SCIENTIFIC REPORT

concerning the project implementation during the period January–December 2013

Systematic search for alpha decay, cluster decay, and spontaneous fission of superheavy nuclei with $Z = 104 - 124$.

Superheavy nuclei produced until now are decaying by α emission and spontaneous fission (SF). For atomic numbers larger than 121 cluster decay (CD) has a good chance to compete. While majority of calculated α decay (αD) half-lives are in agreement with experimental data within one order of magnitude and CD are also very well accounted for, the discrepancy between theory and experiment can be as high as ten orders of magnitude for SF.

In the region of heavy nuclei with atomic number $Z = 87 - 96$, the measured ^{14}C, ^{20}O, ^{23}F, $^{22,24-26}$Ne, ^{28,30}Mg, and ^{32,34}Si cluster radioactivities (CD) confirmed our predictions of 1980 and shows up as a rare phenomenon in a huge background of α particles. Neutrondeficient superheavy (SH) nuclei with $Z = 104 - 118$ synthesized by fusion reactions are decaying mainly by αD or in a few cases by SF. Our calculations have shown a trend toward a branching ratio $b = T_\alpha/T_c$ relative to αD larger than unity for heavier SHs with $Z > 121$. Despite the good agreement between theory and experiment for αD and CD, in the regions of nuclear chart which are not experimentally reached there is a large uncertainty of the calculated half-lives as a consequence of the differences of calculated atomic masses by different models. We continue our systematic search [1] by using new mass tables: experimental AME12 [2] available for neutrondeficient SHs up to $Z = 118$ and theoretical WS-10 [3] extended up to the neutron drip line.

In the three decay modes mentioned above, from one parent nucleus ^AZ, one obtains an emitted particle (or a light fragment) $^{A_2}Z_2$, and a daughter (heavy fragment) $^{A_1}Z_1$. We consider the competition of SF, by performing calculations using the Werner-Wheeler approximation for the nuclear inertia and the two-center shell model to obtain the input for the Strutinky's shell and pairing corrections to the macroscopic deformation energy. We also try some simple laws of variation of nuclear inertia allowing to obtain an agreement with experiment.

The nuclear decay modes we study are explained by quantum tunneling through the potential barrier. The decay constant

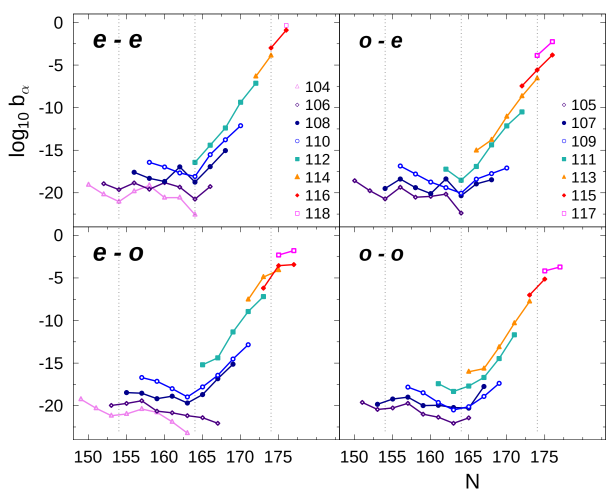

Figure 1: Branching ratio relative to α decay for cluster emission from superheavy nuclei versus the neutron number of the parent nucleus in four groups of nuclides: even-even, even-odd, odd-even, and odd-odd. Vertical dashed lines correspond to $N = 154, 164, 174$. Q values are calculated using the AME12 experimental mass table.

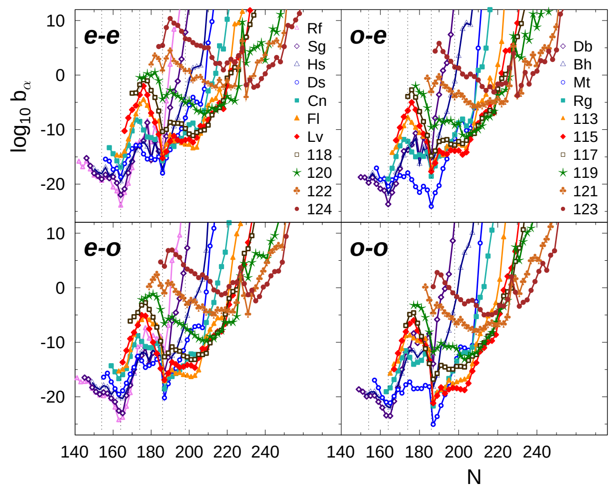

Figure 2: Similar to figure 1. Vertical dashed lines correspond to $N = 154, 164, 174, 186, 198$. Q values are calculated using the WS-10 theoretical mass table.

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

is expressed by a product of three model dependent quantities ν, S and P_s where ν is the

Table 1: The standard rms deviations of calculated half-lives ($\log_{10} T_\alpha$) compared to experiment, before and after optimization of ASAF. UNIV and semFIS model values are included.

