Vol. 28 (1997) *ACTA PHYSICA POLONICA B* No 1–2

PROPERTIES AND SYNTHESIS OF HEAVIEST NUCLEI * **

A. Sobiczewski

Soltan Institute for Nuclear Studies
Hoża 69, PL–00–681 Warsaw, Poland
and
GSI, D-64220 Darmstadt, Germany

(Received December 10, 1996)

Theoretical studies on the properties of heavy and superheavy nuclei, performed in recent years, are shortly reviewed. Such properties as mass and half-lives are discussed. Even-even nuclei with proton number $Z =$ 82–120 and neutron number $N =$ 126–190 are considered. Prospects for synthesis of still heavier nuclei, than obtained up to now, are outlined.

PACS numbers: 25.85. Ca, 21.10. Tg, 24.75. +i, 27.90. +b

1. Introduction

The objective of the present paper is to give a short review of recent theoretical studies on the properties of heaviest nuclei. Such properties like mass, modes of decay and respective half-lives are discussed. Even-even nuclei with proton number $Z =$ 82–120 and neutron number $N =$ 126–190 are considered.

We concentrate on the studies performed in a macroscopic-microscopic approach [1–8]. Reviews of somewhat earlier studies done in this approach have been given in [9, 10].

Properties of heaviest nuclei are also studied by fully microscopic methods, like Hartree–Fock–Bogolubov [11, 12], Relativistic Mean Field [13, 14] or Skyrme–Hartree–Fock [14] approaches.

The theoretical studies are closely connected with, and motivated by, an intensive experimental activity in this field [15–27]. The three new elements: 110,111,112 and new (heavy) isotopes of the elements 106 (Sg), 107 (Ns), 108 (Hs) and 109 (Mt) have been obtained in these experiments.

---

[*] Presented at the XXXI Zakopane School of Physics, Zakopane, Poland, September 3–11, 1996.

[**] Work supported by the Polish Committee for Scientific Research (KBN), grant no. 2 P03B 156 08.

2. Specific features of heaviest nuclei

2.1. Instability

All nuclei of the considered region are unstable, *i.e.* radioactive. As we are interested in the nuclei which are not too far from the β-stability line, their main decay modes are α-decay and spontaneous fission. Both modes are discussed in the present review. Half-lives of the heaviest nuclei already observed, those with the atomic number $Z = 110, 111, 112$, are short. They are in the milli- or even microseconds region.

2.2. Deformation

Most nuclei of the considered region are, or are expected to be, deformed. This is because their outer nucleons fill up large nuclear shells. For protons, this is the shell between the last experimentally known magic number $Z = 82$ and the theoretically predicted [28, 29] number $Z = 114$. Thus, the shell is as large (32 protons) as the largest experimentally observed proton shell between $Z = 50$ and 82. For neutrons, this is the shell between the last experimentally known magic number $N = 126$ and the theoretically predicted [28, 29] number $N = 184$. If the predictions are correct, this shell would be the largest neutron shell (58 neutrons) of all those considered up to now. The largest experimentally observed shell is between the magic numbers: $N = 82$ and $N = 126$ (*i.e.* 44 neutrons).

A specific feature of the deformation of considered nuclei is that high-multipolarity components of it are important for these nuclei. For example, the deformation of the multipolarity $\lambda = 8$, β_8, may increase the shell correction to energy of the nuclei by up to about 0.5 MeV [4]. Such an increase in the shell correction to energy of a nucleus may lead to the increase of the spontaneous-fission half-life $T_{\rm sf}$ of it by about two orders of magnitude [3].

2.3. Essential role of shell effects

Shell effects are important for all nuclei. Their role for the heaviest nuclei is, however, essential, as many of them would simply not exist without these effects [30].

The analysis of shell effects, performed in [30], has shown that these effects elongate the α-decay half-lives T_α by up to about 5 orders of magnitude, and the spontaneous-fission half-lives $T_{\rm sf}$ by up to about 15 orders of magnitude.

