

Elements of the Future

by Kit Chapman

When Dimitri Mendeleev assembled his periodic table in 1869, the heaviest known element was uranium, element 92. As the table filled, it soon became clear that this was the heaviest element that existed in large quantities on Earth. But it was far from the limit of the building blocks of matter.

For more than 80 years, scientists from across the world have repeatedly pushed past the boundaries of the known periodic table. In doing so, they have replicated nuclear processes usually only found in supernovae or stellar collisions, stretching our known world to 118 elements.

Yet this is only the beginning of what may be possible. As we have honed our knowledge of nuclear physics, the number of predicted elements has swelled. John Wheeler suggested element 100 would be the final piece of the jigsaw; physicist Richard Feynman famously suggested 137. In truth, we have no idea where the periodic table will end. The best guess is that there could be 172 or 173 elements—which would mean we are still yet to discover a third of our chemical universe.

Neutron capture

An element is determined by the number of protons in its nucleus. In theory, to create a heavier element, all you need to do is collide two sets of protons into each other and hope they fuse into a new, heavier nucleus. Unfortunately, this isn't so easy in practice. As protons are positively charged, electrostatic repulsion forms a barrier that prevents them being combined easily.

There are two main methods of overcoming this problem. The first is neutron capture, which involves bombarding a target with neutrons in the hope that these will hit an atom's nucleus. Usually, if a neutron does strike home this results in the nucleus becoming unstable, and simply exploding in atomic fission. Rarely, however, the neutron will be captured by the nucleus and, through beta radioactive decay, a neutron will turn into a proton and move the atom one place up the periodic table.

The first attempts to break past uranium were littered with missteps. In 1938, Enrico Fermi was awarded the Nobel prize for the discovery of elements 93 and 94 using neutron capture. Two months later, a group led by Lise Meitner and Otto Hahn showed that Fermi's supposed elements were the by-products of atomic fission—an idea predicted by Ida Noddack right after Fermi first made his announcement, but subsequently overlooked. Soon after, both Yoshio Nishina at RIKEN

in Japan and Edwin McMillan at the University of California, Berkeley, US, probably saw signs of the true element 93. Nishina was unable to prove it, while McMillan was dissuaded of the discovery by his colleague Emilio Segrè, who went so far as to publish a paper: *an unsuccessful search for transuranic elements* [1].

A year later, McMillan sought a second opinion from colleague Philip Abelson, who soon confirmed the discovery as genuine. Neptunium, element 93, blew the lid off the top of the periodic table, and almost immediately lead to the discovery of element 94, plutonium. With Fermi's help, the first nuclear reactors were built to form cauldrons for neutrons to collide with uranium rods and scale-up the production of plutonium a billion times, enabling its use in the first nuclear weapon.

The neutron capture process can be used to make ever-heavier elements, gradually moving one place up the periodic table with each successful beta decay. But the technique has diminishing returns: as fission is more probable than neutron capture, the odds rapidly stack against you. Today, even specially designed reactors, such as the High Flux Isotope Reactor at Oak Ridge National Laboratory, US, cannot produce large quantities of anything beyond californium, element 98. Indeed, einsteinium and fermium, the heaviest elements first discovered from the results of neutron capture, weren't made in a lab—they were scooped up by fighter planes flying through the debris of the first hydrogen bomb test in 1952, a blast so vigorous it produced some 10^{24} neutrons per cm^2 . While the idea of setting off nuclear explosions in series has been considered as a way to make future elements, fortunately there is an easier and less destructive option.

Transfermium wars

Past fermium, all elements are made a single atom at a time by smashing nuclei together in a particle accelerator. Ions of a lighter element are fired at high speed toward a target with enough energy to overcome the electrostatic repulsion and cause the two nuclei to fuse together. Once again, this usually results in fission—the energy is too great and the nucleus breaks apart. But, occasionally, the nucleus will stabilise. Today's accelerators fire around six trillion ions a second at their targets, with their operators hoping to make around one atom a week.

As these newly created elements are highly unstable, they can only be detected by the tell-tale radiation as they emit alpha particles (two protons, two neutrons) and decay into lighter elements or break apart in fission. By plotting the timing of these alpha particle emissions against the half-lives of known isotopes,

the existence of an element can be proven beyond doubt.

