nature physics

PERSPECTIVE
https://doi.org/10.1038/s41567-018-0163-3

The limits of nuclear mass and charge

Witold Nazarewicz

Four new elements with atomic numbers $Z=113$, 115, 117 and 118 have recently been added to the periodic table. The questions pertaining to these superheavy systems are at the forefront of research in nuclear and atomic physics, and chemistry. This Perspective offers a high-level view of the field and outlines future challenges.

In 2016, four new synthetic elements with atomic numbers $Z=113$ (nihonium), 115 (moscovium), 117 (tennessine) and 118 (oganesson) joined the periodic table[1,2]. They were all produced by scientists in the years between 2002 and 2006 using heavy-ion fusion reactions. The road to the final confirmation took a decade and a significant and dedicated experimental effort worldwide.

The term 'superheavy elements' usually refers to transactinides — the chemical elements with atomic numbers $Z \geq 104$. All known superheavy nuclei are radioactive; they have been obtained synthetically in nuclear laboratories. The lighter isotopes of elements $Z=110$–113, forming the 'lower superheavy region', were discovered between 1994 and 2004 in reactions using lead or bismuth targets[3]. Since the production cross section was found to be rapidly decreasing with the atomic number (it is around 0.02 picobarn for $Z=113$), it was concluded that it would be very difficult to reach even heavier elements using such a strategy.

The use of 'hot-fusion' reactions with neutron-rich ^{48}Ca beams and actinide targets has revolutionized the field and resulted in measurements of over fifty isotopes of new elements with $Z=114$–118 in between 1998 and 2008[4]. The nuclei produced in this way constitute the upper superheavy region, which is currently not connected to the known region of the nuclear chart. The nucleus ^{294}Og, produced in 2006 in Dubna, marks the current limit of nuclear charge and mass. It decays to ^{290}Lv by α-decay with a half-life of $0.89^{+1.07}_{-0.31}$ ms, which is currently too short for chemical studies[5]. This means computing its electronic and nuclear structure is the next best thing.

The science questions driving the field of superheavy nuclei and atoms are: what are the heaviest nuclei and atoms that can exist? Do very long-lived superheavy nuclei exist in nature? Can superheavy nuclei be produced in stars? Where is the end of the periodic table of elements and what are the chemical properties of superheavy atoms? This perspective overviews the field of superheavy nuclei in the context of these overarching questions.

The territory

To get some understanding of the current breadth of superheavy research, Fig. 1 shows the nuclear landscape as predicted by nuclear theory[6]. The inset displays the superheavy region in more detail. It is seen that the known superhavy nuclei produced by heavy-ion fusion reactions inhabit a fairly small region of the nuclear chart that is close to the proton drip line — that is, these isotopes are all proton-rich systems. The totally unknown territory of neutron-rich superheavy nuclei is enormous.

To put things in perspective, according to nuclear theory, about 100 isotopes of Og are expected to exist, between $N \approx 170$ (proton drip line) and $N \approx 270$ (neutron drip line). The centre of the β-stability valley for Og is predicted at $N \approx 192$ (refs [7,8]). Since there are currently no obvious ways to synthesize neutron-rich superheavy systems, all information about those nuclei must come from theoretical predictions involving huge extrapolations.

Global properties of superheavy nuclei

The mere existence of superheavy nuclei hangs on the interplay between the short-ranged attractive nuclear force and long-ranged electrostatic repulsion, which becomes very strong at large values of Z. Thanks to its saturation property, the nuclear force favours values of the internal nucleonic density close to the saturation density of nuclear matter, $\rho_{\text{sat}} \approx 0.16$ nucleons fm^{-3}. On the other hand, since the Coulomb repulsion minimizes the total energy by increasing the average distance between protons, the binding energy is significantly lowered by either pushing protons toward the nuclear surface or by deforming the nuclear shape.

