IN APRIL, the Israeli scientist Amnon Marinov announced that he had glimpsed a mysterious island. It was something that he and many rival explorers had long been seeking - but few of those rivals were prepared to accept that he had really found what he said he'd found. Yet if he is right, physicists may have to reconsider what they know about the outer limits of matter.

What Marinov of the Hebrew University of Jerusalem and his colleagues claim to have discovered is a monstrous atom with by far the heaviest nucleus ever seen, packing a whopping 122 protons and 170 neutrons. Crucially, the team had not synthesised it in the lab, but found it in nature, in a sample of purified thorium. The discovery implied that the element had a half-life of no less than 100 million years (www.arxiv.org/0804.3869).

Had his team finally stumbled upon the fabled "island of stability" - a region populated by superheavy atoms that is widely believed to exist beyond the outer reaches of the periodic table? Possibly, but a key problem for Marinov's atomic giant is that 100-million-year half-life. "It couldn't be shorter or we wouldn't see it," he explains. This is incredibly long for such a massive element, and goes against the theoretical grain. No wonder his claim has been viewed with scepticism.

The island of stability is no flight of fancy, though. It is predicted by well-established theory, the same theory that casts doubt on Marinov's claim. By smashing atomic nuclei together, some of the rival teams have synthesised elements just a handful of protons short of Marinov's purported record-breaker. Step by step, they just might reach their goal. "People have always been interested in this problem, especially the limits of the material world's existence," says Yuri Oganessian of the Joint Institute of Nuclear Research (JINR) in Dubna, Russia.

Leaving aside Marinov's possible find, the heaviest known naturally occurring element is uranium, with an atomic number of 92 - the number of protons in its nucleus. In 1941, Nobel prizewinner Glenn Seaborg and his team at the University of California, Berkeley, synthesised the first element heavier than uranium by bombarding it with neutrons. The new element had an atomic number of 94 and was named plutonium. Subsequently, Seaborg made significant extensions to the periodic table, predicting several more elements heavier than uranium. His team went on to synthesise a total of 10 so-called transuranium elements, culminating in 1974 with what was eventually named seaborgium, atomic number 106.

Superheavy monsters

Since then, others have taken on the challenge of making "superheavy" elements (anything with an atomic number of 104 or more qualifies as superheavy). This is more than just an exercise in machismo: pushing the boundaries of matter puts theoretical models of atomic structure to the test.

When Seaborg started his work on transuranium elements, the accepted theory of the nucleus was the "liquid drop model", developed by Niels Bohr and John Wheeler. This envisaged the nucleus as a drop of charged liquid whose surface tension counteracted the mutual repulsion of the protons within, keeping the nucleus stable. In the 1960s, however, researchers at JINR showed that the lifetimes of some isotopes of the transuranium elements were orders of magnitude less than that predicted by the model, so it fell by the wayside.

The liquid drop model has now been replaced by another model in which protons and neutrons populate discrete energy levels, or "shells", within the nucleus, much as electrons exist in shells around it. Each shell has a maximum number of protons and neutrons it can hold. For protons, the capacity of the first shell is 2, followed in turn by shells containing 6, 12, 8, 22, 32 and 44. Neutrons are thought to exist within an identical framework. Crucially, the model shows that when a nucleus has a full complement of protons or neutrons in its outer shell, it is highly stable, and even more stable if it has a full complement of both types of particle. For example, an oxygen nucleus is extremely stable because it contains 8 protons and 8 neutrons, which means its outer shell is full, containing 6 protons and 6 neutrons. As a result of all this, the numbers of protons and neutrons that lead to full shells have been dubbed the "magic numbers". They are 2, 8, 20, 28, 50, 82 and 126 (due to a modification in the theory to account for the effects of huge nuclei, the proton numbers of 114 and 120 are also considered magic).

This model successfully explains why some heavy-ish elements are unstable, such as the highly radioactive polonium (atomic number 84), while their neighbours on the periodic table, such as lead (82), are not. It's because lead is magic. In fact, strictly speaking, it's doubly so: its most stable isotope, lead-208, has a magic number of both protons (82) and neutrons (126). Change the number of neutrons and you get a different isotope of lead, which is not doubly magic any more and therefore less stable.

Another prediction of the shell model is the existence of long-lived superheavy elements - the island of stability - amidst a sea of unstable elements (see diagram, page 34). These elements should have magic numbers of protons and neutrons that lend stability to an otherwise shaky ensemble.

