ALPHA-DECAY AND SPONTANEOUS FISSION HALF-LIVES OF SUPER-HEAVY NUCLEI AROUND THE DOUBLE MAGIC NUCLEUS ^{270}Hs

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The α-decay and spontaneous fission (SF) half-lives of nuclei around ^{270}Hs are calculated with formulas derived from the systematics of data and theoretical results. The coefficients of the systematics result from the fit of half-lives in respect with the reaction energies Q_α , the height of the SF barrier B_f and the fissionability Z^2/A . The calculated partial and total half-lives are compared with the data and the results of other approximations. Half-life predictions are made for many unknown nuclei.

Key words: superheavy nuclei; α-decay; spontaneous fission; partial and total half-lives.

1. INTRODUCTION

New developments of experimental techniques have provided both from in-beam and decay studies new data on fusion-evaporation reactions leading to super-heavy nuclei (SHN), their nuclear properties and structure. Thus, the isotopes of elements with Z=104-112 (Rf, Db, Sg, Bh, Hs, Mt, Ds, Rg, Cn) have been successfully synthesized at GSI-Darmstadt, in cold-fusion reactions, or observed as daughter products in long α-decay chains [1]. The synthesis of element Z=113 in the reaction has been first produced at RIKEN, Japan [2]. Many isotopes of the elements with Z=113-118 has been synthesized at JINR-FLNR Dubna, in hot-fusion evaporation reactions with the ^{48}Ca beam and heavy actinide targets [3]. In more recent experiments with an improved detection technique, α-decay has been successfully used to investigate reactions involving ground, excited and isomeric states of SHN. The known data on these states, energy level schemes, and the structure are included in [4].

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The doubly magic nucleus ^{270}Hs was produced and studied in several reactions [5-11]. Essentially, most of the knowledge about the basic properties of SHN is based on the observation of two main decay modes: α-decay or spontaneous fission (SF). There is also an impressive theoretical activity for the interpretation of the available data, the detailed studies of competing decay modes, energy levels and the shell structure.

2. OUTLINE OF CALCULATIONS

Within the framework of the shell-model rate theory [12, 13] the α-decay half-lives have been obtained in terms of the α clustering and resonance scattering amplitudes given by self-consistent models for the nuclear structure and reaction dynamics. It was proven that the systematics of calculated half-lives well reproduces the systematics of available experimental data. From the systematics of calculated shell-model half-lives has resulted a practical formula the α-decay half-lives of SHN:

$$\log T_\alpha(s) = 10.59(Z_d^{0.6} Q_\alpha^{-0.5}) - 56.618 \quad \text{rms=0.078} \quad Z,N = \text{even} \quad \text{(e-e)} \tag{1}$$

$$\log T_\alpha(s) = 10.148(Z_d^{0.6} Q_\alpha^{-0.5}) - 53.386 \quad \text{rms=0.161} \quad A,\text{odd} \quad \text{(e-o,o-e)} \tag{2}$$

$$\log T_\alpha(s) = 10.225(Z_d^{0.6} Q_\alpha^{-0.5}) - 53.797 \quad \text{rms=0.047} \quad Z,N = \text{odd} \quad \text{(o-o)} \tag{3}$$

where

$$Q_\alpha(\text{MeV}) = A/(A-4)E_\alpha + (6.53 Z_d^{7/5} - 8 Z_d^{2/5})10^{-5} \tag{4}$$

is the released energy including the kinetic energy of fragments and the screening energy.

The SF of nuclei is a rather complicated process and hence the most realistic estimations of the SF half-lives are based on the search for the last action path in the multi-dimensional deformation space. For simplicity, in this work we use for the SF half-life the relation [16] deduced from the systematics of the SF half-lives based on the fissionability parameter Z^2/A, the fission barrier heights B_f [17] and the even-odd corrections:

$$\begin{aligned}\log_{10} T_{SF}(s) = {} & 1146.44 - 75.3153 Z^2/A + 1.63792(Z^2/A)^2 - 0.0119827(Z^2/A)^3 + \\ & + B_f(7.23613 - 0.0947022 Z^2/A) + \begin{cases} 0, Z, N = \text{even}, (e-e) \\ 1.53897, A, \text{odd}, (e-o, o-e) \\ 0.80822, Z, N = \text{odd}, (o-o) \end{cases}\end{aligned} \tag{5}$$

Parameters of a such systematics were fitted [16] to existing experimental data and also the realistic theoretical predictions for the region $100 \leq Z \leq 120$ and $140 \leq N \leq 190$.