The competition between surface energy, which favours compact shapes, and the electrostatic force, which prefers extended configurations, results in Coulomb frustration, also known as redistribution effects[9], that is expected to produce exotic topologies of nucleonic densities, such as voids (bubbles) or tori. Various forms of nuclear matter making up a superheavy nucleus would be expected to appear close in energy, similarly to what is predicted in the inner crust of neutron stars, where different Coulomb-frustrated phases coexist[10]. The properties of superheavy bubble nuclei, including their characteristic density distributions and shell structure, have been investigated in numerous studies[11].

The isotopes of Og are predicted to be strongly frustrated systems. Figure 2 shows the calculated neutron and proton density distributions in ^{294}Og, ^{302}Og and ^{326}Og. In most calculations[8,12], ^{294}Og is expected to be slightly deformed, with a triaxial shape; ^{302}Og is predicted to be spherical; and ^{326}Og is calculated to have an appreciable prolate deformation. In all three cases, the semi-bubble structure in the proton distribution is clearly present.

It would be desirable to obtain model-independent information about the magnitude of charge redistribution. In this respect, experimental studies of nuclear charge radii and quadrupole moments from the hyperfine structure, recently extended to $^{252–254}$No, carry great promise[13].

According to the nuclear shell model, nucleons move in a common potential generated by all the other nucleons. Similar to an electron's motion in an atom, nucleonic orbits bunch together forming shells, and magic nuclei with filled nucleonic shells are exceptionally stable. The quantum enhancement in nuclear binding due to the presence of nucleonic shells can be quantified in terms of the so-called shell energy[9]. While the magic nuclei have the largest shell energies, other nuclei can also be shell-stabilized. By the end of the 1960s, it was realized that the mere existence of the heaviest nuclei

Department of Physics and Astronomy and FRIB Laboratory, Michigan State University, East Lansing, MI, USA. e-mail: witek@frib.msu.edu

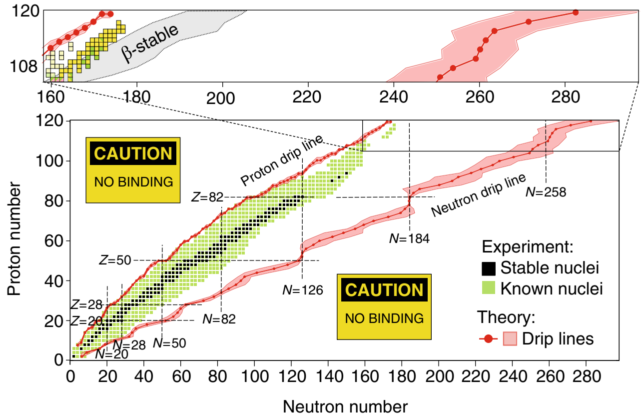

Fig. 1 | Landscape of nucleon-bound nuclei as a function of Z and N. The stable isotopes are shown as black squares and those known experimentally are shown in green. Mean drip lines and their uncertainties (red) were obtained by averaging the results of different models based on nuclear density functional theory (DFT). The inset shows the details of the superheavy territory ($Z>104$ and $N>160$). The isotopes synthesized in heavy-ion fusion reactions are indicated[4] together with the anticipated valley of β-stability[7,8]. Adapted from ref. [6], Macmillan Publishers Ltd.

