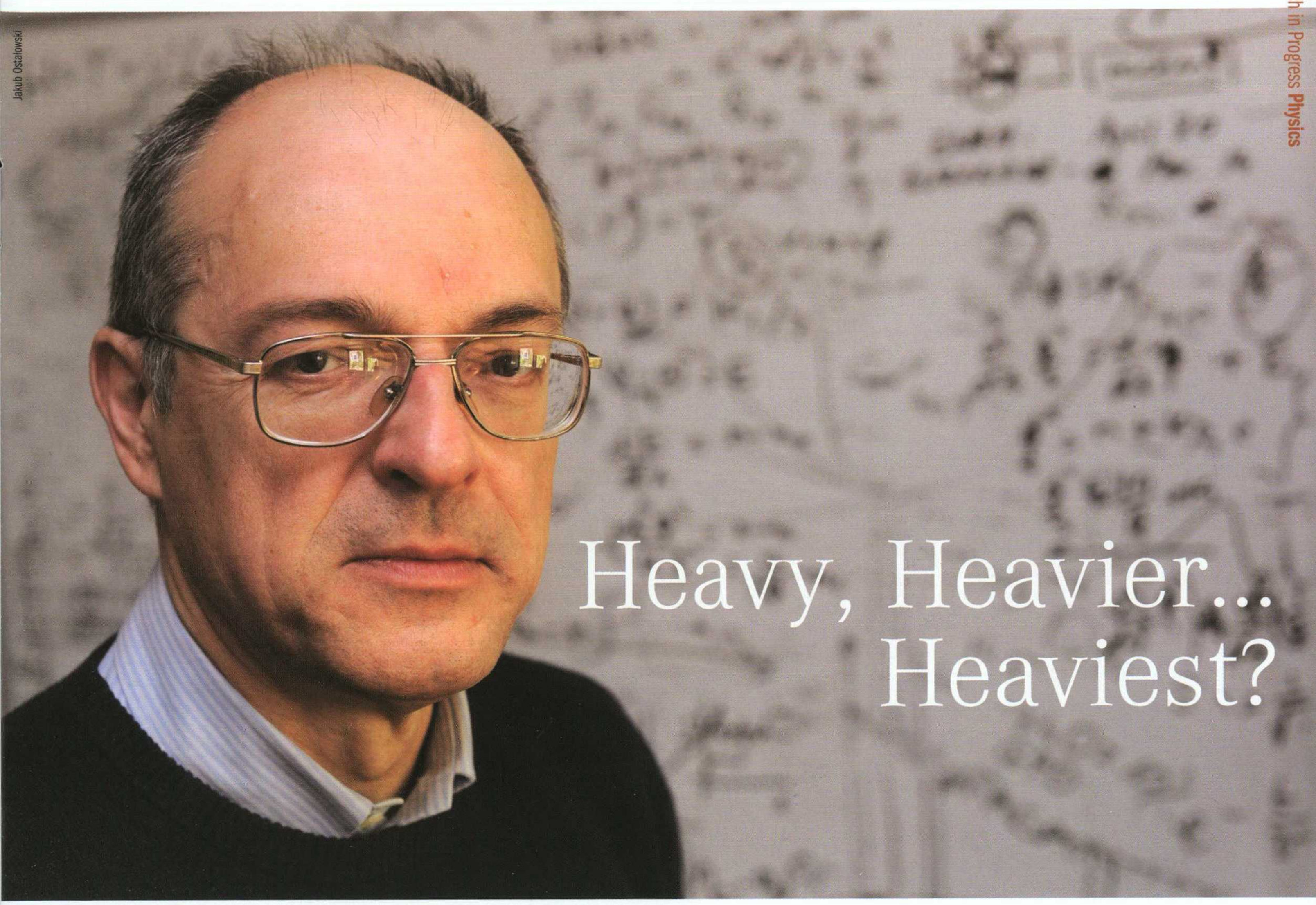
The structure of atomic nuclei and the riddle of the heaviest elements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Heavy, Heavier... Heaviest?

