru's
70th Anniversary

SHE DECAYS NEAR THE MAGIC ISLAND

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(Received January 17, 2007)

Abstract. Synthesis of new superheavy element (SHE) and measurement of it's α-decay lifetime are two of the major goals of the present day nuclear physics. With the advent of radioactive ion beams it is now possible to sail towards the elusive magic island where the ultimate neutron-rich SHE resides. D.N. Poenaru and his collaborators have made fundamental contributions on α-decay properties of SHE. We present theoretical estimations of α-decay half lives of several new SHE. Calculations in a WKB framework using DDM3Y interaction and experimental Q-values are in good agreement with the experimental data. Half life calculations are found to be extremely sensitive to the Q-values and reveal limitations of available mass formula in the superheavy region.

Key words: superheavy nuclei, fusion reactions, cross-section, WKB, DDM3Y.

1. INTRODUCTION

We are living in an exciting period of time when one after another a new superheavy element (SHE) is being discovered [1, 2, 3]. This journey across the sea of instability has been possible because of a tremendous progress in theory, experiments and accelerator technologies. Upcoming radioactive ion beam (RIB) facilities now promise to usher us to the ultimate magic island where the neutron-rich SHE resides. Microscopic nuclear theories suggest a significant enhancement in nuclear stability when approaching the closed spherical shells with $Z = 114$, or, $Z = 120$, 122 and $N = 184$. SHE mainly undergoes sequential α-decay, which ends with spontaneous fission. In 1980 A. Sandulescu, D.N. Poenaru and W. Greiner predicted a new type of decay intermediate between fission and α-decay in heavy and superheavy nuclei and showed that α-decay could be successfully regarded as a fission process with different charge densities of the two fragments [4]. In last 26 years, D.N. Poenaru and his collaborators have made fundamental contributions on α-decay properties and potential energy surface of SHE [5–29].

One of the major goals of theory is to be able to predict the life times of SHE. We have calculated lifetimes of some heavy elements with $Z = 106-116$ and 118 in the WKB framework using DDM3Y effective nuclear interactions [30] and experimental Q-values. To explore the predictive power of the theoretical Q-values in the same framework, we deduced theoretical Q-values using the mass formula of Myers and Swiatecki [31]. But these values are not always in good agreement with the experimental ones. It is found that the half life calculations are extremely sensitive to the choice of Q-values and therefore, theoretical Q-values do not always reproduce the experimental half lives. The α-decay half lives calculated with experimental Q-values are in reasonable agreement with a wide range of experimental data [2, 3, 32, 33].

2. DOUBLE FOLDED POTENTIALS AND THE α-DECAY HALF LIVES OF SUPERHEAVY NUCLEI

The half life of a parent nucleus decaying via α emission is calculated using the WKB barrier penetration probability [34]. The decay half life T of the parent nucleus (A, Z) into a α and a daughter (A_d, Z_d) is given by,

$$T = [(h \ln 2)/(2E_v)][1 + \exp(K)], \tag{1}$$

where E_v is the zero point vibration energy. The action integral K within the WKB approximation is given by

$$K = (2/\hbar) \int_{R_a}^{R_b} [2\mu(E(R) - E_v - Q)]^{1/2} dR, \tag{2}$$

where R_a and R_b are the two turning points of the WKB action integral determined from the equations

$$E(R_a) = Q + E_v = E(R_b), \tag{3}$$

whose solutions provide three turning points. The α particle oscillates between the first and the second turning points and tunnels through the barrier at R_a and R_b representing the second and the third turning points respectively. Note that the zero point vibration energy E_v appearing in the denominator of Eq. (1) is proportional to the released energy Q which, through the action integral [Eq. (2)], also goes to the exponential function in Eq. (1). Hence lifetime calculations become very sensitive to the released energies Q involved in the decay processes.

