Dedicated to Academician Aureliu Sandulescu's 80th Anniversary

DESCRIPTION AND PREDICTIONS OF THE PROPERTIES OF SUPERHEAVY NUCLEI

A. SOBICZEWSKI

National Centre for Nuclear Research, Hoża 69, 00-681 Warsaw, Poland
Email: adam.sobiczewski@fuw.edu.pl

Received August 4, 2011

A short review of the studies of superheavy nuclei (SHN), done recently in our theoretical group of Warsaw, is presented. Main attention is given to description of the decay properties of SHN. The description is performed with the use of our macroscopic-microscopic model. Such properties as mass, α-decay energy and α-decay half-life are considered. Tests of the model done by a comparison of its results with the experimental ones and with results of other (semi-empirical) model are illustrated. After also testing the predictive power of the model, it is used to predict properties of not-yet-observed isotopes of the element 120 and their decay products.

Key words: Superheavy nuclei and elements, nuclear mass, α-decay energy, α-decay half-life, α-decay chains.

PACS: 23.60.+e, 25.85.Ca, 27.90.+b.

1. INTRODUCTION

There is a big activity in experimental studies of heaviest nuclei. These are the studies of their physical (*e.g.* [1–5]) as well as of physical and chemical (*e.g.* [6–12]) properties. In particular, 106 isotopes of 15 superheavy elements (SHE), *i.e.* transactinide elements with the atomic number $Z \geq 104$, have been already observed.

In the physical research, the decay modes (mainly α decay and spontaneous fission) are studied. In the α decay, the transition energy Q_α^{t} and the half-life T_α are measured. In spontaneous fission, the half-life T_{sf} and the kinetic energy of the fission fragments are determined.

The objective of this paper is to give a short review of recent theoretical studies of superheavy nuclei performed in our Warsaw group. Description of already existing experimental results by our theoretical model is illustrated, being a test of the model. Predictions of the properties of not-yet-observed nuclei are also presented.

The model used by us is of a macroscopic-microscopic type (see *e.g.* [13]). One should mention, however, that studies of superheavy nuclei using more recent purely microscopic approaches (*e.g.* [13–16]) are also being performed.

Rom. Journ. Phys., Vol. 57, Nos. 1-2, P. 506–512, Bucharest, 2012

2. ALPHA DECAY

Emission of α particle is the main decay mode of superheavy nuclei. Of 106 of them observed up to present, 86 nuclei decay by α emission and 36 by spontaneous fission. For 16 of the nuclei, both these modes have been observed. This is illustrated in Fig. 1. Alpha decay is denoted by the yellow color and spontaneous fission by the green one.