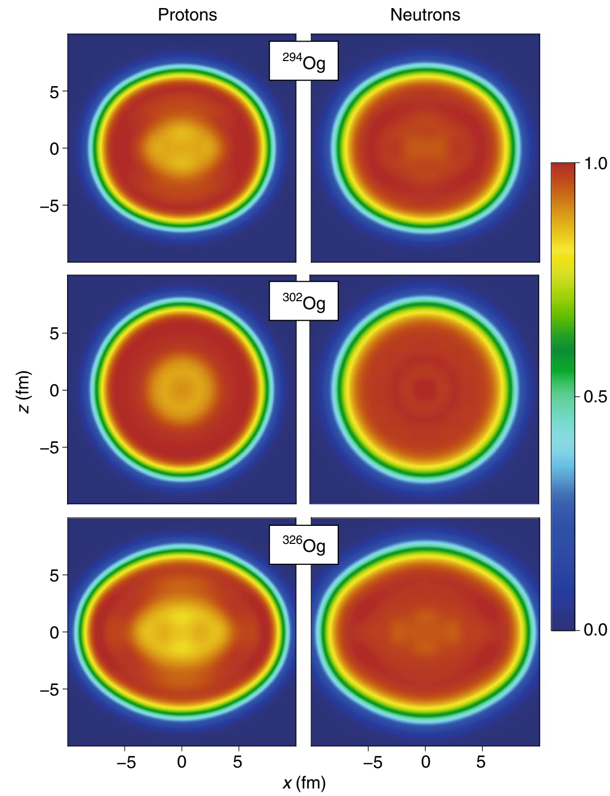

Fig. 2 | Neutron (left) and proton (right) densities of ^{294}Og (top), ^{302}Og (top) and ^{326}Og (bottom) calculated with SV-min in the (x, z) plane at $y=0$. The densities are normalized to the maximum density. The central depression of the proton density (semi-bubble structures) is clearly seen in all three cases. Adapted from ref. [11], APS.

with $Z>104$ was primarily determined by the quantum shell effects, which counterbalance the electrostatic repulsion[9,14].

The pattern of nucleonic shells undergoes significant changes in the superheavy region[7,15–17]. The main factors driving these changes are Coulomb frustration effects and the large density of single-particle levels, which grows faster than expected from the $A^{1/3}$ scaling[16]. The latter implies that differences in theoretical models can impact the order of nucleonic shells significantly when extrapolating mass and atomic number. From this point of view, it is entirely possible that the nucleus ^{208}Pb is the last 'proper' doubly-magic nucleus with the well-localized single-particle gaps at $Z=82$ and $N=126$, and that the notion of 'magicity' has a rather limited meaning in superheavy nuclei.

Coming back to Coulomb frustration, one cannot exclude a possibility that there exist isolated islands of nuclear stability, associated with very exotic topologies of nuclear density, stabilized by shell effects. However, it is difficult to say at present whether such exotic topologies can occur as metastable states and what is their stability to various decay modes, especially fission.

Many superheavy nuclei are deformed in their ground states[8,12,18]. The measured α-decay energies have furnished confirmation of the special stability of the deformed nuclei with $N=162$ predicted by theory[18]. According to calculations, the well-deformed elongated (prolate) superheavy nuclei are separated from spherical elements with $N=184$ by the region of weakly deformed, possibly triaxial systems[8,12].

Decay modes

The lifetimes of most known superheavy nuclei are governed by the competition between α-decay and spontaneous fission (SF). The α-decay lifetimes T_α primarily depend on the energy release Q_α. In general, there is a reasonable agreement between well-optimized global theoretical models with respect to Q_α values[8,12,19]. Since Q_α depends on the binding energy difference of parent and daughter nuclei, many systematic model errors that are present in predicted masses cancel out, thus leading to more robust estimates. Figure 3 displays predictions of several models for the α-decay chain of ^{294}Og. Usually, the agreement between experiment and theory is several hundred keV, and this is sufficient to provide some guidance about the parent-nucleus identification, in the absence of a direct experimental evidence.

Unlike in the case of α-decay, there is no theoretical consensus about SF lifetimes T_{SF} of superheavy nuclei. This is because predictions are very sensitive to both input (forces, functionals, treatment of collective inertia) and theoretical framework used[20,21]. Consequently, theoretical lifetime estimates often differ by many orders of magnitude. In spite of very different modelling, however, the qualitative topological properties of fission pathways are often similar in different models. For instance, theory predicts a region superheavy isotopes with very short SF lifetimes that lie in a corridor separating the upper and lower region of superheavy nuclei[20]. Experimentally, the minimum of SF lifetimes appears to be at ^{282}Cn, beyond which a steep rise of T_{SF} is seen[4]. This, together with the corresponding gradual increase of T_α with neutron number[4], is consistent with the placement of the anticipated region of long-lived superheavy nuclei around $N=184$ and $Z=112$.