The total interaction energy $E(R)$ between the α and the residual daughter nucleus is equal to the sum of the nuclear interaction energy, Coulomb interaction energy and the centrifugal barrier. Thus

$$E(R) = V_N(R) + V_C(R) + \hbar^2 l(l+1)/(2\mu R^2), \tag{4}$$

where $\mu = M_e M_d/M$ is the reduced mass, M_e, M_d and M are the masses of the emitted particle, the daughter nucleus and the parent nucleus respectively, all measured in the units of MeV/c^2.

The nuclear interaction potential $V_N(R)$ between the daughter nucleus and the emitted particle is obtained in a double folding model as [30],

$$V_N(R) = \int\int \rho_1(\vec{r_1})\rho_2(\vec{r_2})v[|\vec{r_2} - \vec{r_1} + \vec{R}|]d^3r_1 d^3r_2, \tag{5}$$

where ρ_1 and ρ_2 are the density distribution functions for the two composite nuclear fragments and $v[|\vec{r_2} - \vec{r_1} + \vec{R}|]$ is the effective NN interaction. The density distribution function in case of α particle has the Gaussian form

$$\rho(r) = 0.4229 \exp(-0.7024 r^2), \tag{6}$$

whose volume integral is equal to $A_\alpha(= 4)$, the mass number of α-particle. The matter density distribution for the daughter nucleus can be described by the spherically symmetric Fermi function

$$\rho(r) = \rho_0/[1 + \exp((r - c)/a)], \tag{7}$$

where the equivalent sharp radius r_ρ, the half density radius c and the diffuseness for the leptodermous Fermi density distributions are given by

$$c = r_\rho(1 - \pi^2 a^2/3r_\rho^2), \quad r_\rho = 1.13 A_d^{1/3}, \quad a = 0.54 \text{ fm} \tag{8}$$

and the value of the central density ρ_0 is fixed by equating the volume integral of the density distribution function to the mass number A_d of the residual daughter nucleus.

The distance s between any two nucleons, one belonging to the residual daughter nucleus and other belonging to the emitted α, is given by $s = |\vec{r_2} - \vec{r_1} + \vec{R}|$ while the interaction potential between these two nucleons $v(s)$ appearing in Eq. (5) is given by the factorised DDM3Y effective interaction. The general expression for the DDM3Y realistic effective NN interaction used to obtain the double-folded nucleus-nucleus interaction potential is given by,

$$v(s, \rho_1, \rho_2, \epsilon) = t^{M3Y}(s, \epsilon) g(\rho_1, \rho_2, \epsilon), \tag{9}$$

where the isoscalar t_{00}^{M3Y} and the isovector t_{01}^{M3Y} components of M3Y interaction potentials [30] supplemented by zero range potentials are given by the following equations:

$$t_{00}^{M3Y}(s,\epsilon) = 7999\frac{\exp(-4s)}{4s} - 2134\frac{\exp(-2.5s)}{2.5s} - 276(1-\alpha\epsilon)\delta(s), \qquad (10)$$

$$t_{01}^{M3Y}(s,\epsilon) = -4886\frac{\exp(-4s)}{4s} + 1176\frac{\exp(-2.5s)}{2.5s} + 228(1-\alpha\epsilon)\delta(s). \qquad (11)$$

If anyone (or, both) of the daughter and emitted nucleus involved in the decay process has $N = Z$, the isovector term does not contribute. Therefore in α-decay calculations only the isoscalar term is considered.

The density-dependent term $g(\rho_1, \rho_2, \epsilon)$ can be factorized into a target term times a projectile term as,

$$g(\rho_1,\rho_2,\epsilon) = C(1-\beta(\epsilon)\rho_1^{2/3})(1-\beta(\epsilon)\rho_2^{2/3}), \qquad (12)$$

where ϵ is the energy per nucleon.

Assuming spherical charge distribution for the residual daughter nucleus and the emitted nucleus as a point particle, the Coulomb interaction potential $V_C(R)$ between them is given by

$$\begin{aligned} V_C(R) &= \left(\frac{Z_e Z_d e^2}{2R_c}\right)\cdot\left[3-\left(\frac{R}{R_c}\right)^2\right] \quad \text{for } R \le R_c, \\ &= \frac{Z_e Z_d e^2}{R} \quad \text{otherwise}, \end{aligned} \qquad (13)$$

where Z_e and Z_d are the atomic numbers of the emitted-cluster and the daughter nucleus respectively. The touching radial separation R_c between the emitted-cluster and the daughter nucleus is given by $R_c = c_e + c_d$, where c_e and c_d have been obtained using Eq. (8). The energetics allow spontaneous emission of a particle only if the released energy

$$Q = [M - (M_e + M_d)]c^2 \qquad (14)$$

is a positive quantity.

