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DECAY PROPERTIES OF SUPERHEAVY NUCLEI $Z = 118 - 122$ AND $N = 182 - 186$

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Abstract. The α-decay and spontaneous fission half-lives of yet-unaccessible superheavy elements are estimated with the formulas derived from the energy-lifetime systematics of both the data and calculated decay properties for the $Z = 104 - 118$ known nuclei. The trend of decay properties in the region of studied nuclei indicates as a possible center of the island of stability at the spherical closed shells $Z = 120$ and $N = 184$. The dominant decay mode in this region of nuclei is the spontaneous fission and not α-decay. Our predictions for decay properties are compared with the ones given by empirical and model approximations.

Key words: superheavy nuclei, decay properties.

1. INTRODUCTION

In the past two decades significant progress has been made in the synthesis of new superheavy nuclei (SHN) and in the study of their atomic and nuclear properties. The superheavy elements $Z = 113 - 118$, ^{113}Nh (Nihonium) [1], ^{114}Fl (Flerovium) [2], ^{115}Mc (Moscovium) [3], ^{116}Lv (Livermorium) [4], ^{117}Ts (Tennessine) [5] and ^{118}Og (Oganesson) [6] were synthesized for the first time. The isotope ^{294}Og produced at Dubna represents the current upper limit of mass and nuclear charge measurements. It decays to ^{290}Lv by α-decay with a half-life of $T_\alpha = 0.89$ ms and a reaction energy Q_α=11.820 MeV. The study of properties and decay phenomena of SHN goes back over fifty years and a wide body of experimental data [7–10] and theoretical analysis exists [11–29]. The experimental data show that the main decay modes of known SHN are α-decay and spontaneous fission (SF). Usually, an α-decay chain terminates at a fissioning nucleus. It is our purpose of this work, to correlate on a theoretical basis the reaction data with the nuclear structure observables. We perform a systematics of all the α-half-lives *versus* reaction energies (T_α, Q_α) for all the measured SHN. For spontaneous fission half-lives the systematics is realized in terms of measured reaction energies and calculated heights of fission barriers. From the both systematics we extract the formulas for half-lives. This paper is organized as follows. In Sec. 2 the formalism is briefly reviewed. In Sec. 3 the results for the α and SF half-lives, the systematics of the α-decay properties for almost all the known SHN at the present date, and the fit formulas for practical estimations of a half-lives are presented. The concluding remarks are summarized in Sec. 4.

2. THEORETICAL FRAMEWORK

2.1. α-DECAY

For calculating the α- decay rates we used the shell model rate approach [16, 19, 27], which combines the Mang shell theory (MST) [30] for the nuclear structure with the Breit- Feshbach theory (BFT) [31, 32] for the resonance scattering. In this Section, we give a short review on the employed MST + BFT approach. The α half-life of a decaying state k into a channel n is given by:

$$T_n^k = \ln 2(\hbar/\Gamma_n^k), \tag{1}$$

where, the α-decay width is

$$\Gamma_n^k = 2\pi \left| \frac{\int_{r_{\min}}^{r_{\max}} I_n^k(r) u_n^0(r) dr}{\int_{r_{\min}}^{r_{\max}} I_n^k(r) u_n^k(r) dr} \right|^2 . \tag{2}$$

In Eq. (2), $I_n^k(r)$ is the formation amplitude (FA) defined as the antisymmetrized projection of the parent wave function (WF) $\mid \Psi_k >$ on the channel WF $\mid n\rangle = \mid [\Phi_D(\eta_1)\Phi_p(\eta_2)Y_{lm}(\hat{r})]_n\rangle$:

$$I_n^k(r) = r\langle \Psi_k \mid \mathcal{A}\{[\Phi_d(\eta_1)\Phi_\alpha(\eta_2)Y_{lm}(\hat{r})]_n\}\rangle, \tag{3}$$

where $\mid \Psi_k >$ is constructed from single-particle (s.p.) wave functions [33–35] and $\Phi_d(\eta_1)$, $\Phi_\alpha(\eta_2)$ are the internal (space-spin) wave functions of the daughter nucleus and of the particle, $Y_{lm}(\hat{r})$ is the wave function of the angular motion, $\mathcal{A}$ is the inter-fragment antisymmetrizer, r connects the centers of mass of the fragments, and the symbol $<|>$ means integration over the internal coordinates of the fragments and angular coordinates of relative motion. The functions $u_n^{0,k}(r)$ are solutions of the system of differential equations:

$$\begin{aligned}&\left[\frac{\hbar^2}{2M}\left(\frac{d^2}{dr^2}-\frac{l(l+1)}{r^2}\right)-V_{nn}(r)+Q_n\right]u_n^0(r)\\&+\sum_{m\neq n}V_{nm}(r)u_m^0(r)=0,\end{aligned} \tag{4}$$

$$\begin{aligned}&\left[\frac{\hbar^2}{2M}\left(\frac{d^2}{dr^2}-\frac{l(l+1)}{r^2}\right)-V_{nn}(r)+Q_n\right]u_n^k(r)\\&+\sum_{m\neq n}V_{nm}(r)u_m^k(r)=I_n^k(r).\end{aligned} \tag{5}$$

where $M = (A_\alpha A_d)/(A_\alpha + A_D)$ is the reduced mass, Q_n is the reaction energy, and $V_{nm}(r)$ are the matrix elements of interaction potential. The matrix elements $V_{nm}(r)$ include the nuclear (Woods-Saxon) and Coulomb components [19] defined with the quadrupole (β_2) and hexadecapole (β_4) deformation parameters and charge radii of the fragments. The solutions of Eqs. (4,5) satisfy the boundary conditions for the scattering and bound states and describe the radial motion of the fragments at large and small separations.

In the case of a single decaying state k and the one channel n we search the solution of Eq. (4) by itterating the depth in origin of nuclear potential ($V_{0n}^{res}(r)$) directly in equation of motion [16]. Following the Breit procedure [31] we obtained the solution $u_{n=1}^0(r)$ as the "one-body" (o.b.) resonance solution $u_{n=1}^{res}(r)$. Replacing in Eq. (5) $I_n^k(r)$ by $u_{n=1}^{res}(r)$ one obtains exactly the Breit o.b. resonance α- width [31] (Eq. 3.34 pag. 34). In the case of a single state k (shell model k=SM) and a set of decay channels n the asymptotic resonance solutions of the system of Eqs. (4) are obtained by using the method developed in [36]. In both cases the half-time is given by eigenvalues (Q_n, $V_{0n}^{res}(r)$ - the resonance depth in origin of the nuclear potential) and eigenfunctions ($u_n^0(r)$ = $u_n^{res}(r)$ and $I_n^k(r)$=$u_n^{res}(r)$). A similar procedure for searching the eigenstates of nuclear potential are used in [37–39].

2.2. SPONTANEOUS FISSION

The spontaneous fission (SF) half-life is expressed as [27]:

$$\begin{aligned}\log_{10}T_{SF}(s) &= 1146.44-75.3153X\\&+ 1.63792X^2-0.0119827X^3\\&+ B_SF(7.23613-0.0947022X)+h_{e-o},\end{aligned} \tag{6}$$

where $X = Z^2/A$, B_f is the hight of SF barrier and h_{e-o} are new even-odd corrections [26]: $h_{e-o} = 0$ for ($Z = e$, $N = e$); 2.007 for ($Z = e$, $N = o$); 2.822 for ($Z = o$, $N = e$), and 3.357 for ($Z = o$, $N = o$). The fission data of SHN are taken from [7–10, 40, 41].

3. FIT OF EXPERIMENTAL AND CALCULATED α-DECAY HALF-LIVES

The relevant systematics of α-decay half-lives has been proposed in [26]:

$$\log_{10} T_{\alpha}^{f}(\mathrm{sec}) = A Z_{d}^{0.6} Q_{\alpha t}^{-1/2} - B, rms \tag{7}$$

where Z_d is the atomic number of the daughter nucleus, $Q_{\alpha t}$ is the total decay energy, and A and B are the fit parameters and rms is the root mean square error. The root mean square error is defined as:

$$rms = [N^{-1/2}][\sum_{i=1}^{N}(log_{10}(T_{\alpha,i}^{f}/T_{\alpha,i})^{2}]^{-1/2}, \tag{8}$$

where N is the number of considered α-emitter nuclei and T_{α}^{f} are the fitted values of T_{α}. The values of parameters extracted from experimental and calculated (shell and one-body models, SM and ob) AD-half-lives are given in Table 1.