A particular feature of the considered region of nuclei is that some deformed nuclei show shell effects which are similarly strong as the effects observed in spherical magic nuclei, *i.e.* that we observe deformed shells in these nuclei. Specifically, effects of the deformed neutron shell at the neutron number $N = 152$ are experimentally observed for a long time. There is also an increasing experimental evidence for the existence of the deformed shells at $N = 162$ and $Z = 108$, predicted theoretically. The nucleus $^{270}108$ (^{270}Hs) is expected theoretically [31, 1] to be a doubly magic deformed nucleus.

3. Theoretical description

As already mentioned in the Introduction, properties of heaviest nuclei are usually described in a macroscopic-microscopic approach, although a purely microscopic Hartree–Fock–Bogolubov formalism is also used.

In the macroscopic-microscopic calculations, the results of which are reviewed in this paper, the macroscopic part of the energy of a nucleus is described by the Yukawa-plus-exponential model [32]. The microscopic part is the Strutinski shell correction, based on the Woods–Saxon single-particle potential [33].

The $\alpha-$decay half-lives are described by the phenomenological formula of Viola and Seaborg, but with its free parameters readjusted to account for recent data. Details of the calculations are given in [1, 4].

The spontaneous-fission half-lives are analyzed in a dynamical way, with the mass tensor (describing the inertia of a nucleus with respect to its deformation) taken into account. Details of the calculations are given in [3].

The 4-dimensional deformation space $\{\beta_\lambda\}$, $\lambda = 2, 4, 6, 8$, is used where β_λ are the usual deformation parameters, appearing in the expression for nuclear radius (in the intrinsic frame of reference) in terms of spherical harmonics.

4. Main theoretical results

4.1. Shell correction

Shell correction to the ground-state mass of a heavy nucleus gives us a first orientation in the stability of this nucleus. Figure 1, taken from [4], shows the shell correction, $E_{\rm sh}$, calculated for the large region of nuclei under consideration. One can see that $E_{\rm sh}$ has three minima in this region. The first one, which is the deepest ($E_{\rm sh}$=−14.3 MeV), is obtained for the doubly magic spherical nucleus ^{208}Pb. The second one ($E_{\rm sh}$=−7.2 MeV) appears at the nucleus $^{270}108_{162}$, which is predicted [1, 31] to be a doubly magic deformed nucleus. The third minimum, with the same depth ($E_{\rm sh}$=−7.2 MeV) as that of the second minimum, is obtained for the nucleus $^{296}114_{182}$, which is close to the nucleus $^{298}114_{184}$ predicted [28, 29] to be a doubly magic spherical nucleus, the next one to the last experimentally known ^{208}Pb. The problem of existence of spherical superheavy nuclei is being considered for already about 30 years [34]. Besides these three minima, there appears a rather wide plateau around the nucleus ^{252}Fm, which, although having a smaller (in absolute value) shell correction ($E_{\rm sh}$=–5.2 MeV) than the nucleus ^{270}108, may also be considered as a doubly magic deformed nucleus [1, 31].