Group	n	σ_{ASAF}	σ^{opt}_{ASAF}	σ_{UNIV}	h_{UNIV}	σ_{semFIS}
e-e	188	0.420	0.415	0.354	0.025	0.221
e-o	147	0.720	0.713	0.640	0.574	0.527
o-e	131	0.651	0.637	0.562	0.437	0.441
o-o	114	0.869	0.876	0.810	0.954	0.605

frequency of assaults on the barrier per second, S is the preformation probability and P_s is penetrability of external barrier. In the eq. above $T = T_\alpha$ or $T = T_c$ or $T = T_f$.

For αD and CD we are using our ASAF (analytical superasymmetric fission) model and the UNIV (universal curve). For αD we also have the semFIS (semiempirical model) based on fission theory. Unlike the majority of other models exhibiting large deviations from experimental values in the vicinity of the magic number of neutrons (e.g. $N = 126$) semFIS model behaves well around; this is one reason why for even-even emitters $\sigma_{semFIS} = 0.221$ compared to 0.415 for ASAF. For 147 even-odd, 131 odd-even, and 114 odd-odd α emitters, the standard deviations within semFIS, UNIV and ASAF are given in table 1. The optimization of ASAF model consists in choosing the best values of the parameters. For universal curve (UNIV model) the values given in tables are slightly different from previous publications for αD and for CD because we included *more experimental data for αD (580 compared to 534 α emitters)* and new $Q-$values calculated using AME12 mass table. h_{UNIV} is the hindrance factor fitted to experimental data. For 16 even-even cluster emitters we obtained $\sigma^{opt}_{ASAF} = 0.681$ compared to $\sigma_{ASAF} = 0.975$ before optimization, as shown in table 2.

The general trend of a larger branching ratio when the atomic and mass numbers of the parent nucleus increases may be seen on the Figs. 1 and 2, obtained within the ASAF model by using AME12 and WS-10 mass tables, respectively, to calculate the Q values. While on Fig. 1, refering to neutrondeficient SH nuclei, this is very clear, on Fig. 2 we can also see this behavior for every SH element with increasing number of neutrons, because αD becomes less and less probable;

Table 2: The standard rms deviations of calculated half-lives ($\log_{10} T_c$) compared to experiment for CD, before and after optimization of ASAF. UNIV model values are included.

Group	n	σ_{ASAF}	σ_{ASAF}^{opt}	σ_{UNIV}	h_{UNIV}
e-e	16	0.975	0.681	0.565	-0.388
e-o	6	2.014	1.791	0.859	0.593
o-e	5	0.303	0.391	0.674	0.583

this region is not interesting due to the long T_c. On the other side, for neutrondeficient nuclides there is a practical low limit of a half-life: under 1 μs the decay mode can't be detected due to the flight time through the recoil separator. The minimum at $N = 186$ in Fig. 2 is the result of the strong shell effect of magic number of neutrons of the daughter $N_d = 184$. Predicted CD and αD half-lives for even-even SH nuclei with $Z = 118 - 124$ are compared in fig. 4. These nuclides are chosen as we expect to observe in this region in the future the competition of CD.

From eq. (1) by denoting $P = SP_s = \exp(-K)$ the half-life, T, expressed in seconds, is calculated as

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

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 dimensionless inertia in units of the nucleon mass m, Q is the released energy expressed in MeV.

Nuclear inertia may be calculated classically within Werner-Wheeler approximation or with cranking formula. By choosing the distance between fragments, R, as deformation coordinate, the inertia at the touching point of the two fragments is equal to the reduced mass $\mu = (A_1 A_2/A)m$ in a binary system. When we only consider one deformation coordinate, R, the inertia tensor becomes a scalar, B. An example of the nuclear inertia for the decay of ^{284}Cn into ^{138}Ba and ^{146}Ba is given by blak full line (W-W) in fig. 3.

We are not able to reproduce the experimental half-life if we use a Werner-Wheeler nuclear inertia, known to be too small. To increase the half-life we need a smaller penetrability, hence a larger action integral, or for a given potential barrier, a larger nuclear inertia. By simply taking $B = B_t = const$ we can come closer to experiment by few orders of magnitude.

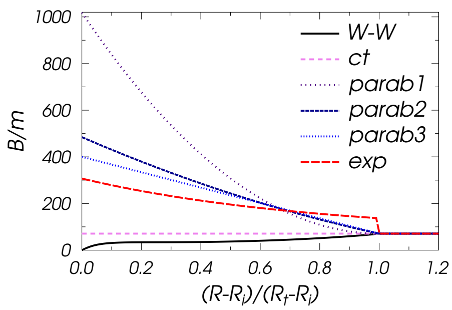

Figure 3: Nuclear inertia variations for the SF of ^{284}Cn with light fragment ^{138}Ba. Besides W-W (Werner-Wheeler) and ct ($B/m = A_\mu$), which are not large enough to fit the data, the three parabolic approximations and the exponential one have optimized parameters fitted to reproduce the experimental half-life.

We can reproduce the experiment by increasing the inertia; we take 4 different laws of variation for B: 3 decreasing parabolic functions and an exponential variation. Since our deformation parameter is the separation between fragments, R, or $\xi = (R - R_i)/(R_t - R_i)$ we should have always at the touching point $R = R_t = R_1 + R_2$ and beyond $B_t = A_\mu = A_1 \cdot A_2/A$.