Table 1: Values of the parameters A, B and the standard error rms determined from the fit of experimental and calculated α half-lives [42]. The fits are performed for 80 nuclei with measured values of Q_{α}.

Fit of half-lives	$Z-N$	A	B	rms
Experimental	e-e	9.746	52.236	0.493
(T_{α}^{fexp})	o-e	9.209	48.550	0.600
	e-o	10.299	53.958	0.511
	o-o	8.793	45.919	0.550
Calculated	e-e	8.824	46.846	0.252
Shell Model	o-e	8.489	44.652	0.496
(T_{α}^{fSM})	e-o	7.742	40.432	0.265
	o-o	8.276	42.865	0.428
Calculated	e-e	10.481	57.391	0.439
One-Body	o-e	9.933	54.620	0.429
(T_{α}^{fob})	e-o	11.700	63.634	0.487
	o-o	9.676	53.229	0.406

4. RESULTS

The α-decay energies Q_{α} for nuclei $Z = 118 - 122$ and $N = 182 - 186$ are taken from Ref. [43]. To these theoretical predictions we add the screening corrections. In order to explore the main decay properties of these nuclei, theoretical estimates for charge radii of the parent and daughter nuclei are necessary. These estimates are obtained by using the prescriptions of Refs. [44–46]. The results for partial lifetimes and branching ratios are summarized in Tables 1 and 2. Here, we notice:

- the same or very close values for T_α^{fSM} and T_α^{fexp}.
- the values T_α^{fSM} are greater than those of T_α^{fob} by $2-3$ orders of magnitude.
- lifetimes increase with increasing N and decreases with increasing Z.
- a strong α-SF competition is manifested in even-even nuclei.
- the unpaired nucleon considerably increases the SF half-lives.
- the odd-even effects are seen in lifetimes neighbouring isotopes.
- the neutron defficient isotopes of the elements $Z = 118 - 119$ appear as prominent α-emitters and if they will be produced they may be identified by observing the α-particles.
- for the isotopes of elements $Z = 120 - 122$ the dominant decay mode is fission not α-decay.

It is also interesting to note that the predicted α-half lives for parent nuclei $^{308}122_{186}$, $^{212}Po_{128}$, $^{104}Te_{52}$ that correspond to doubly magic daughter nuclei ($^{304}120_{184}$, $^{208}Po_{126}$, $^{100}Sn_{50}$) are approximately of the same order of magnitude $T_\alpha = 10^{-6}$ s [42]. Thus, we can see that the nuclei with an α particle outside the double closed shells are prominent α-emitters and show identical half-lives. The observation in experiments of such shorter lived nuclei is a difficult problem in searching for new elements. Decay properties of SHN with $Z > 118$ have been investigated in Refs. [47–54].

5. COMPARISON BETWEEN VARIOUS MODELS FOR α-DECAY HALF-LIVES

Table 2: Calculated decay properties for some isotopes of the SHN with $Z = 118 - 122$ and $N = 182 - 186$. Q_α values are obtained with the prescriptions of [43] and the fission barriers are taken as in Ref.[42]. The branching ratio, $b_\alpha = T_\alpha^{fSM}/T_{SF}$, is calculated from the fit of shell model α and fission half-lives.

Nucleus	Q_α(MeV)	T_α^{fSM} (s)	T_α^{fob} (s)	T_α^{fexp} (s)	b_α	b_{SF}
^{300}Og	12.049	0.736×10^{-1}	0.365×10^{-4}	0.263×10^{-1}	0.01	0.99
^{301}Og	12.159	0.912×10^{-2}	0.174×10^{-4}	0.474×10^{-2}	0.73	0.27
^{302}Og	12.251	0.332×10^{-1}	0.144×10^{-4}	0.113×10^{-1}	0.00	1.00
^{303}Og	12.751	0.910×10^{-3}	0.117×10^{-5}	0.389×10^{-3}	0.00	1.00
^{304}Og	13.302	0.712×10^{-3}	0.161×10^{-6}	0.191×10^{-3}	0.00	1.00
^{301}119	12.472	0.129×10^{-2}	0.661×10^{-5}	0.206×10^{-3}	0.21	0.79
^{302}119	12.462	0.141×10^{-1}	0.471×10^{-5}	0.233×10^{-2}	0.04	0.96