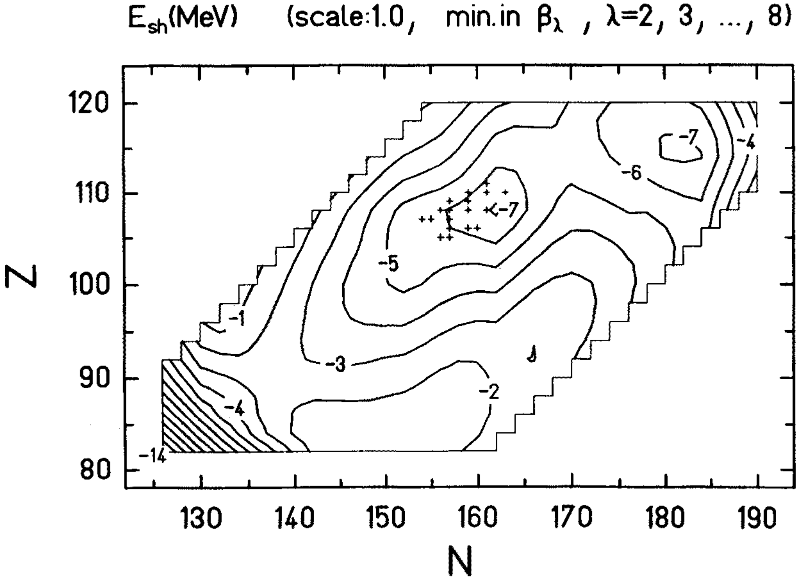

Fig. 1. Contour map of the shell correction to energy, $E_{\rm sh}$. Crosses denote the heaviest nuclides synthesized up to now [4].

One can see in Fig. 1 that some of the already synthesized nuclei profit by 6–7 MeV in their binding energy from the shell correction. Without this profit they could not exist, as discussed in Sect. 2.

The appearance of the region of nuclei around the second minimum (deformed superheavy nuclei) constitutes the main change in our view of stability of heaviest nuclei in recent years. Before, it was believed for a long time that spherical superheavy nuclei, predicted to be situated around the third minimum, would constitute an island, separated from the usual peninsula of relatively long-lived nuclei by an "ocean" of full instability. After the appearance of the deformed superheavy nuclei, however, the peninsula is expected to be extended, to include also the spherical superheavy nuclei.

4.2. Mass

It is interesting to see how well are the experimental masses reproduced by the theoretical ones, calculated with the shell correction given in Fig. 1. This is illustrated in Fig. 2, taken from [5], which shows the discrepancy between the calculated and experimental masses. One can see that for most of the considered nuclei this discrepancy is within the limits ±0.25 MeV, *i.e.* it is not large. The largest discrepancy is obtained for the doubly magic nucleus ^{208}Pb. The theoretical binding energy is too small for this nucleus by about 1 MeV. One can also see that the isotopic dependence of the theoretical mass is not correct, except only the isotopes of uranium, and it varies from one element to another.

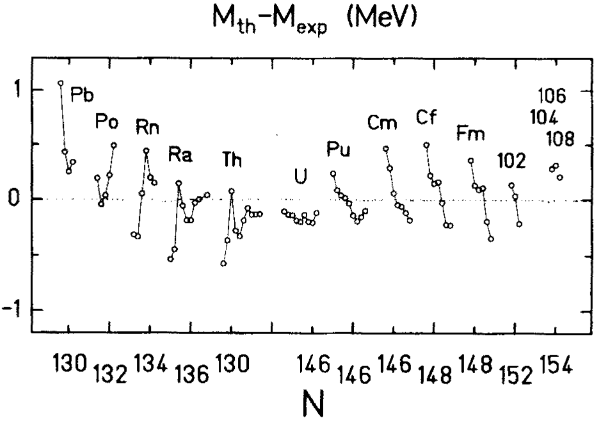

Fig. 2. Discrepancies between masses calculated in [4] and experimental ones [5].

4.3. Half-lives of deformed superheavy nuclei

Figure 3 shows the spontaneous-fission and α−decay half-lives, $T_{\rm sf}$ and T_α, respectively, calculated for deformed superheavy nuclei situated around the nucleus $^{270}108$. One can clearly see the effect of the deformed $N = 162$ shell. A weaker effect of the $N = 152$ shell is also seen, especially for lighter elements. These effects make the systematics of the half-lives quite complex.

