SCIENTIFIC REPORT

concerning the project implementation during the period January–December 2014

Regions of nuclides in which one of the three decay modes is expected to be the dominant disintegration.

Following our previous works [1, 2] we continue to study the competition of three decay modes of superheavy nuclei: α decay (αD), cluster radioactivity (CR) and spontaneous fission (SF). Previously we have shown [3] that calculated α decay half-lives are in agreement with experimental data within one order of magnitude, while the discrepancy between theory and experiment can be as high as ten orders of magnitude for spontaneous fission [4, 5, 6, 7, 8, 9, 10]. This discrepancy may be seen from the Table 1. For example in case of $^{294}118$, the minimum predicted value is $\log_{10} T_f(s) = -0.66$ [10], and the maximum one is $\log_{10} T_f(s) = 17.87$ [8], i.e. a difference larger than 18 orders of magnitude!! In this table we stress the data for two nuclei, ^{282,284}Cn, we studied last year [3] and this year [11].

Table 1: Comparison of the decimal logarithm of half-lives for spontaneous fission, $\log_{10} T_f(s)$, calculated by different models and the experimental results.

Nuclei	N	exp.	[4]	[5]	[8]	[9]	[10]	[7]	[6]
^{254}Rf	150	-3.30	-4.22		-0.41			-3.11	-3.12
^{256}Rf	152	-2.16	-2.04		1.85		0.60	-1.18	-0.98
^{258}Rf	154	-1.69	-1.56		1.77		0.62	0.09	0.44
^{260}Rf	156	-1.29	-1.27		1.90		0.56	0.72	1.14
^{262}Rf	158	0.32	-0.67		2.03			0.73	1.14
^{258}Sg	152	-2.54	-2.74		-0.11		-1.54	-4.84	-4.84
^{260}Sg	154	-2.14	-1.79		0.70		-2.39	-2.89	-2.67
^{262}Sg	156	-1.82	-1.07		1.20		-4.41	-1.60	-1.22
^{264}Sg	158	-1.43	0.37		2.68			-0.94	-0.49
^{266}Sg	160	-0.44	1.76		5.75			-0.86	-0.46
^{264}Hs	156	-2.70	-1.67		0.35	-3.64	-7.29	-3.83	-3.52
^{270}Ds	160	-1.10	-0.27		3.94	-3.10		-2.69	-1.96
^{282}Cn	170	-3.09	-1.15		-0.27	-8.03		-2.59	-1.89
^{284}Cn	172	-1.01	0.60		2.36	-9.15		-3.98	-3.93
^{286}Fl	172	-0.58	0.17		5.00	-7.53	-1.16	-1.22	0.38
^{290}118	172			-1.32	6.27	-1.20		5.23	10.26
^{292}118	174			1.57	9.44	0.93	-3.85	4.73	9.73
^{294}118	176			3.13	17.87	2.91	-0.66	3.77	8.49

In the above mentioned decay modes, from a parent nucleus ^{A}Z we obtain an emitted particle (or light fragment) $^{A_2}Z_2$ and a daughter (heavy fragment) $^{A_1}Z_1$. The studied decay modes are explained by quantum tunnelling of potential barrier. The decay constant

$$\lambda = \ln 2/T = \nu S P_s \tag{1}$$

is expressed as a product of three model dependent quantities ν, S and P_s, where ν is the frequency of assaults on the barrier per second, S is the preformation probability and P_s is the penetrability of the external barrier (separated fragments). In the above equation $T = T_\alpha$ or $T = T_c$ or $T = T_f$.

Starting from eq. (1) we denote $P = SP_s = \exp(-K)$. The half-life expressed in seconds is calculated with a relationship

$$T = \frac{\ln 2}{\nu P} = \frac{h \ln 2}{2} \frac{1}{E_v P} \quad ; \quad K = \frac{2\sqrt{2m}}{\hbar} \int_{R_a}^{R_b} \{B(R)[E(R) - Q]\}^{1/2} dR \tag{2}$$

where h is the Planck constant, $E_v = h\nu/2$ is the zero-point vibration energy, K is the action integral, R_a and R_b are the turning points $[E(R_a) = E(R_b) = Q]$, B is the nuclear inertia in units of nucleon mass m, Q is the released energy expressed in MeV.