Nucleus	Q_α (MeV)	T_α^{fSM} (s)	T_α^{fob} (s)	T_α^{fexp} (s)	b_α	b_{SF}
^{303}119	12.454	0.139×10^{-2}	0.721×10^{-5}	0.223×10^{-3}	0.00	1.00
^{304}119	12.762	0.494×10^{-2}	0.963×10^{-6}	0.576×10^{-3}	0.00	1.00
^{305}119	13.452	0.302×10^{-4}	0.763×10^{-7}	0.325×10^{-5}	0.00	1.00
^{302}120	12.853	0.894×10^{-2}	0.310×10^{-5}	0.280×10^{-2}	0.00	1.00
^{303}120	12.753	0.239×10^{-2}	0.363×10^{-5}	0.111×10^{-2}	0.00	1.00
^{304}120	12.653	0.187×10^{-1}	0.737×10^{-5}	0.614×10^{-2}	0.00	1.00
^{305}120	13.353	0.265×10^{-3}	0.277×10^{-6}	0.102×10^{-3}	0.00	1.00
^{306}120	13.653	0.546×10^{-3}	0.118×10^{-6}	0.144×10^{-3}	0.00	1.00
^{303}121	13.453	0.799×10^{-4}	0.243×10^{-6}	0.954×10^{-5}	0.00	1.00
^{304}121	13.353	0.164×10^{-2}	0.182×10^{-6}	0.133×10^{-3}	0.00	1.00
^{305}121	13.253	0.168×10^{-3}	0.585×10^{-6}	0.216×10^{-4}	0.00	1.00
^{306}121	13.753	0.272×10^{-4}	0.674×10^{-7}	0.289×10^{-5}	0.00	1.00
^{307}121	14.403	0.656×10^{-4}	0.140×10^{-8}	0.183×10^{-5}	0.00	1.00
^{304}122	13.654	0.135×10^{-2}	0.340×10^{-6}	0.376×10^{-3}	0.00	1.00
^{305}122	13.704	0.198×10^{-3}	0.197×10^{-6}	0.746×10^{-4}	0.00	1.00
^{306}122	13.804	0.817×10^{-3}	0.189×10^{-6}	0.220×10^{-3}	0.00	1.00
^{307}122	14.704	0.760×10^{-5}	0.434×10^{-8}	0.217×10^{-5}	0.00	1.00
^{308}122	15.154	0.126×10^{-4}	0.144×10^{-8}	0.261×10^{-5}	0.00	1.00

Table 3: The present calculated α-half lives T_α^{fob}, T_α^{fSM}, T_α^{fexp}, and those estimated in [55] T_α for some even-even isotopes of the SHN with $Z = 118$, 120, 122. The Q_α values are taken from [55].

Nucleus	Q_α(MeV)	T_α^{fob} (s)	T_α (s)	T_α^{fSM} (s)	T_α^{fexp} (s)
^{300}Og	11.956	0.444×10^{-4}	0.598×10^{-5}	0.870×10^{-1}	0.314×10^{-1}
^{302}Og	12.041	0.239×10^{-4}	0.365×10^{-5}	0.332×10^{-1}	0.113×10^{-1}
^{304}Og	13.122	0.272×10^{-6}	0.212×10^{-7}	0.111×10^{-2}	0.306×10^{-3}
^{302}120	12.890	0.212×10^{-5}	0.253×10^{-6}	0.664×10^{-2}	0.198×10^{-2}
^{304}120	12.763	0.364×10^{-5}	0.427×10^{-6}	0.102×10^{-1}	0.323×10^{-2}
^{306}120	13.787	0.574×10^{-7}	0.436×10^{-8}	0.294×10^{-3}	0.745×10^{-4}
^{304}122	13.738	0.198×10^{-6}	0.214×10^{-7}	0.850×10^{-3}	0.230×10^{-3}
^{306}122	13.803	0.154×10^{-6}	0.152×10^{-7}	0.686×10^{-3}	0.183×10^{-3}
^{308}122	14.940	0.248×10^{-8}	0.153×10^{-9}	0.200×10^{-4}	0.428×10^{-5}