A comparison between the calculated $T_{\rm sf}$ and T_α shows that, for $Z = 104$, $T_{\rm sf}$ is smaller than T_α for all N. For $Z = 106$, $T_{\rm sf}$ is comparable with T_α for a large number of isotopes ($N = 152$–164). For higher Z, it is even larger than T_α and for an even larger number of isotopes. This seems to be the effect of shells, mainly of that at $N = 162$, to which $T_{\rm sf}$ is more

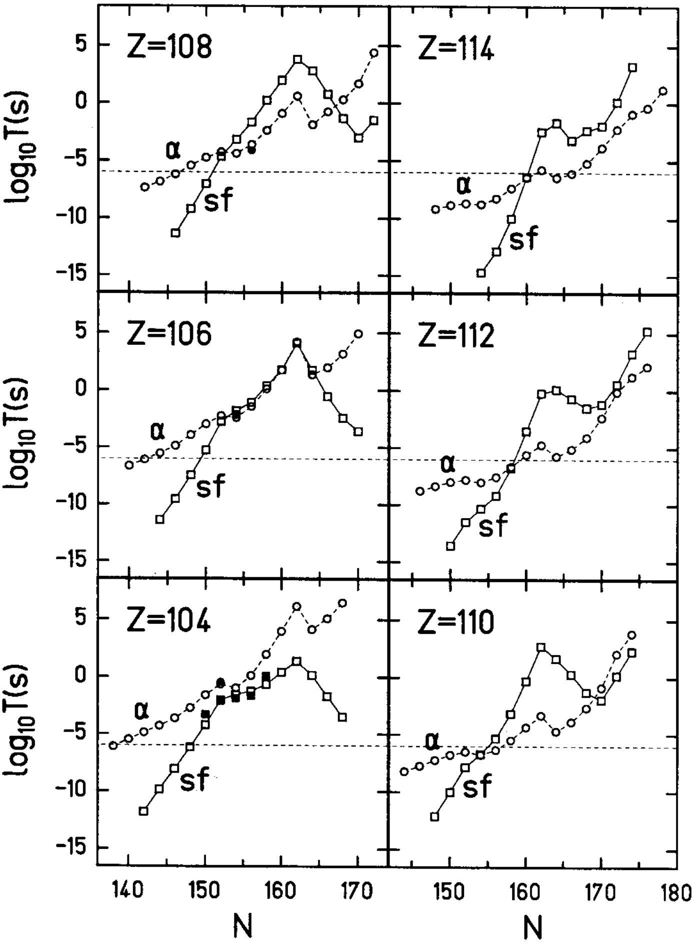

Fig. 3. Logarithm of calculated spontaneous-fission (sf) and α-decay (α) half-lives (given in seconds), as functions of the neutron number N, for the elements 104–114. Experimental values are given as full symbols. The horizontal dashed line indicates about the lowest half-life (1 μs) of a nucleus, which can be detected in a present-day set-up, after its synthesis [3].

sensitive than T_α. Only for the lightest isotopes, T_{sf} is shorter than T_α for all elements investigated.

Figure 4 gives a comparison between predicted theoretically [4] and measured values of α–decay half-lives T_α, for isotopes of the element 110. The measured values are taken from [20] for $^{259,261}110$ and from [26] for $^{273}110$ One can see that the measured values seem to confirm the existence of the predicted neutron deformed shell at N = 162. When comparing the two

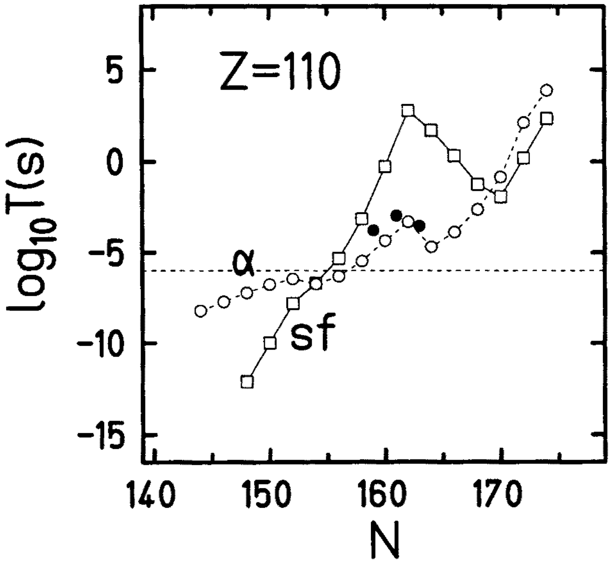

Fig. 4. Comparison between predicted theoretically (open cirles) [4] and measured (full circles) [20, 26] α–decay half-lives.