3. RESULTS AND DISCUSSION

Table 1 shows in the columns 5-7 our results for the partial and total half-lives of more than 40 nuclei around ^{270}Hs with Z=104–112, and N=158–166. A reasonably good agreement between the values T_t^{calc} and $T_t^{\exp}$ is observed in most cases. Our results for the α and SF half-lives are in a good agreement to the available data and also with previous theoretical predictions [12, 13] and [18–27].

The α decay chains from newly discovered element Z=117 have in fact received a lot of attention in recent studies based on different models such as the shell model rate theory [13, 14], the Coulomb and proximity potential model for deformed nuclei [23–24], or generalized–density dependent cluster model [25] in which the calculated results are generally consistent with each other.

If comparing in Table 1 and Fig. 1 the total T_t^{calc} and $T_t^{\exp}$ and partial T_α and T_{SF} half-lives the conclusions are summarized as follows:

(1) The nuclides situated above ^{270}Hs present half-lives shorter than ones situated below ^{270}Hs, and this provides a direct evidence of the manifestation of the new closed shells Z=108, N=162 in the region of the SHN.

(2) In Fig.1 we can see that the stabilizing shell effect is maximum for ^{270}Hs. For this we get $T_\alpha = 9.48$ s ($E_\alpha = 9.13 \pm 0.03$ MeV [10]), while experimental estimation are $T_\alpha = 22$s ($E_\alpha = 9.02$ MeV [6]) and $T_t^{\exp} = (5.4–12.5)$s ($E_\alpha = 9.01 \pm 0.03$ MeV [10]) respectively, wile the estimation from systematic trends is $T_\alpha \approx 3.597$s ($E_\alpha = 9.162 \pm 0.03$ MeV [11]).

(3) Half-lives of even-even nuclei always are shorter than of odd-even, even-odd and odd-odd nuclei.

(4) The odd nucleon increases significantly T_{SF} in comparison with T_α.

There are small uncertainties ~(0.01–0.05) MeV in the measured α-decay energies, and possible large theoretical uncertainties in the calculated α-decay energies [14, 15] and in the underlying single-particle structure of the shell model [13]. The rms values in Eq. (1–3) are clearly connected with pairing properties affect moderately the predicted half-life and they represent only a secondary source for the uncertainties. Achieving better agreement with the experimental α-data will require to reduce significantly all these uncertainties.

The fusion and the α–decay of superheavy elements have been successfully treated with the two center shell model in a wide range of mass asymmetries

[28–30]. Deep insight into physics of fusion-fission processes can be obtained from the capture of the α-particle by the nuclei [31].

The above results suggest that the logarithm of the half-life of these decay modes depends exponentially on $Q_\alpha^{(-1/2)}$ and on the powers of the parameter Z^2/A, respectively. The analysis of uncertainties in the prediction of reaction energies, the position of the one and two-neutron and the one and two-proton drip lines has recently attracted great interest because of the possibility to estimate the number of “stable” isotopes of a given element.

Table 1

Experimental and calculated α-decay energies, total and partial α and SF half-lives for isotopes of elements with Z=104–112 and N=158–166.

Element	**N**	**A**	E_α **(MeV)**	**Log** T_α **(s)**	**Log** T_{SF} **(s)**	**Log** T_t^{calc} **(s)**	**Log** $T_t^{\exp}$ **(s)**
$_{104}$Rf	158	262	8.665	1.764	0.611	0.581	0.361
	159	263	8.420	3.360	3.408	3.082	2.819
	160	264	8.836*	1.195	1.548	1.035	3.556
	161	265	7.963	4.968	2.716	2.714	2.033
	162	266	7.759*	5.077	4.374	4.295	4.556
	163	267	7.931	5.084	5.529	4.951	3.670
	164	268	8.164*	3.527	3.709	3.307	3.556
$_{105}$Db	158	263	8.533	3.310	0.869	0.867	1.462
	159	264	7.974*	5.297	2.482	2.481	–
	160	265	8.085*	4.858	2.974	2.968	–
	161	266	8.247	4.310	5.469	4.281	3.681
	162	267	7.942	5.381	5.690	5.207	4.219
	163	268	8.337	3.994	6.781	3.994	5.044
	164	269	8.540*	3.286	5.007	3.278	–
	165	270	8.336	3.997	4.520	3.883	3.597
	166	271	8.072*	4.905	2.394	2.393	–
$_{106}$Sg	158	264	8.898	1.655	–0.797	–0.798	–1.431
	159	265	9.142	1.702	1.217	1.094	0.903
	160	266	8.979	1.394	2.047	1.307	–0.443
	161	267	8.369	4.188	4.413	3.985	1.924
	162	268	8.135*	4.328	4.590	4.138	1.470
	163	269	8.744	2.941	5.738	2.941	2.079
	164	270	8.175*	4.180	3.989	3.773	2.770
	165	271	9.067	1.927	3.651	1.918	2.158
	166	272	8.874*	1.735	1.356	1.205	–
$_{107}$Bh	158	265	9.426	1.169	0.110	0.073	0.075
	159	266	9.477	1.027	2.269	1.002	0.397
	160	267	9.009	2.419	2.631	2.211	1.342
	161	268	9.066*	2.253	4.371	2.250	–
	162	269	8.708*	3.377	5.203	3.370	–