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The heaviest element known today has the atomic number of 118. Can still heavier atomic nuclei exist? Where do the boundaries of the periodic table of elements lie?

All matter is formed of atoms: electrically-bound systems comprising nuclei and electrons. Atoms are numbered according to their atomic number Z, equal to the number of protons in each nucleus: so hydrogen is number 1, helium - 2, lithium - 3, beryllium - 4, iron - 26, gold - 79, lead - 82, and so on. The elements above uranium (U) - number 92 - are not present in the Earth's crust at anything above trace levels. Not all elements with atomic number $Z<93$ were discovered on Earth; for example, the spectral lines of helium were first found in the spectrum of the Sun (giving the element its name), whereas the unstable technetium (Tc, $Z=43$) was synthesized artificially. Creating a new element involves making an atomic nucleus with a previously unseen atomic number. This raises the question: how large can Z get?

Protons, neutrons, isotopes

An atomic nucleus consists of protons and neutrons, together known as "nucleons." Protons are positively-charged particles (approx. 1836 times heavier than the negatively-charged electrons), and neutrons are electrically neutral particles with a slightly greater mass than protons. The nucleus is bound together by the strong, short-range nuclear force between nucleons, which balances the electrical repulsion between the protons. A nucleus of atomic number Z, therefore, comprises Z protons plus some number (N) of neutrons. Atomic nuclei of the same element with different numbers of neutrons are different isotopes of the element, denoted as ^{Z+N}X, where X is the chemical symbol. For example, a hydrogen atom (Z=1) with a single neutron is known as deuterium ^2H, and one with two neutrons is tritium ^3H. Usually, a few different isotopes of each element are found in the Earth's crust; for example, naturally-occurring chlorine (Z=17) is a mixture of ^{35}Cl and ^{37}Cl at a ratio of 3:1.

The nuclear mass is the combined mass of the protons and neutrons, minus the binding energy (just less than 1% of total mass), roughly proportional to the number of nucleons ($Z+N$). The binding energy, counted per nucleon, increases with the value of Z for light nuclei, peaks for iron and nickel, and then decreases gradually in heavier elements due to the increasingly powerful repulsion between protons. The N/Z ratio of the isotope with the highest binding energy is 1 for light nuclei but increases gradually for higher Z values. Isotopes with an N/Z ratio far from the optimum are subject to beta-decay (an exchange of a proton for a neutron, or vice versa), accompanied by the emission of low-mass particles. All elements heavier than uranium - known as "transuranium elements" - are unstable; their beta-stable isotopes are subject to fission (splitting into two large nuclei) or alpha-decay (splitting into a helium nucleus and daughter nucleus).

From neptunium to Z=118

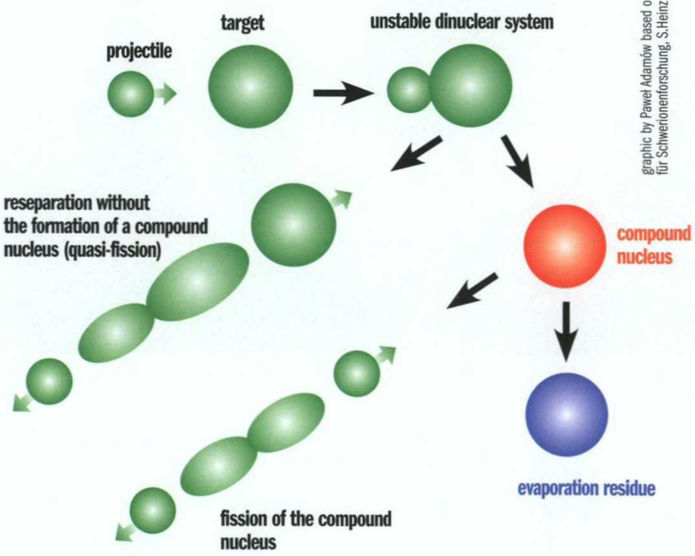
The history of discovery of elements heavier than uranium has taken some unexpected turns. In 1938, Enrico Fermi received the Nobel Prize for physics for work including his alleged discovery of a new element 93, which he thought had resulted from bombarding uranium with neutrons, leading to the formation of ^{239}U and its beta-decay. At the time when he was collecting the award, however, Otto Hahn and Fritz Strassmann already knew that the unexpected product of this reaction was actually the much lighter barium (Z=56). They had thus discovered nuclear fission (though they did not realize it at the time).