Recently, Zhang and Wang [55] calculated the half-lives of α decay for some SHN with the UD [56], UNIV [57], Horoi [58], and UDL [59, 60] formulas. However, α-decay half-lives by four mentioned formulas are almost in the same order with "fit one body" formula (calculated by us, without considering the nuclear structure). They also calculated α-decay half-lives for some even-even isotopes of $Z = 118$, 120, and 122 by using the UDL formula. Again, small differences (less than 1 MeV) are observable between Q_α values of Ref. [55] and our study. Half-lives within the UDL formula are in good agreement with the "fit one body" α-decay half-lives. For example, α-decay half-lives of $^{308}122$ are 1.53×10^{-8} (s) and 0.144×10^{-8} (s), using UDL and "one body" models, respectively. Also α-decay half-lives for some odd-odd and odd-even superheavy nuclei have been calculated in Ref. [61], using six different models: CPPMDN [62], CPPM [63], the Viola-Seaborg-Sobiczewski (VSS) semiempirical relation [64, 65], the universal curve (UNIV) [57, 66], the analytical formula of Royer [67], and the universal decay law (UDL) [59, 60]. In that study (Ref. [61]), Q_α values that were calculated by WS4 [68] and WS3 [69] mass tables are quite similar to our results. Moreover, α-decay half-lives by those six models are of the same order of magnitude with our results by "one body" model. The decay modes and half lives of all the even Z isotopes of SHN within the extended range $Z = 104 - 136$ have been predicted by using the the shell effect-dependent formula [29] and CPPMDN potential. Our predicted α- half-lives T_α^{fob} for isotopes of elements $Z = 118$, 120, and 122 are very close to the ones (T_α^{SKP}) from [29]. However, the values of (T_α^{fSM}) and (T_α^{fexp}) are greater by $2 - 3$ orders of magnitude than the values of T_α^{fob}. Recently, others nuclear models have been proposed for estimating the rates of α and SF [70–73].

6. ATTEMPTS TO PRODUCE Z=120 ISOTOPES

In [74] the ^{244}Pu(^{58}Fe, xn)$^{302-xn}$120 reaction was studied. No decay chains consistent with fusion-evaporation reaction products ^{298,299}120 were observed during an irradiation with a beam dose of 0.7×10^{19}A$330 MeV$ ^{58}Fe projectiles. In [75] the reaction ^{54}Cr + ^{248}Cm was investigated at the velocity filter SHIP at GSI, Darmstadt, with the intention to study production and decay properties of the isotope of element 120: ^{299}120 .

These attempts to form isotopes of the new element ^{298,299}120 [74] and ^{299}120 [7] have been unsuccessful. Using the same reaction energies assumed in [75] we get [42] for the decay modes and half-lives of these isotopes:

- for ^{298}120, Q_α=12.4 MeV; T_α^{fSM} =0.040 s; T_α^{fexp}=0.013 s; $T_\alpha^{SM} = 2.00 \times 10^{-4}$; b_α=1.0; b_{SF}=0.0;

- for ^{299}120, Q_α=12.3 MeV; T$_\alpha^{fSM}$ =0.011 s; T_α^{fexp}=0.006 s; $T_\alpha^{SM} = 2.34 \times 10^{-3}$, b$_\alpha$=1.0; b$_{SF}$=0.0 and [74];

- for ^{299}120, Q$_\alpha$=13.318 MeV; $T_\alpha^{fSM} = 7.81 \times 10^{-4}$; $T_\alpha^{fexp} = 3.30 \times 10^{-4}$ s; $T_\alpha^{SM} = 2.21 \times 10^{-5}$; b_α=0.55; b_{SF}=0.45.

Notice that the reaction energies are not measured in Refs. [74, 75], these being only rough model estimates.

7. SUMMARY AND CONCLUSIONS

In this article we have investigated the decay modes and half-lives of not yet accessible isotopes of the elements $Z = 118 - 122$ and $N = 182 - 186$. By comparing the α-half-lives calculated with and without nuclear structure (involving the microscopic ”shell-model” and ”one-body” resonance formation amplitudes) one may conclude that the effects due to the quantum shell structure, finite sizes of nucleons, and the α-cluster have a stabilizing role in heaviest nuclei. The stabilization of nuclei is realized only for near - spherical shapes and the double magic shells, since the potential energy surface for elongate shapes of the two touching colliding nuclei becomes repulsive due to the strong Coulomb potential. We have found a remarkable agreement between our results of calculations and other results essentially based on most usual empirical parametrizations. The decay properties of the studied nuclei revealed a significant increase in their stability as they approached the predicted neutron shell $N = 184$.

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