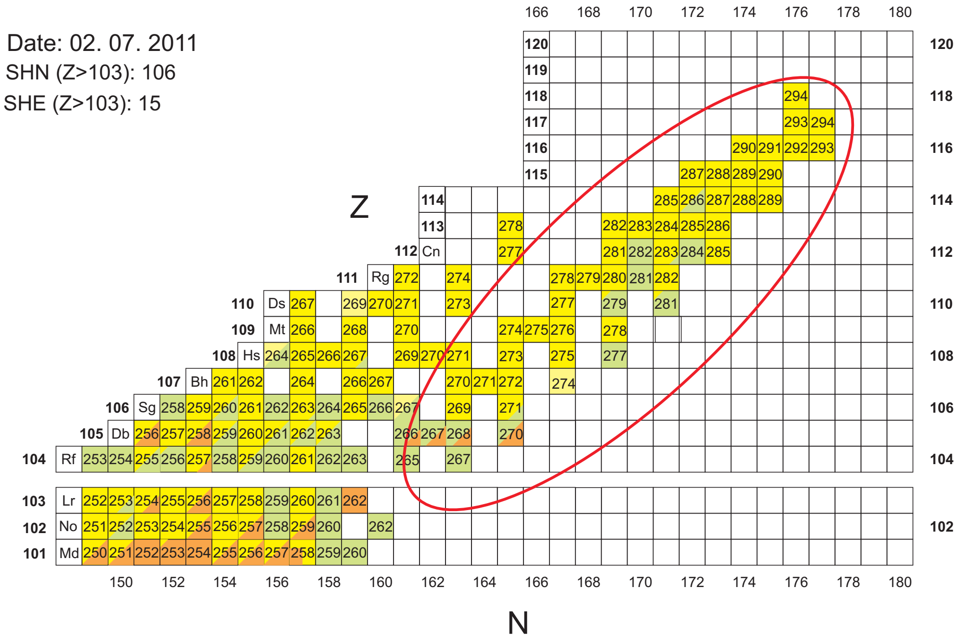

Fig. 1 – Present-day chart of superheavy nuclei (SHN). Superheavy nuclides obtained in the hot-fusion reactions (*i.e.* the reactions in which the actinide targets are used) are shown inside the contour line.

Due to this, we mainly concentrate here on the description of α decay. The basic quantity is the α-decay energy Q_α. It is obtained from the ground-state masses of the parent and daughter nuclei. The masses are calculated within a macroscopic-microscopic approach. The Yukawa-plus-exponential model [17] (which is an improvement of the liquid-drop model used in earlier work) is taken for the macroscopic part of the mass and the Strutinski shell correction based on the Woods-Saxon single-particle potential [18], is used for its microscopic part. The short-range pairing interaction between nucleons is treated within the Bardeen-Cooper-Schrieffer approximation. The model is specially adapted to the description of heavy nuclei and is denoted by HN (Heavy Nuclei). Details of the approach may be found in [19].

The α-decay half-lives are calculated with the use of a recently proposed [20] simple phenomenological formula:

$$\log_{10} T_\alpha^{\rm ph}(Z,N) = aZ[Q_\alpha(Z,N) - \bar{E}_i]^{-1/2} + bZ + c, \tag{1}$$

where the parameters a,b,c are

$$a = 1.5372, \ \ b = -0.1607, \ \ c = -36.573 \tag{2}$$

and the parameter $\bar{E}_i$ (average excitation energy of the daughter nucleus) is

$$\begin{array}{l} \bar{E}_i = 0 \text{ for e-e}, \ \ \bar{E}_i = \bar{E}_{\rm p} = 0.113 \text{ MeV for o-e}, \\ \bar{E}_i = \bar{E}_{\rm n} = 0.171 \text{ MeV for e-o}, \ \text{ and } \bar{E}_i = \bar{E}_{\rm p} + \bar{E}_{\rm n} \text{ for o-o nuclei}. \end{array} \tag{3}$$

Here, *e.g.* o-e, means (odd-Z, even-N) nuclei, where Z is the proton and N is the neutron number.

The above values of the 5 parameters $a, b, c, \bar{E}_{\rm p}$ and $\bar{E}_n$ have been obtained by fitting the calculated half-lives $T_\alpha^{\rm ph}$ of Eq. (1), with the use of experimental decay energies Q_α [21], to experimental T_α [22]. Details of the fit are described in [20].

The formula (1) is of the Viola-Seaborg type [23]. The main difference between the original formula of Ref. [23] and the new one is that the latter gives a specific interpretation of the hindrance of the α-transition in the presence of odd nucleons, namely it is assumed that the whole effect of these nucleons is to reduce the transition energy,

$$Q_\alpha^{\rm t} = Q_\alpha - \bar{E}_i, \tag{4}$$

with respect to the α-decay energy Q_α (the ground-state (g.s.) to the ground-state transition) by the average excitation energy $\bar{E}_i$ of the daughter nucleus. Such an assumption is rather natural as the half-life is determined by the most probable transition and this is assumed to occur between states with the same structure (the same quantum numbers). As, in general, the structure of the ground states of parent and daughter nuclei is different, transition to an excited state occurs, reducing the transition energy. With such a reduction, there is no other hindrance, and the transition occurs with the same probability as in an even-even nucleus, described by the three parameters: a, b, c. One should remember, however, that in specific cases (existence of isomeric states in the parent nucleus), the excitation of the parent nucleus may also contribute to the transition energy $Q_\alpha^{\rm t}$. An additional difference between the two formulae is that the new one has one adjustable parameter less.