For T_α in αD and for T_c in CR we use our models ASAF (analytical superasymmetric fission) and UNIV (universal curve). For αD we also have semFIS (semiempirical model based on fission theory). We considered competition of SF by making calculations within the Werner-Wheeler approximation of inertia and the two center shell model to obtain the microscopical input for Strutinky's shell and pairing corrections [3]. Werner-Wheeler approximation gives a too low value of the nuclear inertia; we checked few simple laws of variation of B(R) in order to get agreement with experimental result for ^{284}Cn. Recently we tried a better solution based on the microscopic cranking model [11] illustrated for ^{282}Cn. The experimental result from table 1 could be reproduced by using a reasonable zero point vibration energy, $E_v = 0.437$ MeV. For αD we have a comprehensive set of 580 experimental data: 188 even-even, 147 even-odd, 131 odd-even and 114 odd-odd. The standard rms deviations, calculated with

$$\sigma = \left\{ \sum_{i=1}^{n} [\log(T_i/T_{exp})]^2/(n-1) \right\}^{1/2} \tag{3}$$

are given in Table 2. In a similar way we present the 27 data for CR in the Table 3. No odd-odd cluster emitter was detected up to now. For superheavy nuclei with $Z = 118 - 124$, where we

Table 2: The standard rms deviations of calculated half-lives ($\log_{10} T_\alpha$). Calculations with UNIV and semFIS models are included.

Group	n	σ_{ASAF}	σ_{UNIV}	σ_{semFIS}
e-e	188	0.415	0.354	0.221
e-o	147	0.713	0.640	0.527
o-e	131	0.637	0.562	0.441
o-o	114	0.876	0.810	0.605

expect to observe CR as a dominant decay modes, the three decay modes are compared in fig. 1. For fission we used the tables or equations from the references mentioned in Table 1. It is clear that fig. 1 concerns only the neutrondeficient nuclei; there are no calculations for the isotopes with $N > 190$. Among the T_α calculated with different models there are no big differences. CR are calculated only by us. On the other hand there are large differences from model to model for

Table 3: The standard rms deviations of calculated half-lives ($\log_{10} T_c$). Calculations with UNIV model are included.

Group	n	σ_{ASAF}	σ_{UNIV}
e-e	16	0.681	0.565
e-o	6	1.791	0.859
o-e	5	0.391	0.674

SF. half-lives given by Bao et al. [10] for $Z = 118$ are shorter than fis SMO, but for $Z = 120$ these are longer, except for $^{294}120$. Fis Sta are in agreement with fis Smo when $Z = 118$, but for $Z = 120$ fis Sta gives longer half-lives. Even longer are predicted by fis War which are closer to fis Sta for neutron numbers near $N = 190$. In fact some of the calculations in fig. 1 for $N < Np$ (169, 174, 179 and 183, respectively when $Z = 118, 120, 122, 124$) are not realistic because they refer to nuclei beyond the "proton drip line", i.e. instable against emission of one or two protons. We extend these calculations for a larger range of neutron numbers, using semFIS for αD (blue