	163	270	9.109	2.122	6.514	2.122	2.357
	164	271	8.873*	2.845	5.108	2.842	0.176
	165	272	9.189	1.877	4.671	1.876	0.944
	166	273	9.160*	1.956	2.404	1.824	–
${}_{108}$Hs	158	266	10.381	–2.058	–1.935	–2.302	–2.519
	159	267	10.076	–0.322	–0.231	–0.580	–1.259
	160	268	9.669	–0.085	–0.4.16	–0.582	0.152
	161	269	9.313	1.807	2.054	1.612	1.431
	162	270	9.133	0.977	2.547	0.965	0.556
	162	270	9.024	1.322	2.547	1.297	0.556
	162	270	8.991	1.428	2.547	1.396	0.556
	162	270	8.920	1.657	2.547	1.604	0.556
	163	271	9.485	1.306	4.004	1.305	0.602
	164	272	9.804*	–0.475	2.867	–0.476	–
	165	273	9.778	0.479	2.770	0.477	–0.619
	166	274	9.596*	0.130	0.695	0.025	–
${}_{109}$Mt	158	267	10.663*	–1.518	–2.729	–2.755	–
	159	268	10.482	–1.086	–1.036	–1.363	–1.677
	160	269	10.761*	–1.756	–0.248	–1.769	–
	161	270	10.227	–0.433	2.078	–0.434	–0.244
	162	271	10.358*	–0.761	2.679	–0.761	–
	163	272	10.189*	–0.334	4.258	–0.334	–
	164	273	10.715*	–1.645	2.950	–1.645	–
	165	274	9.951	0.303	3.003	0.302	–0.346
	166	275	10.528	–1.188	0.896	–1.191	–2.013
${}_{110}$Ds	158	268	11.061*	–3.177	–6.090	–6.091	–
	159	269	11.345	–2.824	–3.663	–3.722	–3.638
	160	270	12.379	–6.102	–2.749	–6.103	–3.795
	161	271	10.947	–1.915	–0.292	–1.926	–0.677
	162	272	10.661*	–2.183	0.320	–2.184	–
	163	273	11.312	–2.751	1.893	–2.751	–3.769
	164	274	10.825*	–2.597	0.695	–2.597	–
	165	275	11.131*	–2.341	0.616	–2.341	–
	166	276	10.606*	–2.042	–1.212	–2.102	–
${}_{111}$Rg	158	269	11.917*	–3.784	–7.235	–7.235	–
	159	270	13.969*	–7.637	–4.541	–7.637	–
	160	271	11.526*	–2.950	–3.789	–3.847	–
	161	272	11.242	–2.341	–1.286	–2.386	–2.698
	162	273	11.897*	–3.743	–0.875	–3.743	–
	163	274	11.413	–2.728	0.809	–2.728	–2.193
	166	277	11.369*	–2.603	–1.706	–2.655	–
${}_{112}$Cn	160	272	11.812*	–4.341	–6.922	–6.924	–
	162	274	11.990*	–4.731	–3.925	–4.794	–
	165	277	11.666	–2.983	–2.866	–3.229	–2.958
	166	278	11.482*	–3.596	–4.544	–4.590	–

* Calculated E_α – values using the method [14, 15].