3. TEST OF THE MODEL

A good test of the ability of a model to describe heaviest nuclei is the analysis, with the use of it, of the decay chain of the heaviest nucleus observed up to now. This is the even-even nucleus ^{294}118 produced in Dubna in the reaction ^{249}Cf (^{48}Ca, 3n) ^{294}118 [5]. The observed chain of this nucleus is composed of three α decays and one spontaneous fission. Measured Q_α and T_α are given in Table 1. The spontaneous fission half-life of the last nucleus in the chain, $^{282}112$, is 0.23 s.

Table 1.

Experimental data for Q_α^{t} (in MeV) and T_α for the indicated three nuclei.

Nucleus	$^{294}118$	$^{290}116$	$^{286}114$
Q_α^{t}	11.81	11.00	10.33
T_α	0.89 ms	7.1 ms	0.26 s

The calculated values, obtained with the use of our model, are given in Table 2. These are the α-decay energy Q_α and the α-decay half-life T_α. The spontaneous-fission half-life T_{sf} is taken from Refs. [24, 25]. One can see that, according to the calculations, at least three α decays should be observed (as T_{sf} are much larger than T_α for the respective nuclei). This agrees with experiment. According to the theory, a longer chain could also appear, but its observation would require a larger statistics, while only one chain has been observed in experiment.

Table 2.

Values of the characteristic quantities for the decay chain of $^{294}118$ (HN).

Nucleus	$^{294}118$	$^{290}116$	$^{286}114$	^{282}Cn	^{278}Ds	^{274}Hs	^{270}Sg	^{266}Rf
Q_α^{t}	12.09	11.08	10.86	10.46	10.76	9.55	8.74	7.05
T_α	0.43 ms	23 ms	19 ms	46 ms	2.0 ms	0.62 s	32 s	0.27 y
T_{sf}	22 m	12 m	1.5 s	71 ms	56 ms	5.8 s	55 s	23 s
T_{sf}/T_α	$3.2 \cdot 10^6$	$3.3 \cdot 10^4$	78	1.6	28	9.3	1.7	$2.7 \cdot 10^{-6}$

It is also seen in the table that the calculated Q_α and T_α are quite close to the experimental ones. Also the theoretical spontaneous-fission half-life of the nucleus $^{282}112$, 71 ms, reproduces the measured value, 230 ms, with a good accuracy (within a factor of about 3).

Figures 2 and 3 show the comparison in a graphical form. To have an idea of the sensitivity of the description to changes of a model, theoretical values of Q_α and T_α obtained with the use of a semi-empirical (SE) model of Ref. [26] are also shown. The semi-empirical model of Ref. [26] is known for a very good description of masses of heaviest nuclei (see Ref. [13]). It is seen that the results of the SE and HN models are quite close. Still, the HN results are closer to experimental values.

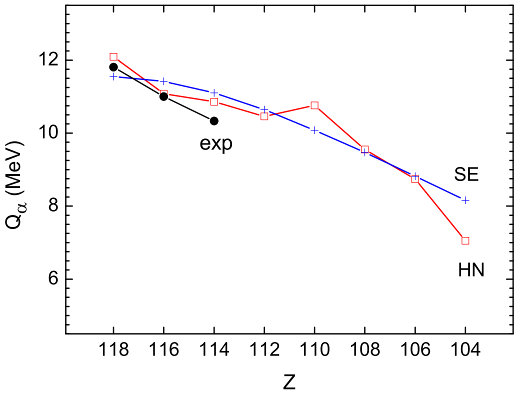

Fig. 2 – α-decay energies Q_α calculated within HN and SE models for the decay chain of the nucleus $^{294}118$, compared with the experimental values.