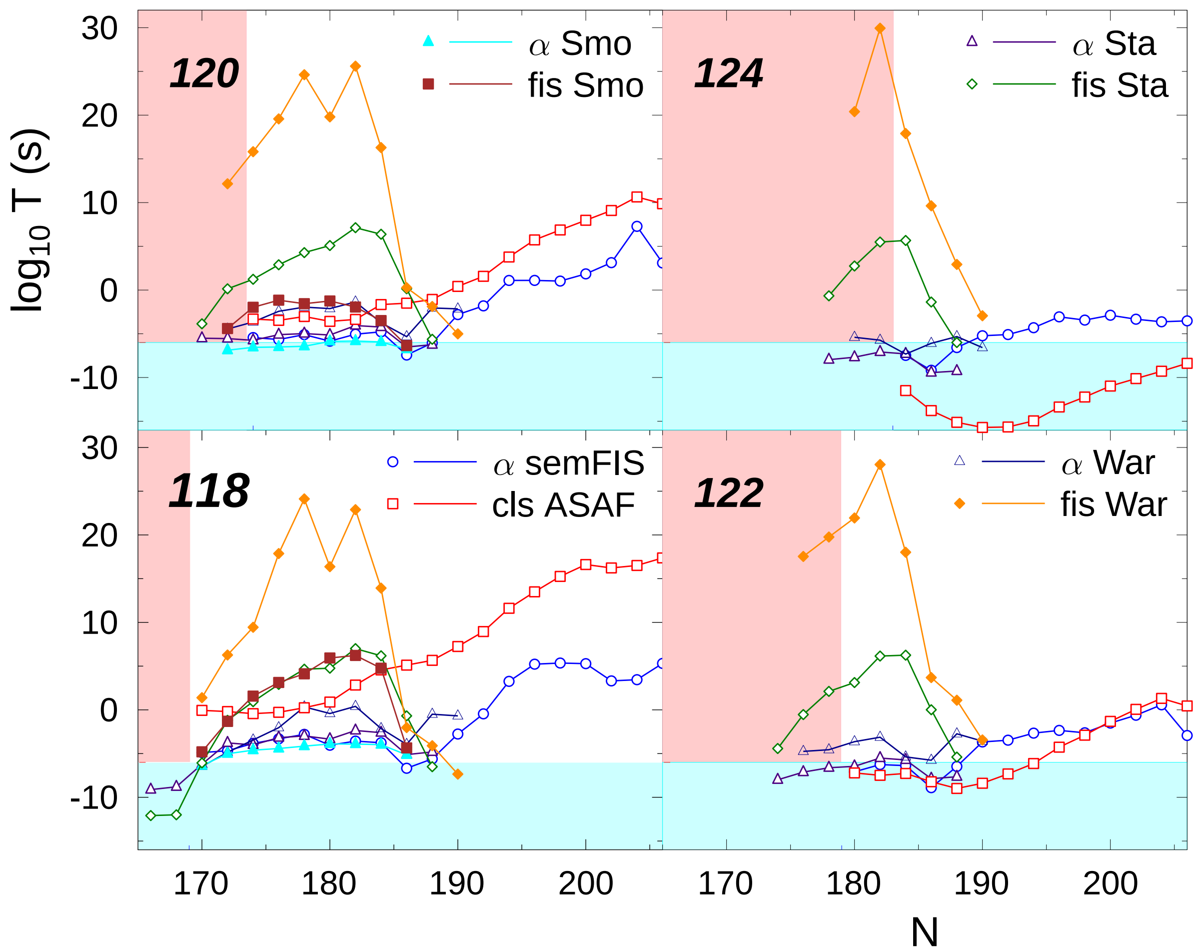

Figure 1: Comparison of half-lives for αD, CR and SF of superheavy nuclei with $Z = 118 - 124$. Proton drip line is limited by $N_p = 169, 174, 179$ and 183, respectively. The pink surface is beyond the drip line and the half-lives in the blue one are not measurable, being shorter than 1 μs.

circles in fig. 1) and ASAF for CR (red squares in fig. 1). Q-values are calculated with theoretical mass table WS3-11 [12]. We may try to establish in details the three different regions of interest keeping in mind that for $T < 1\mu s$ $(\log T(s) < -6)$ the decay mode is not measurable and the nuclides with $N < N_p = 169, 174, 179, 183$ considered by Sta and War are beyond the proton drip line.

αD is the main decay mode for $Z = 118$ with $N = 172 - 186; 192 - 206$ and for $Z = 120$ with $N = 176 - 188; 192 - 206$. Very likely SF are important for $Z = 118$ and $N = 188, 190$ but too short to be measured. When $Z = 120$ and $N = 190$ SF could be detected if War predictions are confirmed.