Comparison between experimental and calculated α-decay half-lives for zero angular momenta transfers, using spherical charge distributions for the Coulomb interaction and the DDM3Y effective interaction is given in Table 1 and 2. The lower and upper limits of the theoretical half lives corresponding to the upper and lower limits of the experimental Q_α values are also provided. This calculation is valid for nuclei having small or zero deformation. To study the predictive power of the mass formula, Q-values are also calculated using the mass formula of Myers and Swiatecki [31]. As shown in Table 1 and 2, the half lives calculated by these theoretical Q-values do not always reproduce the experiment data. For example, the theoretical half life of $^{289}114$ obtained using the Q-value extracted from ref. [31] is $\sim$ 700 times the experimental one. Where as, calculations in the same framework but with experimental Q-values, agree well with a wide range of experimental data.

Tables 1 and 2 show that the $T_{1/2}$-value decreases as Q increases. But, this trend seems to be violated in the experimental data (Table 2) of $^{274}111$ and $^{270}109$ given in Ref. [3], origin of which needs to be explored.

Table 1

Comparison between experimental and calculated α-decay half-lives of nuclei having even atomic number (Z). Q_{ex} and Q_{th} are expressed in MeV

Parent Nuclei	Expt. Ref. [31]	Theor. This Work	Expt. This Work	DDM3Y	DDM3Y	Refs.
^AZ	Q_{ex}	Q_{th}	$T_{1/2}$	$T_{1/2}[Q_{ex}]$	$T_{1/2}[Q_{th}]$	Expt.
$^{294}118$	11.81(6)	12.51	$0.89^{+1.07}_{-0.31}$ms	$0.66^{+0.23}_{-0.18}$ms	0.02 ms	[2]
$^{293}116$	10.67(6)	11.15	53^{+62}_{-19}ms	206^{+90}_{-61}ms	12.8 ms	[33]
$^{292}116$	10.80(7)	11.03	18^{+16}_{-6}ms	39^{+20}_{-13}ms	10.4 ms	[33]
$^{291}116$	10.89(7)	11.33	18^{+22}_{-6}ms	$60.4^{+30.2}_{-20.1}$ms	5.1 ms	[2]
$^{290}116$	11.00(8)	11.34	$7.1^{+3.2}_{-1.7}$ms	$13.4^{+7.7}_{-5.2}$ms	2.0 ms	[2]
$^{289}114$	9.96(6)	9.08	$2.7^{+1.4}_{-0.7}$s	$3.8^{+1.8}_{-1.2}$s	1885 s	[33]
$^{288}114$	10.09(7)	9.39	$0.8^{+0.32}_{-0.18}$s	$0.67^{+0.37}_{-0.27}$s	76.96 s	[33]
$^{287}114$	10.16(6)	9.53	$0.48^{+0.16}_{-0.09}$s	$1.13^{+0.52}_{-0.35}$s	77.74 s	[2]
$^{286}114$	10.33(6)	9.61	$0.13^{+0.04}_{-0.02}$s	$0.16^{+0.07}_{-0.05}$s	17.70 s	[2]
$^{285}112$	9.29(6)	8.80	34^{+17}_{-9}s	75^{+41}_{-26}s	3046 s	[33]
$^{283}112$	9.67(6)	9.22	$3.8^{+1.2}_{-0.7}$s	$5.9^{+2.9}_{-2.0}$s	134.7 s	[2]
$^{279}110$	9.84(6)	9.89	$0.20^{+0.05}_{-0.04}$s	$0.40^{+0.18}_{-0.13}$s	0.29 s	[2]
$^{275}108$	9.44(6)	9.58	$0.19^{+0.22}_{-0.07}$s	$1.09^{+0.61}_{-0.35}$s	0.44 s	[2]
$^{271}106$	8.67(8)	8.59	$1.9^{+2.4}_{-0.6}$min	$0.86^{+0.71}_{-0.39}$min	1.59 min	[2]