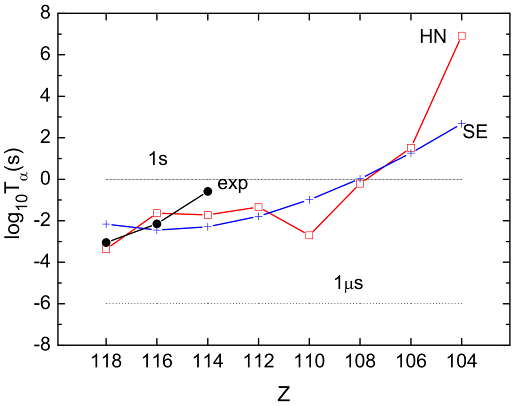

Fig. 3 – Same as in Fig. 2, but for the logarithm of the α-decay half-lives T_α (given in seconds). Two lines indicating approximate lower limits of the half-life of a nucleus which could be observed (1 μs) and of an atom which could be studied chemically (1 s), are shown.

4. PREDICTIVE POWER OF THE MODEL

The predictive power of the HN model has been tested in the cases of isotopes of the element 117. On the suggestion of our experimental colleagues, calculations have been performed [27] for two isotopes: $^{293}117$ and $^{294}117$ before the synthesis of them. The α-transition energies Q_α^{t} and respective half-lives T_α were calculated for the decay chains of both isotopes. The results have been presented together with experimental ones, for a comparison, in the original paper announcing the discovery of the element 117 [28]. This is shown in Fig. 4 taken from that paper. The lifetimes are given on the left side of the box representing a nucleus and the α-particle energies are shown under the box. The predicted values (color blue) are shown below the measured ones (color black). One can see a good agreement between the two results. All eleven nuclei appearing in the two decay chains of Fig. 4 were obtained for the first time.

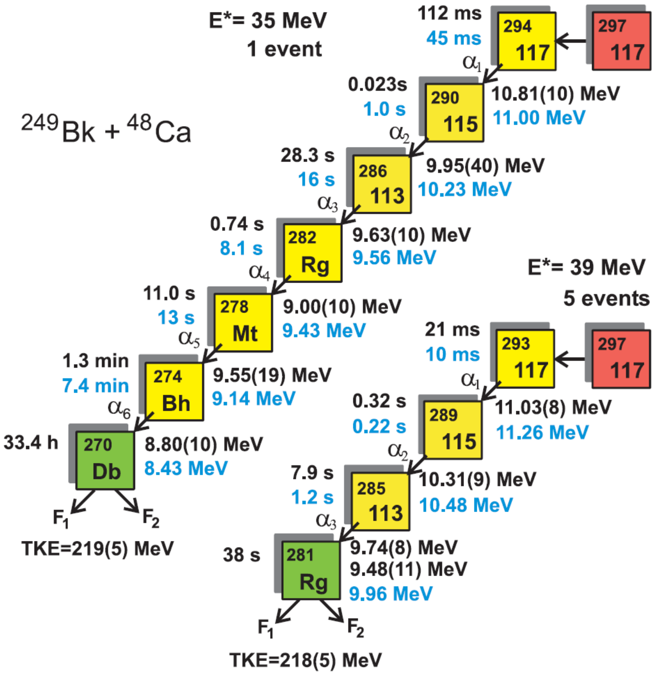

Fig. 4 – The α-decay chains of two isotopes of the new element 117 [28].

5. PREDICTIONS FOR THE ELEMENT 120

Encouraged by the realistic predictions for the element 117, calculations of the properties of isotopes of not-yet-observed element 120 have been done [29]. The α-transition energies Q_α^{t} and half-lives T_α of nuclei in the decay chains of the isotopes: ^{298}120 and ^{299}120 have been calculated. It was found that T_α of the initial nuclei of the chains, ^{298}120 and ^{299}120, were already quite small, 11 μs and 15 μs, respectively. They are not far from the lowest value (about 1 μs) needed for a nucleus to be detected.