The true discoverer of transuranium elements was Edwin McMillan; he was the first to synthesize neptunium (Z = 93) and precisely identify the products of this reaction. Reactions with neutrons, deuterium and helium later allowed Glenn Seaborg and his team at Berkeley to create further new actinides (elements in the series Z = 89 to 103).

Einsteinium (Es, Z=99) and fermium (Fm, Z=100) were detected in air over the Enewetak atoll following the explosion of the hydrogen bomb in the famous test in 1952. This meant that during the explosion some uranium nuclei must have captured at least 15 and 17 neutrons (the fissile uranium served as the primary, and likely the secondary hydrogen synthesis igniter), something no one had expected.

The rivalry between research centers in the US (Berkeley) and the USSR (Dubna) led to arguments about which team was the first to discover elements 104, 105, and 106 - the first "superheavy elements" (lawrencium, Z=103, is the last element in the actinide group, and the term superheavy is generally used to describe those with Z>104). Elements 107-112 were discovered at GSI Darmstadt in Germany through reactions of ^{208}Pb or ^{209}Bi with ions of chromium, iron, nickel and zinc, with the likelihood of synthesis dropping around 100,000 times between Z=102 and Z=112. The next breakthrough was achieved by Yuri Oganessian's team from Dubna, who used reactions with calcium, in particular ^{48}Ca, on actinide nuclei. In these reactions, the probability of synthesis is far less dependent upon Z, which has led to further discoveries and today's boundary of the periodic table being pushed up to Z=118.

How much further could this boundary be shifted? This depends on the stability of the new isotopes and how difficult they are to synthesize. With today's state-of-the-art technologies, a new nucleus has to exist for at least 10μs for it to be detected, so it must remain stable for at least that length of time. As Z increases, synthesis becomes increasingly less likely, and researchers have to wait months to detect just a few decay chains (mainly alpha-decays) of a successfully created nucleus and its daughter nuclei. Since such experiments only tell us about decay energies and half-lives, our understanding of superheavy nuclei is largely based on theoretical predictions of their structure and decay. This is the kind of work our team is engaged in at Poland's National Centre for Nuclear Research.



graphic by Paweł Adamów based on GSI Helmholtzzentrum für Schwerionenforschung, S.Heinz.

Name	Symbol	Year of discovery	Most stable isotope	Half-life
mendelevium	Md	1955	^{258}Md	51.5 days
nobelium	No	1958	^{259}No	58 m
lawrencium	Lr	1961	^{266}Lr	11 h
rutherfordium	Rf	1964-1969	^{267}Rf	1.3 h
dubnium	Db	1967-1970	^{268}Db	30.8 h
seaborgium	Sg	1974	^{271}Sg	2.4 m
bohrium	Bh	1981	^{270}Bh	3.8 m
hassium	Hs	1984	^{269}Hs	27 s
meitnerium	Mt	1984	^{278}Mt	7.6 s
darmstadtium	Ds	1994	^{281}Ds	9.6 s
roentgenium	Rg	1994	^{281}Rg	26 s
copernicium	Cn	1996	^{285}Cn	29 s
	Uut	2003-2004	^{286}Uut	19.6 s
flerovium	Fl	1999-2000	^{289}Fl	2.6 s
	Uup	2003	^{289}Uup	220 ms
livermorium	Lv	2000	^{293}Lv	53 ms
	Uus	2010	^{294}Uus	51 ms
	Uuo	2002	^{294}Uuo	0.89 ms