kinds of values, one should remember, however, that the theoretical ones are obtained for even-N isotopes, while the measured values correspond to odd-N nuclei. Assuming that the theory is about as good for 110 as it is for the element 106 (Fig. 3), the comparison of two kinds of values gives an estimate of the odd-neutron effect in the α-decay half-lives of isotopes of 110. One can see that the effect is about one order of magnitude or less.

4.4. Half-lives of spherical superheavy nuclei

Figure 5 shows logarithm of the α–decay half-lives T_α. Besides the results for spherical superheavy nuclei (situated around the nucleus $^{298}114$), the figure includes also the results for lighter (deformed) nuclei, to see how well are the experimental values of T_α reproduced by the calculations.

The effects of spherical shells at $N = 184$ and $Z = 114$ are clearly seen in the figure. The effect of the shell at $N = 184$ is especially large for nuclei with smaller atomic number Z, as the half-lives, themselves, are large for these nuclei. As the spontaneous-fission half-life T_{sf} is expected to be larger than T_α, for nuclei around the nucleus $^{298}114$, the latter should be the total half-life for them. One can see in Fig. 5 that this half-life may be of the order of about 10 min for isotopes of the element 114 with neutron number

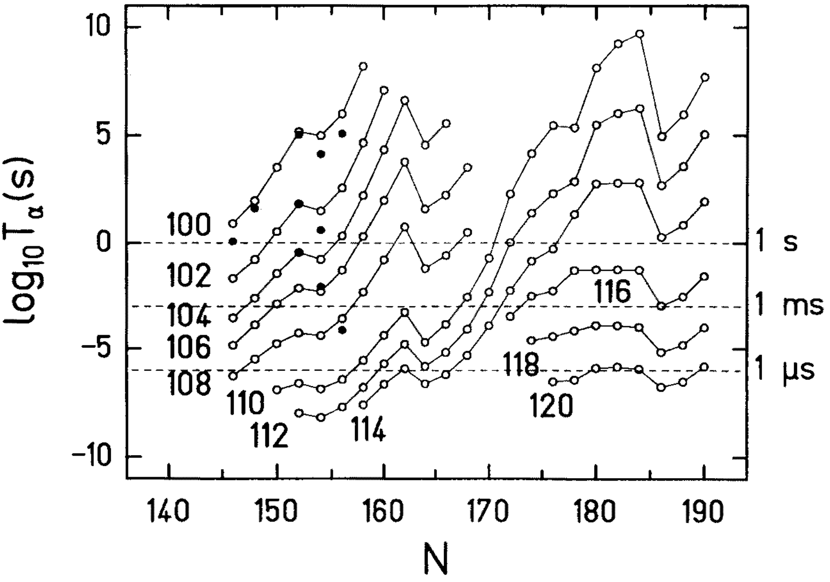

Fig. 5. Calculated logarithm of the α-decay half-life T_α (given in seconds) as a function of the neutron number N, for the elements 100–120 [4].

$N = 180 - 184$.

Spontaneous-fission half-lives T_{sf}, calculated recently, are discussed in [8].

5. Prospects for synthesis of still heavier nuclei

The heaviest nucleus synthesized up to now is $^{277}112$ [25]. It has been obtained at GSI-Darmstadt in the cold fusion reaction

$$^{70}_{30}\mathrm{Zn} + ^{208}_{82}\mathrm{Pb} \rightarrow {}^{278}112^{*}_{166} \rightarrow {}^{277}112_{165} + 1n, \tag{1}$$

in which the excitation energy of the compound nucleus is small and only one neutron is emitted.