This isn't without problems. Throughout the Cold War, teams from the US and the then-USSR disputed the discovery of elements up to 106, leading to the so-called 'transfermium wars'. For a period of around 40 years, the world effectively had two periodic tables, depending on whether you accepted the Russian or US names. During the 1990s, this resulted in a series of proposed names to try and bring the sides together—the most controversial of which was seaborgium, after US chemist Glenn Seaborg, who was still alive at the time.

Fortunately, such disputes are now in the past, and in collaboration IUPAC and IUPAP have put together guidelines both on what constitutes proof of an element discovery [2] and how an element's name is chosen to prevent any arguments [3]. Any new element must be named after a mineral; property of the element; place; mythical creature or scientist. Sadly, this means the most-requested element name of all time—lemmium, after the lead singer of heavy metal band Motörhead—will never sit on the periodic table. (Unless, of course, you argue that Lemmy is a rock god!)

Hot and cold

When it comes to creating elements through fusion, the choice of beam and target matters. There are two techniques that have proved successful for the heaviest elements. Elements 107 to 113 were discovered by teams in Germany and Japan using 'cold fusion'—combining two elements relatively close together on the periodic table, using just enough energy to squeeze past the electrostatic repulsion. This becomes increasingly difficult as elements get heavier, resulting in greater time between successful hits. The Japanese team that discovered nihonium, for example, needed a cumulative 553 days of beam time spaced across nine years to make three atoms. Cold fusion is simply not a practical option for discovery anymore.

Instead, the current technique used to discover new elements is called 'hot fusion'. Pioneered by a collaboration led by Yuri Oganessian at the Joint Institute for Nuclear Research in Dubna, Russia with Lawrence Livermore National Laboratory, US, this relies on using a relatively light element and firing it into a heavier radioactive target. Neutron-rich isotopes are used so that

neutrons are jettisoned during the reaction, reducing the energy in the nucleus in a hope that this will prevent fission.

An ideal beam for this kind of reaction is calcium-48, which was fired into targets made from plutonium to californium (94 to 98) for the final five elements discovered so far. Calcium-48 has eight extra neutrons compared with the element's most common isotope, a property ideal for hot fusion reactions. It is also 'doubly magic', having complete shells of both neutrons and protons in its nucleus, making it exceptionally stable.

Unfortunately, calcium-48 can't be used to go beyond element 118. Such an experiment would require a target made from einsteinium or higher, which currently can't be produced in significant quantities. This means an alternative beam must be used, which is likely to have a much smaller probability of a successful reaction. Nobody is entirely sure which alternative will work best.

Currently, two teams are in the hunt for the next element. In the red corner, the Dubna-Livermore collaboration will be using a titanium beam to hunt for the next elements using their state-of-the-art Superheavy Element Factory—a new cyclotron accelerator that promises to produce the superheavy elements in greater quantities than ever before. In the blue corner, the team at RIKEN in Japan are using a vanadium beam, and have secured funding to keep searching for the new elements until they are successful.

The most optimistic predictions from the superheavy element community predict that the first glimpses of these two new elements will emerge in the next five years. After that, no one is sure when the next element discovery will come. There is no obvious route



Images Credits, see page 3.



to make element 121 and, until we do, we won't know where it's likely to go on the periodic table—or if the periodic table still applies at all.

The end of periodicity

It's easy to ask why this hunt matters. While some transuranic elements have found important uses—plutonium in power, americium in smoke detectors, curium in medicine—none of the elements beyond californium can be produced in large enough quantities to have practical applications. Why should we care about elements that exist for a split second? Nor is such a hunt cheap. Even ignoring the vast expense of a particle accelerator's operating and staffing costs, one gram of calcium-48 costs around \$200,000. An accelerator uses 0.5mg an hour.

The answer is that these elements unlock fundamental rules of our universe, often in a way that doesn't correspond to expectations. Before the discovery of americium in the 1940s, no one imagined that the actinides would exist: uranium sat under tungsten on the periodic table. Today, physicists argue where element 121 is likely to end up on the periodic table or what its electron configuration may be – does it form a 'superactinide' series or something else entirely? Until we make it, there is simply no way to know for certain.