As shown in Fig. 1, the heaviest nuclei synthesized so far are all proton-rich; hence, they can in principle decay by means of electron capture (EC) or β^+ process. So far, no such decay modes have been observed in the upper superheavy region, and this indicates that they cannot compete with α-decay and SF. Indeed, according to theory[7,8], β^+/EC lifetimes shorter than 1 s are expected in nuclei that lie rather far from the current superheavy region.

An interesting, albeit yet experimentally unexplored, decay mode of superheavy nuclei is cluster radioactivity. This phenomenon has been observed in a number of heavy nuclei with $Z>86$, which decay by emitting light clusters ranging between ^{14}C and ^{34}Si. For superheavy nuclei with $Z\geq 118$, cluster radioactivity is expected to become competitive with alpha decay and SF[22]. Microscopically, cluster emission can be considered as an extremely asymmetric fission, with the heavy fragment corresponding to a nucleus in the neighborhood of the doubly-magic ^{208}Pb (ref. [23]).

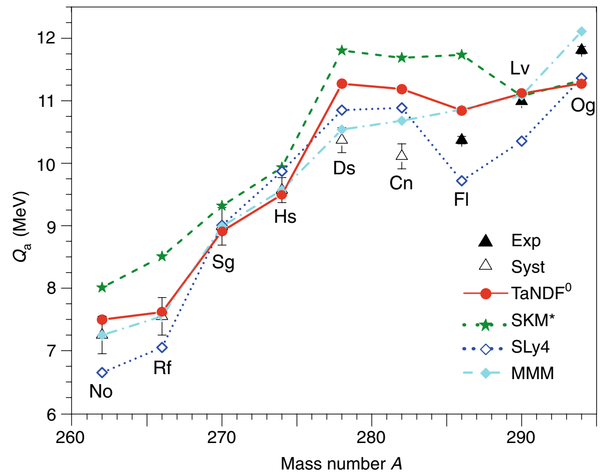

Fig. 3 | Q_α values for the α-decay chain of ^{294}Og predicted by several global theoretical models compared to experimental and estimated values. Adapted from ref. [19], Springer.

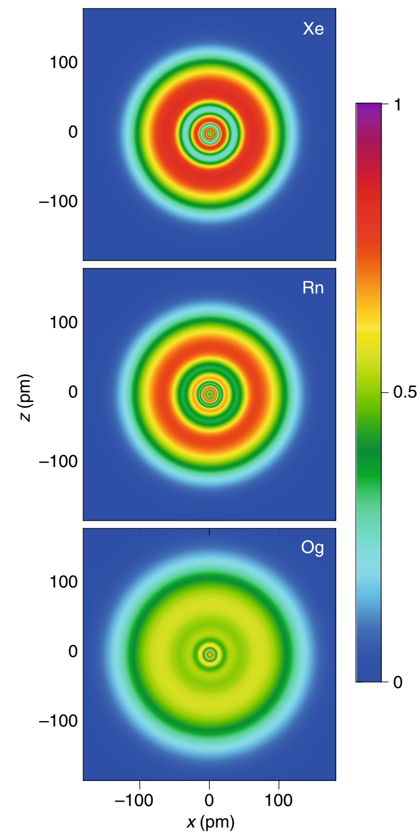

Fig. 4 | Electron localization function for group-18 elements xenon, radon and oganesson predicted in relativistic calculations. The valence and sub-valence shells of Og are calculated to be smeared out uniformly, as evidenced by the vanishing pattern of concentric rings. This is expected to result in significant changes in chemical and physical properties of the Og atom. Adapted from ref. [17], APS.

Beyond the standard periodic table of elements

What are the chemical properties of superheavy elements? Since atomic relativistic effects scale approximately with Z^2, chemical properties of superheavy atoms cannot be properly described by non-relativistic quantum mechanics[24]. Moreover, since the product of the fine structure constant and atomic number (αZ) is large, quantum electrodynamic corrections become substantial. The experimental chemical tests are extremely difficult because one-atom-at-a-time chemistry requires half-lives of the order of 1–2 s and production rates of at least a few atoms per day. In spite of these difficulties, there has been major progress in the chemical characterization of transactinides[5,13], with the element Fl ($Z=114$) marking the limit of chemistry today.