In a near future, synthesis of the elements 113 and 114 is planned. The element 113 is projected to be synthesized at GSI–Darmstadt in a cold fusion reaction. One of the two reactions

$$^{68}_{30}\mathrm{Zn} + ^{209}_{83}\mathrm{Bi} \rightarrow {}^{277}113^{*}_{164} \rightarrow {}^{276}113_{163} + 1n, \tag{2}$$

or

$$^{70}_{30}\mathrm{Zn} + ^{209}_{83}\mathrm{Bi} \rightarrow {}^{279}113^{*}_{166} \rightarrow {}^{278}113_{165} + 1n, \tag{3}$$

is proposed [35].

The element 114 is planned to be obtained at JINR–Dubna in a hot fusion reaction, with the use of the ^{48}Ca projectile. One of the proposed reactions is [36]

$$^{48}_{20}\mathrm{Ca} + ^{244}_{94}\mathrm{Pu} \;\rightarrow\; ^{292}114^{*}_{178} \;\rightarrow\; ^{289,288}114_{175,174} + (3,4)n. \qquad (4)$$

Here, the excitation energy of the compound nucleus is higher than in Eqs. (2) and (3), and 3 or 4 neutrons are expected to be emitted. The use of the neutron-rich projectile ^{48}Ca in the latter reaction, together with the use of a heavier target, lead to heavier isotopes of 114 than those which could be obtained in a cold fusion reaction.

Theoretically, all four evaporation residues: $^{276,278}113$ and $^{289,288}114$ are expected to decay by α emission, with half-lives in the microseconds region for $^{276,278}113$ and milliseconds region for $^{289,288}114$. Thus, they are expected to live long enough to be observed, if synthesized. The cross-section for their production, however, is a big problem.

The author would like to thank his coworkers: S. Ćwiok, Z. Patyk, J. Skalski and R. Smolańczuk, in cooperation with whom most of the reviewed results have been obtained. He is also grateful to P. Armbruster, F.P. Hessberger, D.C. Hoffman, S. Hofmann, E.K. Hulet, M. Leino, G. Münzenberg, V. Ninov, W. Nörenberg, Yu. Ts. Oganessian, A.G. Popeko, S. Saro, M. Schädel and A.V. Yeremin for a very helpful and fruitful interaction.

REFERENCES

[1] Z. Patyk, A. Sobiczewski, *Nucl. Phys.* **A533**, 132 (1991).

[2] S. Ćwiok, A. Sobiczewski, *Z. Phys.* **A342**, 203 (1992).

[3] R. Smolańczuk, J. Skalski, A. Sobiczewski, *Phys. Rev.* **C52**, 1871 (1995).

[4] R. Smolańczuk, A. Sobiczewski, Proc. XV Nucl. Phys. Conf.:*Low Energy Nuclear Dynamics*, St. Petersburg (Russia) 1995, eds Yu.Ts. Oganessian, W. von Oertzen, R. Kalpakchieva, World Scientific, Singapore 1995, p.313.

[5] R. Smolańczuk, J. Skalski, A. Sobiczewski, Proc. 24th Intern. Workshop: *Extremes of Nuclear Stucture*, Hirschegg (Austria) 1996, eds H. Feldmeier, J. Knoll, W. Nörenberg GSI, Darmstadt 1996, p.35.

[6] A. Staszczak, Z. Lojewski, A. Baran *et al.*, Proc. 3rd Int. Conf.: Dynamical Aspects of Nuclear Fission, Casta-Papiernicka (Slovakia) 1996, in press.

[7] R. Smolańczuk, Proc. 3rd Int. Conf.: Dynamical Aspects of Nuclear Fission, Casta-Papiernicka (Slovakia) 1996, in press.

[8] R.A. Gherghescu, Z. Patyk, A. Sobiczewski, *Acta Phys. Pol.* **B28**, (1997). (these Proceedings)

[9] A. Sobiczewski, *Fiz. Elem. Chastits At. Yadra* **25**, 295 (1994); *Phys. Part. Nucl.* **25**, 119 (1994).