These aren't purely theoretical discussions. The properties of an element can also be dramatically different than predicted thanks to relativistic effects—alterations in an element's predicted properties due to the theory of relativity, such as gold's colour or mercury's low melting point. These relativistic effects become more pronounced as the elements become heavier, drifting away from periodicity. Current predictions, for example, suggest that oganesson, supposedly a noble gas with filled electron shells, is a reactive solid at room temperature – and may not even form shells at all, but rather carry its electrons around in a Fermi gas [4]. If this is the case, the very structure of the periodic table is called into question.

Sadly, the unstable nature of the superheavy elements makes experimentation difficult, so only the most basic tests can be performed. Even so, one-atom-at-a-time chemistry is possible and has provided a valuable insight into these transient creations. Seaborgium, for example, has been shown to form a hexacarbonyl complex, in line with its homologues tungsten and molybdenum [5]. Flerovium, meanwhile, has been found to be more contentious: while some results suggest it is inert compared with its supposed homologue lead, other findings have hinted at it behaving more like mercury. Currently, researchers are investigating

its properties in rapid experiments, such as capturing the atoms in thiocrown ether rings or passing the atom down a temperature gradient dotted with gold-plated arrays to calculate its enthalpy of sublimation. These experiments will give us a better understanding of the mechanics at work inside the atom.

Finding the island

While these chemical questions are important, the true prize of superheavy element research is the fabled 'island of stability'. First put forward in the 1970s, this idea suggests that isotopes exist with magic numbers of protons and neutrons that could have radioactive half-lives of thousands, perhaps even millions of years.

The best bet for such an island is around element 114, flerovium. Already, the longest-lived isotope known, flerovium-290, is believed to have a half-life of some 19s—far higher than its neighbour moscovium-290's 650ms. However, the centre of the island is predicted to be around flerovium-298. Currently, we are still only on the shoals of stability—and, once again, researchers are stuck. There's no easy way to synthesise such a neutron-rich isotope.

Even so, the long half-lives of flerovium give heavy element scientists hope. If such a long-lived isotope does exist, it is possible it could be found on Earth. Since the 1970s, teams from around the world have looked in some strange places, from the depths of the San Francisco mass transit system and stained-glass windows of Russian churches to moon rocks and the brine shrimp of the Indian oceans. So far, there has been no sign of the elusive superheavies in nature.

As we predict superheavy elements exist in neutron star collisions, researchers have also turned their eyes skywards. Meteorites are so-called 'messengers from space', flying through the cosmos as handy detectors. When something impacts a meteorite, it often leaves a trace in crystals such as olivine. By measuring the depth of these impacts, we can determine what collided with the meteorite. The hope is that eventually one of these olivine traces will show signs of superheavy elements in nature—and, once again, help to hone our understanding of the world we live in. 🌌

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Elements of Stars (cont. from page 11)

continued from page 11

Together, these different processes in different types of stars determine the chemical evolution of galaxies (Figure 3). The next generation of stars forms out of matter of a different composition, depending on the time and place of their birth, and on the full history of their host galaxy. One of the aims of current large (millions of stars) stellar surveys with high-resolution spectroscopy is to derive such chemical diversity and exploit it to understand the formation and history of galaxies within a cosmological framework.

Far-reaching implications

The chemical fingerprints left by the nuclear reactions that take place in stars provide us the opportunity not only to answer the questions of what are stars made of and where the chemical elements come from, but also to study the evolution of the cosmos in a huge range of scales. Observations of the chemical composition of the oldest stars provide us with a glimpse into the early Universe and analysis of the chemical signatures of stellar populations can tell us how galaxies formed.

Closer to home, investigating and interpreting the composition of meteoritic materials and the signature of the nuclear processes left there by different types of stardust provide us with insights on how our own Solar System formed. For example, we now know that the Earth is roughly $1/10^4$ times richer in nuclei produced by the s process in giant stars than Solar System bodies that formed further away from the Sun (Poole *et al.*

2017). How this tiny but robust difference came about in the solar proto-planetary disc is a matter of debate. It represents one of many current questions whose answers allow us to use the chemical elements in stars to understand the evolution of the cosmos, from the Big Bang to life on habitable planets. 🌌

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