A case in point is is the heaviest element Og. According to its atomic number of $Z=118$, Og should belong to group 18, period 7 of the periodic table of elements; hence, it should exhibit properties of a noble gas. Theoretically, however, this does not seem to be the case: the element 118 is calculated to be quantitatively different from the lighter homologues[17,25]. Relativistic effects producing in a huge spin–orbit splitting of valence shells and high density of single-electron states in Og result in blurring the shell structure of its outer electrons[17]; an effect clearly seen in the electron localization function in Fig. 4. Consequently, Og is expected to have an enormous polarizability and van der Waals interactions that are significantly larger compared to the lighter noble gases. Due to the significantly reduced energy gap between $8s_{1/2}$ and $7p_{3/2}$ orbitals, Og is predicted to be the first group-18 element with positive electron affinity[26]. So is Og a rare gas after all? While it is certainly rare, the current theory suggests that it is not a gas but a solid at room temperature[25].

Where is the end of the periodic table? Predictions on the placements of elements up to $Z=172$ have been made based on atomic Dirac–Fock calculations[27]. But the existence of elements with $Z>118$ also depends on nuclear physics. Indeed, according the report of Transfermium Working Group[28]: "the discovery of a chemical element is the experimental demonstration, beyond reasonable doubt, of the existence of a nuclide with an atomic number Z not identified before, existing for at least 10^{-14} s. (…) This lifetime is chosen as a reasonable estimate of the time it takes a nucleus to acquire its outer electrons. It is not considered self-evident that talking about an 'element' makes sense if no outer electrons, bearers of the chemical properties, are present." Consequently, if for all isotopes of some superheavy element, nuclear lifetimes will be shorter than 10^{-14} s, there will be no chemistry for that atomic mumber. Reliable predictions of lifetimes of nuclei with $Z>118$ are currently not available, primarily due to difficulties related to the assessment of Coulomb frustration effects on fission. Therefore, to paraphrase the conclusions of ref. [27], one can state that the limit of nuclear mass and charge is still undiscovered. We don't know what it looks like and that's the challenge.

The cosmic perspective

The laboratory discovery of long-lived superheavy nuclei with atomic numbers beyond $Z=110$ has spurred the exciting question whether there have been pathways in nature to produce such nuclei: can long-lived superheavy nuclei be created in the cosmos? Have they been created already? Traces of primordial superheavy nuclei, with half-lives of at least 10^8 years, have been searched for both in terrestrial matter using accelerator mass spectrometry[29] and in galactic cosmic rays[30]. However, in neither case was positive evidence found.

Short-lived superheavy nuclei can be synthesized in the astrophysical rapid neutron capture process (r-process), which takes place in the dynamical ejecta of neutron stars mergers where free neutrons of high density are available. Superheavy nuclei produced in the r-process are expected to fission into lighter fragments, thus recycling the material down to lighter mass regions[21,31]. In this way, fleeing superheavy nuclei created in the r-process may impact the shape of the r-process abundances, which is an observable quantity. The hope is that through advanced r-process simulations — including the relevant microphysics — scientists will be able to 'see' neutron-rich superheavy nuclei through the observed abundance pattern. Figure 5 shows the dominating decay channel of superheavy