[10] P. Möller, J.R. Nix, *J. Phys.* **G20**, 1681 (1994).

[11] J.F. Berger, L. Bitaud, J. Dechargé *et al.*, Proc. 24th Intern. Workshop: Extremes of Nuclear Stucture, Hirschegg (Austria) 1996, eds H. Feldmeier,J. Knoll, W. Nörenberg GSI, Darmstadt 1996, p. 43.

[12] S. Ćwiok, J. Dobaczewski, P.-H. Heenen *et al.*, Preprint JIHIR–96–02 (Oak Ridge 1996) and these Proceedings.

[13] G.A. Lalazissis, M.M. Sharma, P. Ring, Y.K. Gambhir, *Nucl. Phys.* **A608**, 202 (1996).

[14] K. Rutz, M. Bender, T. Bürvenich *et al.*, *Phys. Rev.* **C** (submitted).

[15] G. Münzenberg, *Rep. Prog. Phys.* **51**, 57 (1988).

[16] E.K. Hulet, J.F. Wild, R.J. Dougan *et al.*, *Phys. Rev.* **C40**, 770 (1989).

[17] R.W. Lougheed, K.J. Moody, J.F. Wild *et al.*, *J. Alloys Comp.* **213/214**, 61 (1994).

[18] Yu.A. Lazarev, Yu.V. Lobanov, Yu.Ts. Oganessian *et al.*, *Phys. Rev. Lett.* **73**, 624 (1994).

[19] P. Armbruster, Proc. Intern. Conf.: *Nuclear Shapes and Nuclear Structure at Low Excitation Energies*, Antibes (France) 1994, eds M. Vergnes, D. Goutte, P.H. Heenen and J. Sauvage, Editions Frontieres, Gif-sur-Yvette 1994, p.365.

[20] S. Hofmann, V. Ninov, F.P. Hessberger *et al.*, *Z. Phys.* **A350**, 277 (1995).

[21] S. Hofmann, V. Ninov, F.P. Hessberger *et al.*, *Z. Phys.* **A350**, 281 (1995).

[22] A. Ghiorso, D. Lee, L.P. Somerville *et al.*, *Phys. Rev.* **C51**, R2293 (1995).

[23] D.C. Hoffman, M.R. Lane, *Radiochim. Acta* **70/71**, 135 (1995).

[24] Yu.A. Lazarev, Yu.V. Lobanov, Yu.Ts. Oganessian *et al.*, *Phys. Rev. Lett.* **75**, 1903 (1995).

[25] S. Hofmann, V. Ninov, F.P. Hessberger *et al.*, *Z. Phys.* **A354**, 229 (1996).

[26] Yu.A. Lazarev, Yu.V. Lobanov, Yu.Ts. Oganessian *et al.*, *Phys. Rev.* **C54**, 620 (1996).

[27] M. Schädel, W. Brüchle, B. Schausten *et al.*, Preprint GSI–96–56 (Darmstadt 1996); *Radiochim. Acta* (in press).

[28] A. Sobiczewski, F.A. Gareev, B.N. Kalinkin, *Phys. Lett.* **22**, 500 (1966).

[29] H. Meldner, *Ark. Fys.* **36**, 593 (1967).

[30] Z. Patyk, A. Sobiczewski, P. Armbruster, K.-H. Schmidt, *Nucl. Phys.* **A491**, 267 (1989).

[31] Z. Patyk, A. Sobiczewski, *Phys. Lett.* **B256**, 307 (1991).

[32] H.J. Krappe, J.R. Nix, A.J. Sierk, *Phys. Rev.* **C20**, 992 (1979).

[33] S. Ćwiok, J. Dudek, W. Nazarewicz *et al.*, *Comput. Phys. Commun.* **46**, 379 (1987).

[34] W.D. Myers, W.J. Swiatecki, *Nucl. Phys.* **81**, 1 (1966).

[35] S. Hofmann *et al.*, private communication 1996.

[36] Yu.Ts. Oganessian, private communication 1996.