Table 2

Comparison between experimental and calculated α-decay half-lives of nuclei having odd atomic number. Q_{ex} and Q_{th} are expressed in MeV

Parent Nuclei	Expt. Ref. [31]	Theor. This Work	Expt. This Work	DDM3Y	DDM3Y	Refs.
^{A}Z	Q_{ex}	Q_{th}	$T_{1/2}$	$T_{1/2}[Q_{ex}]$	$T_{1/2}[Q_{th}]$	Expt.
$^{288}115$	10.61(6)	10.34	87^{+105}_{-30}ms	$410.5^{+179.4}_{-122.7}$ms	2161.6 ms	[32]
$^{287}115$	10.74(9)	10.48	32^{+155}_{-14}ms	$51.7^{+35.8}_{-22.2}$ms	245.2 ms	[32]
$^{284}113$	10.15(6)	9.36	$0.48^{+0.58}_{-0.17}$s	$1.55^{+0.72}_{-0.48}$s	330.19 s	[32]
$^{283}113$	10.26(9)	9.56	100^{+490}_{-45}ms	$201.6^{+164.9}_{-84.7}$ms	19845 ms	[32]
$^{278}113$	11.90(4) $^{*)}$	12.77	344 μs $^{**)}$	$101^{+27}_{-18}\mu$s	1.8 μs	[3]
$^{280}111$	9.87(6)	10.34	$3.6^{+4.3}_{-1.3}$s	$1.9^{+0.9}_{-0.6}$s	0.10 s	[32]
$^{279}111$	10.52(16)	11.12	170^{+810}_{-80}ms	$9.6^{+14.8}_{-5.7}$ms	0.34 ms	[32]
$^{274}111$	11.36(7) $^{*)}$	11.07	9.26 ms $^{**)}$	$0.39^{+0.18}_{-0.12}$ms	1.92 ms	[3]
$^{276}109$	9.85(6)	10.11	$0.72^{+0.87}_{-0.25}$s	$0.45^{+0.23}_{-0.14}$s	0.09 s	[32]
$^{275}109$	10.48(9)	10.26	$9.7^{+46}_{-4.4}$ms	$2.75^{+1.85}_{-1.09}$ms	10.33 ms	[32]
$^{270}109$	10.23(7) $^{*)}$	9.73	7.16 ms $^{**)}$	$52.05^{+27.02}_{-17.68}$ms	1235 ms	[3]
$^{272}107$	9.15(6)	9.08	$9.8^{+11.7}_{-3.5}$s	$10.1^{+5.4}_{-3.4}$s	16.8 s	[32]
$^{266}107$	9.26(4) $^{*)}$	9.00	2.47 s $^{**)}$	$5.73^{+1.82}_{-1.38}$s	36.01 s	[3]

$^{*)}$ These Q_{ex} values are calculated using the measured α-decay energies [3].
$^{**)}$ These are experimental decay times [3] (not $T_{1/2}$ values).

3. SUMMARY AND CONCLUSION

Finding the ultimate long-lived neutron-rich superheavy element (SHE) on the magic island of stability is a long cherished dream of the physicists. While such searches are on, it is imperative to find a tool to predict their decay half-lives to guide the experiments. We show that calculations of their α-half lives in the framework of a WKB approximation with DDM3Y interaction and experimental Q-values give a reasonably good agreement with the experimental data. But, the experimental Q-values are not always reproduced by the theoretical ones extracted from the existing mass formulae. As calculations of α-decay half lives are extremely sensitive to the choice of Q-values, further improvement of mass formulae in the superheavy region is essential for accurate predictions of unknown half-lives.

Acknowledgements. The author acknowledges P. Roy Chowdhury and D.N. Basu for their valuable collaboration in this project.

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