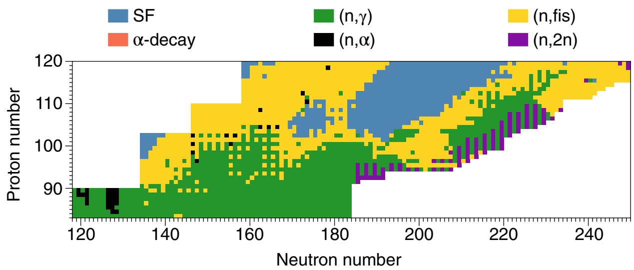

Fig. 5 | Dominating decay channels predicted in density functional theories calculations. Here, typical conditions of r-process in neutron star mergers apply ($T = 0.9$ GK, $n_n = 1.0 \times 10^{28}$ cm^{-3}): SF, α-decay, neutron capture (n,γ), neutron-induced α-emission (n,α), neutron-induced fission (n,fis) and two-neutron emission (n,2n). Adapted from ref. [21], APS.

nuclei predicted in ref. [21] for typical conditions of r-process in neutron star mergers. One can see that the r-process nucleosyntesis of nuclei with $N > 184$ will be strongly hindered due to the dominance of fission channels over neutron capture.

Outlook

The past ten years have been marked by remarkable progress in the science of superheavy elements and nuclei. The highlights include the synthesis of new elements up to $Z = 118$, $A = 294$. The elements 113–118 have been officially recognized and added to the periodic table. The experimental lifetimes indicate increasing stability for isotopes with $Z > 110$ when moving towards the region of long-lived superheavy nuclei with $N \approx 184$ anticipated by theory. High-quality experimental data have been accumulated on global properties of superheavy nuclei and their spectroscopy[32]. Last but not least, chemical studies of ^{112}Cn and ^{114}Fl have illuminated the importance of relativistic effects on properties of superheavy atoms, thus making the search for chemistry beyond the standard periodic table the major science driver.

The field of superheavy element research puts nuclear and atomic theory to the test. There are strong theoretical suggestions that superheavy atoms and nuclei differ from lighter species because of their large charges and masses. The presence of large electrostatic forces gives rise to strong Coulomb frustration effects in the nuclear system and huge relativistic effects in the atomic system; both present unusual challenges for many-body theory.

Since theories of superheavy nuclei heavily rely on extrapolations, it is essential to provide uncertainty quantification on predictions. To constrain nuclear models in the superheavy region, new high-quality data on bulk properties and spectroscopy of superheavy systems are required. Another challenge for theory is to develop predictive models of superheavy nuclei production, capable of guiding future experimental searches[33]. In chemistry and atomic physics, fully relativistic quantum calculations, including QED effects, will continue providing guidance and stimulation.

How to go beyond Og to reach new elements? How to move towards more neutron-rich systems with longer lifetimes? In the short term, the search for new elements $Z = 119$ and 120 will continue in several laboratories[4]. The reactions considered involve beams of ^{48}Ca and heavier ions, such as Ti, Cr, Ni and actinide targets. Another difficult task on the horizon is to synthesize more neutron-rich, longer-lived isotopes of known superheavy elements with Z = 110–118, with the goals of moving closer to $N = 184$ and enabling chemical studies. To find the optimal production methods, systematic fusion reaction studies are being carried out[34]. Reactions using multi-nucleon transfer and radioactive neutron-rich beams are also being considered[35]. An important short-term goal is to connect lower and upper superheavy regions, which will allow us to provide a direct mass/charge identification of nuclei produced in the hot fusion reactions.

The long-term prospects in the unexplored regions of mass and charge are fascinating. They include the exploration of the region of long-lived superheavy nuclei around $N = 184$, the bold expansion of the chart of the nuclides, pinning down the presence of voids and other exotic topologies of nucleonic densities due to Coulomb frustration, delineating the role of superheavy nuclei in nucleosynthesis, and carrying out atomic and chemistry studies in the regime governed by huge relativistic effects. The discovery of new elements beyond Og will add the eighth period to the periodic table. This perspective has been nicely captured by the haiku on element 119 (Uue)[36]:

Will the curtain rise?
Will you open the eighth act?
Claim the center stage?

The outstanding discovery potential has greatly motivated worldwide development of new facilities and novel experimental tools. The new-generation high-current stable-beam accelerators will enable new discoveries at a picobarn level. This includes the dedicated Superheavy Element Factory in Dubna, which will soon become operational; it will allow a substantial increase in the production of superheavy species for physics and chemistry[37]. The voyage continues into the uncharted regions of the periodic table of elements and table of nuclides. Based on the current progress, the prospects in the field of superheavy elements and nuclei are excellent.