Few fission channels could be efficiently used to test different methods of calculating SF half-lives of ^{284}Cn who's experimental value is known, e.g. $^{284}Cn \to ^{138} Ba + ^{146} Ba$. Potential barriers are calculated within macroscopic-microscopic method. The macroscopic deformation energy is of Yukawa-plus-exponential type. The microscopic two center shell model was used to obtain the nuclear level schemes — the input data for shell and BCS pairing corrections. In our calculation using Werner-Wheeler inertia for a given mass asymmetry $\eta = (A_1 - A_2)/A = 0.0282$ (light fragment ^{138}Ba) we obtained $\log_{10} T_f(s) = -4.12$ when the tunneling was taken from the 2nd (lowest in energy and well deformed) minimum with no pairing and -10.44 with pairing. For the SH nucleus ^{284}Cn the SF half-life was measured, $T_f^{exp} = 104$ ms, i.e. $\log_{10} T_f(s) = -0.98$. Theoretical values already published are the following: $\log_{10} T_f(s) = 0.60$ (Smolanczuk 1995); 2.36 [4]; -9.15 [5]. Simple relationships give -3.93 and -4.43. The closest value to the experiment was obtained by Smolanczuk. Predictions for the heavier even-even SHs with $Z = 118 - 124$ are given in fig. 4. On the line of β-stability $N_\beta = 194, 198, 202, 206$ for $Z = 118, 120, 122, 124$. It is clear that SF half-lives in fig. 4 refer to neutrondeficient nuclei; there are no numbers for nuclides with $N > 190$. In fig. 4 we can see how behave the various

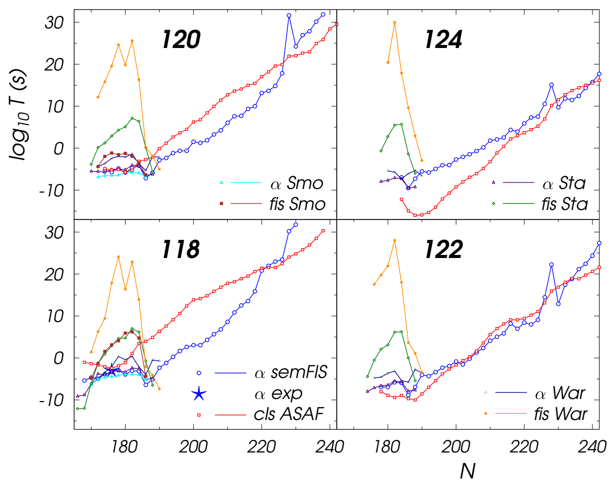

Figure 4: Comparison of theoretical half-lives for αD, CD and SF for neutron numbers $N \leq 206$. On the line of β-stability $N_\beta = 194, 198, 202, 206$ for $Z = 118, 120, 122, 124$, respectively. The proton drip-line goes through $N_p = 169, 174, 179, 183$.

decay modes (αD, CD, SF) of even-even nuclei in the region of the heaviest SHs with atomic numbers $Z = 118 - 124$. αD half-lives predicted by all models we considered are not very far from each-other and they are close to the experimental point for ^{294}118. CDs are calculated only by us.

For SF there are very large differences from model to model. The Bao half-lives [6] of $Z = 118$ isotopes are shorter than that given by fis Smo, but for $Z = 120$ they are longer, except for ^{294}120. The fis Sta are in good agreement with fis Smo when $Z = 118$, but for $Z = 120$ the fis Sta half-lives are longer. Much longer SF half-lives are predicted by fis War which nevertheless are closer to fis Sta for heavier neutron numbers approaching $N = 190$. There are no predictions for $N > 190$.

We extend these calculations, using semFIS for αD and ASAF for CD, for a broader range of neutron numbers using the theoretical mass table [3]. For even-even neutrondeficient isotopes of the elements 118 and 120 αD is the dominant decay mode (shortest half-life). For few isotopes of the elements 118, 120, and 122 SF may compete with αD. CD is the most important decay mode (gives the shortest half-life) of the element 124. It could also be important for several neutron-rich isotopes of 118, 120, and 122. From this point of view the element 122 is a transitional one because the dominance of CD may alternate with that of αD when the neutron number is increased.

In conclusion we should stress the need to make reliable calculations for spontaneous fission half-lives of heavy and SH nuclei and the need to extend these calculations for superheavy nuclei closer to the line of β-stability and for neutron-rich nuclei. Our ASAF and UNIV models may reproduce both α and cluster decays with deviations not larger than two orders of magnitude, except for αD of ^{228}Ac and ^{24,25}Ne radioactivities of ^{235}U. Within ASAF, UNIV, and semFIS models the deviations for 512 (88%), 527 (91%), and 555 (96%) α emitters out of the total of 580, are under one order of magnitude. Similarly, ASAF and UNIV may reproduce 23 (85%), and 24 (89%) experimental data from the total of 27 cluster emissions with deviations under one order of magnitude.

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