At $Z = 122$ the CR for $N = 180 - 194$ are too short but for $N = 196, 198$ they could be measured. For $N = 200 - 206$ the αD dominates again.

For $Z = 124$ and $N = 184 - 196$ CR are too short. Despite that αD for $N = 190 - 206$ are measurable, the branching ratio would be too short, hence nothing would be observed.

In fact a more reliable conclusion could be only drawn after the accuracy of SF calculations would be improved and extended for neutron-rich nuclei where the SF is expected to be a major decay mode.

In conclusion we stress the necessity to perform reliable calculations for SF of superheavy nuclei and the necessity to extend them to nuclei closer to the line of β-stability and neutron-rich nuclei. Our models ASAF and UNIV are able to reproduce αD and CR with deviations smaller than two orders of magnitude. Also our SF calculations with cranking inertia for ^{282}Cn, are very promising in what concerns the agreement with experimental results.

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Publications and Presentations at Conferences in 2014

Articles

1. D.N. Poenaru, R.A. Gherghescu, Fission decay of ^{282}Cn studied using cranking inertia, Journal of Physics G: Nuclear and Particle Physics, 41 (2014) 125104 **LabTalk article** http://iopscience.iop.org/0954-3899/labtalk-article/58987 si E-print at Cornell University, arXiv:1409.3155 [nucl-th]. http://arXiv.org/abs/1409.3155.
2. N.S. Shakib, R.A. Gherghescu, D.N. Poenaru, M.M. Firoozabadi, M.F. Rahimi, Fission paths influenced by proton and neutron magicity, Romanian Journal of Physics, 59 (5-6) (2014) 515-528.
3. D.N. Poenaru, R.A. Gherghescu, Fission approach to cluster radioactivity, Pramana Journal of Physics, 82 (2014) to be published.
4. R. A. Gherghescu, D. N. Poenaru, Spontaneous fission of superheavy nuclei, Pramana Journal of Physics, 82 (2014) to be published.
5. D. N. Poenaru, Nobel Prize Winners Born in Romania, Revista de Politica Stiintei si Scientometrie Serie Noua, 3 (4) (2014) to be published.

Invited Presentation published in Proceedings

6. D. N. Poenaru, R. A. Gherghescu, W. Greiner. Cluster decay of the heaviest superheavy nuclei. Invited talk, in Fission and Properties of Neutron-Rich Nuclei (Proc. of the 5th International Conference, Sanibel Island) (World Scientific, Singapore, 2014) Eds. J. H. Hamilton, A. V. Ramaya, pp. 152-159.

Invited Presentations at International Conferences

7. D.N. Poenaru, R.A. Gherghescu, Fission approach to cluster radioactivity, International Conference "75-years of Nuclear Fission: Present status and future perspectives", 8-10 Mai 2014, Mumbai, India.
8. R.A. Gherghescu, D.N. Poenaru, Spontaneous fission of superheavy nuclei, International Conference "75-years of Nuclear Fission: Present status and future perspectives", 8-10 Mai 2014, Mumbai, India.
9. D.N. Poenaru, R.A. Gherghescu, Newest developments in Cluster Radioactivity, International Workshop on "Collectivity in Relativistic Heavy Ion Collisions", 14-20 Sept. 2014, Kolymbari, Conference Center of the Orthodox Academy of Crete, Greece.

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Bharatiar University, Coimbatore - 641046, Tamilandu, India

Referee, 2014

1. Physical Review Letters (SRI=8.688) 2 referee reports
2. Physics Letters B (SRI=3.608) 1 referee report
3. Journal of Physics G: Nucl Part Phys (SRI=1.849) 2 referee reports
4. Physical Review C (SRI=1.308) 4 referee reports
5. European Physical Journal A (SRI=1.130) 1 referee report
6. Nuclear Physics A (SRI=0.880) 3 referee reports
7. Physica Scripta (SRI=0.443) 3 referee reports
8. International J. Mod. Phys. E (SRI=0.301) 2 referee reports

Citations, Hirsch index, i10 index, factor G

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Project Director: Dr. Dorin N. Poenaru