The heaviest known, artificially created elements, with atomic numbers $Z = 101$ through 118. Their names are derived from the names of eminent scientists or discoverers (e.g. 112 after Nicolaus Copernicus), or the city or land of the laboratory where they were discovered (105 – Dubna, 110 – Darmstadt, 108 – Hessen, 116 – Livermore). As-yet unnamed elements are denoted by Latin numerals, for example Uut – Ununtrium. Among the most stable isotopes, we have not included unconfirmed isomeric states: of ^{281}Ds with a half-life of 3.7 m and of ^{289}Fl with a half-life of 1.1 m. The numbers of presently known isotopes of each element are, for example: Hs – 12, Mt – 8, Cn – 6, Uut – 6, Lv – 4, Uuo – 1.

Magic nuclei

Due to the complexity of nuclear interactions and the large number of nucleons involved, predictions are made based on simplified models. An important feature of all such models is that nuclei can assume a deformed shape. The dependence of the binding energy on deformation is crucial in the study of nuclear stability, especially with respect to fission. The analysis requires that all relevant deformations should be considered, otherwise one risks seriously overestimating half-lives. This, as our results show, has been a main reason for overly optimistic estimates, both in earlier and quite recent studies.

Although the models are adjusted to fit the properties of known nuclei, their results for $Z>110$ differ, so extrapolation to superheavy nuclei is not unique. The main reason for this lies in various predictions of the "magic numbers" that are posited to exist (beyond those of lead), especially the magic number for protons. A magic number is a number of nucleons which shows a higher binding energy per nucleon than neighboring numbers; they are known to be 2, 8, 20, 50, 82 and (for neutrons) 126. For example, lead ^{208}Pb (Z=82, N=126) is an especially stable "doubly-magic" nucleus.

As for the magic proton number in the superheavy region, it remains uncertain whether Z=114 or Z=126 is more stable with respect to fission. However, we are certain that the half-lives of superheavy nuclei are significantly reduced by alpha-decay. It determines the stability of nuclei around ^{300}120, on which current efforts towards new superheavy element synthesis are focused.

Delaying decay?

Might it be possible, therefore, to obtain superheavy isotopes with a structure that slows down fission and alpha-decay? Of particular interest would be half-lives of several seconds or even minutes, since this would make it possible to analyze the chemical properties of individual radioactive atoms; for example, groundbreaking research on flerovium (Z=114) conducted between 2007 and 2012 indicates that its properties fall somewhere between those of a metal and a noble gas. We know that fission is slower for odd numbers of nucleons. On the other hand, alpha-decay is delayed by differences in structure of parent and daughter configurations, resulting either from their very different deformations or a different angular momentum coupling of nucleons. It turns out that many models predict both effects for nuclei Z=119, 120, N=165, 166 (taking the shape of a flattened spheroid with axis ratio 3:2 and prolate spheroids for the alpha-daughter nuclei) and the angular momentum coupling effect around Z=109, N=163. Synthesis of the former nuclei is currently impossible, while it may be possible to verify the half-lives of the latter experimentally.

We have also studied whether it is possible for more stable nuclei with $Z>126$ to exist. We have discovered that the results are strongly dependent on the model. In models in which 126 is a magic number for protons, it may be possible for odd-Z and/or odd-N nuclei around Z=134, N=228 with a flattened spheroid shape to have measurable half-lives. Unfortunately, no one currently has any idea how to go about creating such heavy systems. Previously suggested stable systems with unusual density distributions of $Z\approx500$ and above seem equally impossible to verify at present.

It may be that the heaviest element that can be created and identified will simply be limited by our synthesis techniques. Synthesis of element Z=120 will require a projectile heavier than ^{48}Ca (as fermium cannot be used as a target), and such reactions have thus far proven fruitless. Still, perhaps Mother Nature has a surprise in store for us. ■

Further reading:

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