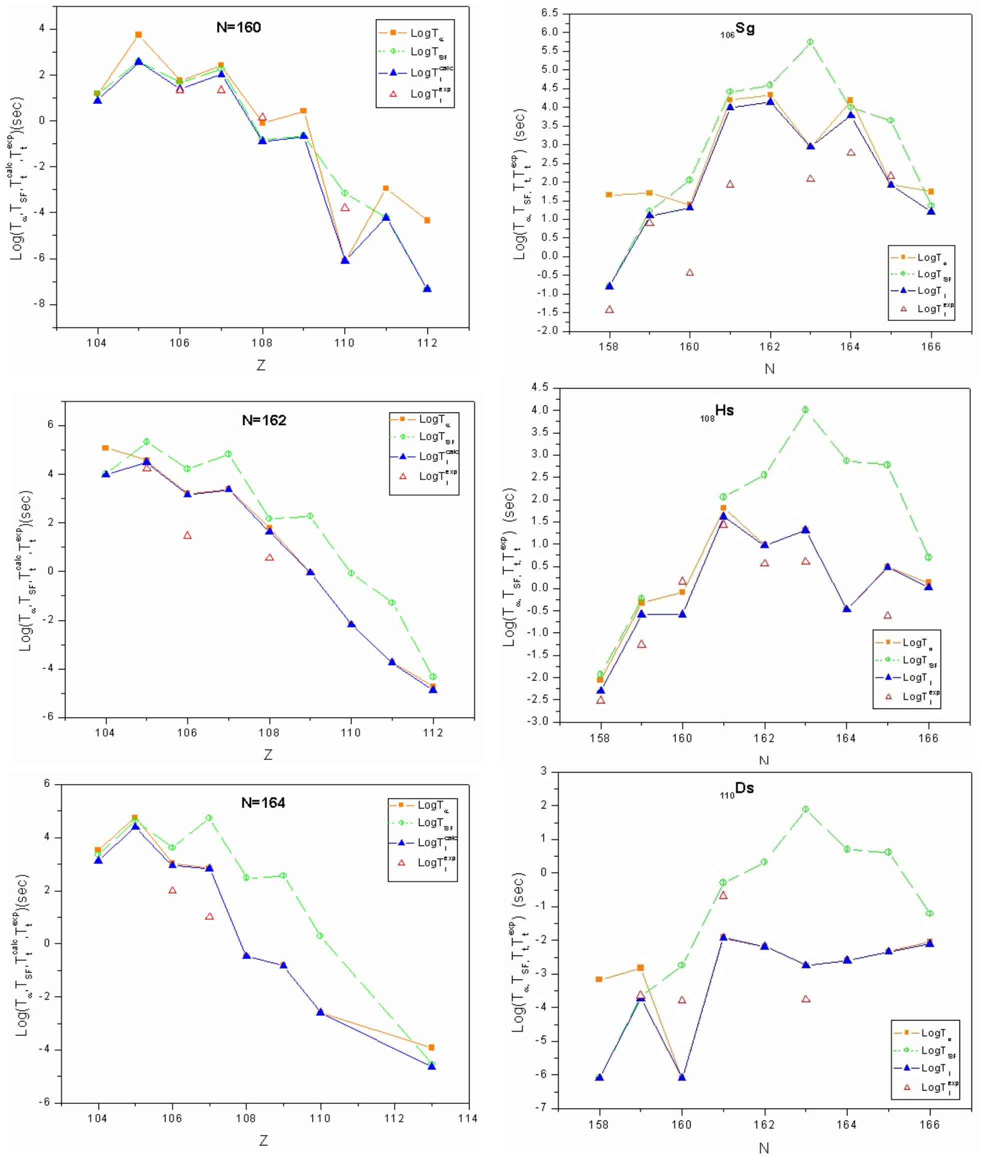

Fig. 1 – Experimental and calculated α decay and spontaneous fission and total half-lives for isotones (left column) and isotopes (right column) of the elements around ^{270}Hs .

4. SUMMARY AND OUTLOOK

We have presented a general framework to calculate the rates for α-decay and SF half-lives using the models for the structure and reaction mechanisms. Our attempts to correlate the decay data with theoretical expectations have been successful in:

i) the deducing formula for rates from the systematics of decay data and theoretical results;
ii) extrapolations of some reaction energies to neighboring nuclides;
iii) new half-life predictions for almost complete series of isotopic and isotonic sequences around the doubly magic closures Z=108, N=162 at ^{270}Hs.

The present systematic study of decay properties in long sequences of nuclides across the major shell closures Z=108 and N=162 provides a new stringent test of our theoretical understanding of the nuclear structure at the limits of stability.