In the trials done up to now, the synthesis of these isotopes was not succeeded. The most probable reason for that is a too small cross section.

Acknowledgments. At the end of this article honoring Professor Aureliu Sandulescu's 80th birthday, I would like to say that I was always admiring his intuition in physics. In all considerations, physics and not (even of a high level) formalism was most important. And between various possible solutions of a problem, he was able, as a rule, to choose the right one.

The author would like to thank Sigurd Hofmann and Yuri Oganessian for helpful discussions. Support by the Polish Ministry of Science and Higher Education, within the research project No. N N 202 204938 carried out in the years 2010-2013, and by the Polish-JINR (Dubna) Cooperation Programme is gratefully acknowledged.

REFERENCES

1. S. Hofmann, G. Münzenberg, Rev. Mod. Phys. **72**, 733 (2000).
2. K.E. Gregorich *et al.*, Phys. Rev. C **72**, 014605 (2005).
3. Yu.Ts. Oganessian, J. Phys. G **34**, R165 (2007).
4. K. Morita *et al.*, J. Phys. Soc. Jpn **76**, 045001 (2007).
5. Yu.Ts. Oganessian *et al.*, Phys. Rev. C **74**, 044602 (2006).
6. A. Türler *et al.*, Eur. Phys. J. A **17**, 505 (2003).
7. M. Schädel (ed.), *The Chemistry of Superheavy Elements* (Kluwer Acad. Publ., Dordrecht 2003).
8. R. Eichler *et al.*, Nature (London) **447**, 72 (2007).
9. J. Dvorak *et al.*, Phys. Rev. Lett. **100**, 132503 (2008).
10. Yu.Ts. Oganessian, S.N. Dmitriev, Russian Chem. Rev. **78**, 1077 (2009).
11. H.W. Gäggeler, Russian Chem. Rev. **78**, 1139 (2009).
12. H.W. Gäggeler, Radiochim. Acta **99**, 503 (2011).
13. A. Sobiczewski, K. Pomorski, Prog. Part. Nucl. Phys. **58**, 292 (2007).
14. P. Ring, Prog. Part. Nucl. Phys. **37**, 193 (1996).
15. M. Bender, P.-H. Heenen, P.-G. Reihard, Rev. Mod. Phys. **75**, 121 (2003).
16. J.P. Delaroche, M. Girod, H. Goutte, J. Libert, Nucl. Phys. A **771**, 103 (2006).
17. H.J. Krappe, J.R. Nix, A.J. Sierk, Phys. Rev. C **20**, 992 (1979).
18. S. Ćwiok, J. Dudek, W. Nazarewicz, J. Skalski, T. Werner, Comput. Phys. Commun. **46**, 379 (1987).
19. I. Muntian, Z. Patyk, A. Sobiczewski, Acta Phys. Pol. B **32**, 691 (2001).
20. A. Parkhomenko, A. Sobiczewski, Acta Phys. Pol. B **36**, 3095 (2005).
21. A.H. Wapstra, G. Audi, C. Thibault, Nucl. Phys. A **729**, 129 (2003).
22. G. Audi, O. Bersillon, J. Blachot, A.H. Wapstra, Nucl. Phys. A **729**, 3 (2003).
23. V.E. Viola, Jr., G.T. Seaborg, J. Inorg. Nucl. Chem. **28**, 741 (1966).
24. R. Smolańczuk, J. Skalski, A. Sobiczewski, Phys. Rev. C **52**, 1871 (1995).
25. R. Smolańczuk, Phys. Rev. C **56**, 812 (1997).
26. S. Liran, A. Marinov, N. Zeldes, Phys. Rev. C **62**, 047301 (2000).
27. A. Sobiczewski, Acta Phys. Pol. B **41**, 157 (2010).
28. Yu.Ts. Oganessian *et al.*, Phys. Rev. Lett. **104**, 142502 (2010).
29. A. Sobiczewski, Acta Phys. Pol. B **42**, 1871 (2011).