Received: 28 March 2018; Accepted: 2 May 2018;
Published online: 4 June 2018

References

1. Karol, P. J., Barber, R. C., Sherrill, B. M., Vardaci, E. & Yamazaki, E. Discovery of the elements with atomic numbers $Z = 113$, 115 and 117. *Pure Appl. Chem.* **88**, 139–153 (2016).
2. Karol, P. J., Barber, R. C., Sherrill, B. M., Vardaci, E. & Yamazaki, E. Discovery of the element with atomic number $Z = 118$ completing the 7th row of the periodic table (IUPAC Technical Report). *Pure Appl. Chem.* **88**, 155–160 (2016).
3. Münzenberg, G. & Morita, K. Synthesis of the heaviest nuclei in cold fusion reactions. *Nucl. Phys. A* **944**, 3–4 (2015).
4. Oganessian, Y. T. & Utyonkov, V. K. Super-heavy element research. *Rep. Prog. Phys.* **78**, 036301 (2015).
5. Düllmann, C. E. Studying chemical properties of the heaviest elements: one atom at a time. *Nucl. Phys. News* **27**, 14–20 (2017).
6. Erler, J. et al. The limits of the nuclear landscape. *Nature* **486**, 509–512 (2012).
7. Ćwiok, S., Dobaczewski, J., Heenen, P.-H., Magierski, P. & Nazarewicz, W. Shell structure of the superheavy elements. *Nucl. Phys. A* **611**, 211–246 (1996).
8. Heenen, P.-H., Skalski, J., Staszczak, A. & Vretenar, D. Shapes and α- and β-decays of superheavy nuclei. *Nucl. Phys. A* **944**, 415–441 (2015).
9. Myers, W. D. & Swiatecki, W. Nuclear masses and deformations. *J. Nucl. Phys.* **81**, 1–60 (1966).
10. Magierski, P. & Heenen, P.-H. Structure of the inner crust of neutron stars: crystal lattice or disordered phase? *Phys. Rev. C.* **65**, 045804 (2002).
11. Schuetrumpf, B., Nazarewicz, W. & Reinhard, P.-G. Central depression in nucleonic densities: trend analysis in the nuclear density functional theory approach. *Phys. Rev. C.* **96**, 024306 (2017).
12. Ćwiok, S., Heenen, P. H. & Nazarewicz, W. Shape coexistence and triaxiality in the superheavy nuclei. *Nature* **433**, 705–709 (2005).
13. Düllmann, C. E. & Block, M. Island of heavyweights. *Sci. Am.* **318**, 46–53 (2018).
14. Nilsson, S. G. et al. On the nuclear structure and stability of heavy and superheavy elements. *Nucl. Phys. A* **131**, 1–66 (1969).
15. Bender, M., Nazarewicz, W. & Reinhard, P.-G. Shell stabilization of super- and hyperheavy nuclei without magic gaps. *Phys. Lett. B* **515**, 42–48 (2001).
16. Agbemava, S. E., Afanasjev, A. V., Nakatsukasa, T. & Ring, P. Covariant density functional theory: reexamining the structure of superheavy nuclei. *Phys. Rev. C.* **92**, 054310 (2015).
17. Jerabek, P., Schuetrumpf, B., Schwerdtfeger, P. & Nazarewicz, W. Electron and nucleon localization functions of Oganesson: approaching the Thomas-Fermi limit. *Phys. Rev. Lett.* **120**, 053001 (2018).