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REFERENCES

1. S. Hofmann and G. Münzenberg, Rev. Mod. Phys. **72**, 733 (2000).
2. K. Morita *et al.*, Jpn. Phys. Soc. J. **73**, 2593 (2004).
3. Yu. Ts. Oganessian, V.K. Utyonkov, Yu. V. Lobanov *et al.*, Phys. Rev. C **74**, 044602 (2006);
   Yu. Ts. Oganessian, F. Sh. Abdullin, C. Alexander *et al.*, Phys. Rev. C **87**, 054621 (2013).
4. S. Hofmann, F.P. Hessberger, D. Ackermann *et al.*, Eur. Phys. Journ. A **10**, 5-10 (2001).
5. I. Muntian, Z. Patyk, A. Sobieczewski, Phys. Lett. B **500**, 241-246 (2001).
6. J. Dvorak, W. Bruechle, M. Chelnokov *et al.*, Phys. Rev. Lett. **97**, 242501 (2006);
J. Dvorak, W. Bruechle, M. Chelnokov *et al.*, Phys. Rev. Lett. **100**, 132503 (2008).
7. P.A. Ellison *et al.*, Phys. Rev. Lett. **105**, 182701 (2010).
8. R. Graeger *et al.*, Phys. Rev. C **81**, 061601(R) (2010).
9. A. Tuerler, Radiochimica Acta **100**, 75-83 (2012).
10. Yu. Ts. Oganessian, V.K. Utynkov, F. Sh. Abdulin, *et al.*, Phys. Rev. C **87**, 034605 (2013).
11. Chart of Nuclides, NNDC Brookhaven National Laboratory, sonzogni@bnl.gov.
12. A.I. Budaca and I. Silisteanu, Phys. Rev. C **88**, 044618 (2013).
13. I. Silisteanu and A. I. Budaca, At. Data Nucl. Data Tables **98**, 1096 (2012).
14. C.I. Anghel, I. Silisteanu, Rom. Journ. Phys. 59, 724–732 (2014).
15. J. Dong, W. Zuo, and W. Scheid, Phys. Rev. Lett. **107**, 012501 (2011).
16. I.V. Karpov *et al.*, Int. J. Mod. Phys. E **21**, 1250013 (2012);
    Y.M. Palenzuela *et al.*, Bull. Russ. Acad. Sci., Physics, **76,** 1165-1171 (2012).
17. P. Möller *et al.*, Phys. Rev. C **79**, 064304 (2009).
18. A. I. Budaca and I. Silisteanu, Rom. Rep. Phys. **63**, 1147 (2011);
    I.Silisteanu *et al.*, Rom.Rep. Phys. **59**, 1173 (2007);
    I.Silisteanu *et al.*, Rom.J. Phys. **53**, 1191 (2008).

19. A. I. Budaca and I. Silisteanu, J. Phys.: Conf. Series **413**, 012027 (2013); **337**, 012022 (2012).
20. Chang Xu, Zhongzhou Ren, and Yanging Go, Phys. Rev. C **78**, 044329 (2008).
21. D. Ni and Z. Ren, Phys. Rev. C **80**, 051303(2009);
    D. Ni and Z. Ren, Nucl. Phys. A **828**, 348 (2009).
22. O.V. Kiren, S.B. Gudennavar, and S.G. Bubbly, Rom. J. Phys. **57,** 1335 (2012).
23. K.P. Santhosh *et al.,* J. Phys. G: Nucl. Part. Phys. **36**, 115101 (2009);
    K.P. Santhosh *et al.*, Phys. Rev. C **85**, 034604 (2012).
24. K.P. Santhosh, B. Priyanka, Phys. Rev. C **89**, 064604 (2014);
    K.P. Santhosh, B. Priyanka, Phys. Rev. C **90**, 054614(2014).
25. Yibin Qian, Zhongzhou Ren, Phys. Rev. C **90**, 064308 (2014).
26. D.S. Delion, A. Dumitrescu, At. Data Nucl. Data Tab., 101, 1-40 (2015).
27. A. Sandulescu, M. Mirea, D. Delion, EPL 101, 62001(2013).
28. A. Sandulescu, M. Mirea, Rom. Rep. Phys. **65**, 688 (2013);
    A. Sandulescu, M. Mirea, Rom. J. Phys. **58**, 1148 (2013).
29. M. Mirea, Rom. J. Phys. **60**, 156 (2015).
30. D. Aranghel, A. Sandulescu, Rom. J. Phys. **60**, 147 (2015).
31. S.P. Maydanyuk, P.-M. Zang, S.V. Belchikov, Nucl. Phys. A **940**, 89–118 (2015).