18. Möller, P., & Nix, J. R. Stability of heavy and superheavy elements. *J. Phys. G* **20**, 1681–1747 (1994).
19. Tolokonnikov, S. V., Borzov, I. N., Kortelainen, M., Lutostansky, Y. S. & Saperstein, E. E. Alpha-decay energies of superheavy nuclei for the Fayans functional. *Eur. Phys. J. A* **53**, 33 (2017).
20. Baran, A. et al. Fission barriers and probabilities of spontaneous fission for elements with $Z \geq 100$. *Nucl. Phys. A* **944**, 442–470 (2015).
21. Giuliani, S. A., Martnez-Pinedo, G. & Robledo, L. M. Fission properties of superheavy nuclei for r-process calculations. *Phys. Rev. C.* **97**, 034323 (2018).
22. Poenaru, D. N., Gherghescu, R. A., Greiner, W. & Shakib, N. S. *How Rare Is Cluster Decay of Superheavy Nuclei?* 131–140 (Springer, Cham, 2015).
23. Warda, M. & Robledo, L. M. Microscopic description of cluster radioactivity in actinide nuclei. *Phys. Rev. C.* **84**, 044608 (2011).
24. Schwerdtfeger, P., Pašteka, L. F., Punnett, A. & Bowman, P. O. Relativistic and quantum electrodynamic effects in superheavy elements. *Nucl. Phys. A* **944**, 551–577 (2015).
25. Schwerdtfeger, P. Toward an accurate description of solid-state properties of superheavy elements: A case study for the element Og ($Z = 118$). *EPJ Web Conf.* **131**, 07004 (2016).
26. Eliav, E., Fritzsche, S., & Kaldor, U. Electronic structure theory of the superheavy elements. *Nucl. Phys. A* **944**, 518–550 (2015).
27. Pyykkö, P. A suggested periodic table up to $Z \leq 172$, based on Dirac–Fock calculations on atoms and ions. *Phys. Chem. Chem. Phys.* **13**, 161–168 (2011).
28. Wapstra, A. H. et al. Criteria that must be satisfied for the discovery of a new chemical element to be recognized. *Pure Appl. Chem.* **63**, 879–886 (1991).
29. Korschinek, G., & Kutschera, W. Mass spectrometric searches for superheavy elements in terrestrial matter. *Nucl. Phys. A* **944**, 190–203 (2015).
30. Ter-Akopian, G., & Dmitriev, S. Searches for superheavy elements in nature: cosmic-ray nuclei; spontaneous fission. *Nucl. Phys. A* **944**, 177–189 (2015).
31. Goriely, S. & Pinedo, G. M. The production of transuranium elements by the r-process nucleosynthesis. *Nucl. Phys. A* **944**, 158–176 (2015).
32. Ackermann, D. & Theisen, C. Nuclear structure features of very heavy and superheavy nuclei—tracing quantum mechanics towards the 'island of stability'. *Phys. Scr.* **92**, 083002 (2017).
33. Zagrebaev, V., & Greiner, W. Cross sections for the production of superheavy nuclei. *Nucl. Phys. A* **944**, 257–307 (2015).
34. Itkis, M., Vardaci, E., Itkis, I., Knyazheva, G., & Kozulin, E. Fusion and fission of heavy and superheavy nuclei (experiment). *Nucl. Phys. A* **944**, 204–237 (2015).
35. Loveland, W. Synthesis of transactinide nuclei using radioactive beams. *Phys. Rev. C.* **76**, 014612 (2007).
36. Lee, M. S. Elemental haiku. *Science* **357**, 461–463 (2017).
37. Dmitriev, S., Itkis, M. & Oganessian, Y. Status and perspectives of the Dubna superheavy element factory. *EPJ Web Conf.* **131**, 08001 (2016).

Acknowledgements

Discussions with Y. Oganessian and P. Schwerdtfeger, and useful comments from D. Lee are gratefully appreciated. This work was supported by the US Department of Energy under award numbers DOE-DE-NA0002847 (NNSA, the Stewardship Science Academic Alliances programme), DE-SC0013365 (Office of Science) and DE-SC0018083 (Office of Science, NUCLEI SciDAC-4 collaboration).

Competing interests

The author declares no competing interests.

Additional information

Reprints and permissions information is available at www.nature.com/reprints.

Correspondence should be addressed to W.N.

Publisher's note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.