According to the theory, the next doubly magic element will have 114 protons and 184 neutrons. Hot on the trail is Oganessian's team. Along with colleagues at the Lawrence Livermore National Laboratory (LLNL) in...
California, the team has pioneered the synthesis of atoms heavier than seaborgium. So far, they have made elements with atomic numbers 113, 114, 115, 116 and 118—the heaviest made to date. But because these elements have only 173 to 177 neutrons, far fewer than the magic number 184, they are incredibly unstable with half-lives from fractions of a millisecond to a few seconds. Still, the researchers are mastering the techniques that could help them reach the island of stability.

The procedure involves bombarding certain heavy elements with a beam of lighter “naked” nuclei—atoms with their electrons stripped away—in the hope that they might fuse into a new element. The key is to use nuclei for the beam that have just the right number of protons to form the superheavy element you want. For example, element 118 was formed by fusing californium, which has 98 protons, and calcium, which has 20.

It’s a fiddly and laborious procedure. The beam has to have just the right amount of energy to encourage fusion with the target. If the atoms have too little energy, electrostatic repulsion between the two atomic nuclei causes them to ricochet apart. Use too much energy and the resulting combined nucleus is overexcited and unstable. “The probability of fusing a beamed particle with one of the target nuclei is extremely small,” says LLNL team member Dawn Shaughnessy. Experiments can last for months, and produce as little as one superheavy element per month. “But one atom is all that’s needed to confirm the existence of a new element,” she says.

Despite the difficulties, the race is on to synthesise element 120 (which should be easier than 119). Shaughnessy’s challenge is to produce the exotic materials required for the beam and the heavy target atom. One reason the joint Russian-US team successfully synthesised element 118 is their use of the very rare and expensive isotope calcium-48. This doubly magic isotope has 20 protons and 28 neutrons, which also makes it unusually neutron-rich for such a light element. That’s important, because when synthesising a superheavy element you need all the neutrons you can get. Something like element 118 needs 184 neutrons to reach its peak stability. Nevertheless, Shaughnessy reckons calcium-48 may have outlived its usefulness. “We have basically run out of reactions using the calcium-48 beam, so we are now trying to develop new beams, such as iron,” she says.

Combine a beam of iron nuclei with a plutonium target, and element 120 could be within reach. However, this is not any old plutonium. It has to be plutonium-244, an extremely rare and extraordinarily stable isotope. “We currently have what amounts to the world’s supply of plutonium-244,” says Shaughnessy. This highlights the challenge of synthesising superheavy elements: researchers are being forced to use exotic elements such as curium, americium and californium, which themselves have to be made in the lab.

Meanwhile, theoreticians are investigating just how stable some of these superheavy elements are. Early this year, Partha

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**THE OUTER REACHES OF MATTER**

Nuclear physicists are extending the periodic table way beyond the heaviest naturally occurring element, uranium (atomic number 92), edging ever closer to the fabled "island of stability"—a region of extraordinarily long-lived monster atoms (right).
Atomic needle in a cosmic stack

If superheavy elements really exist with half-lives in the order of thousands or millions of years, could they be lingering right under our noses here on Earth? "It cannot be excluded, in theory, though it seems rather unlikely," says Yuri Oganesian of the Joint Institute of Nuclear Research in Dubna, Russia. His team has been trying to find hassium, element 108, in samples of natural osmium. They haven't found any natural hassium yet, and it may take years to do so.

Indeed, research since the 1950s has failed to find any signs of superheavy elements from either cosmic or terrestrial sources. This might be because they simply cannot be created through natural processes, says David Hinde, a nuclear physicist at the Australian National University in Canberra. Even the high pressure and temperature in exploding stars—which can form elements as heavy as uranium—may not be capable of creating a superheavy element. The problem is working out how to jam enough neutrons into a heavy nucleus to get to the magic number of 184 without the nucleus undergoing fission first. "It's a bit of a stretch," Hinde admits.

Perhaps the only place these fleeting superheavy elements exist in the entire universe is in nuclear physics labs on Earth.

Chowdury and Chhanda Samanta of the Saha Institute of Nuclear Physics in Kolkata, India, modelled the stability of 1700 isotopes of superheavy elements, with atomic numbers from 100 to 130 (Physical Review C, vol 77, p 044603). Their calculations confirm that a smattering of superheavy elements should be stable enough to resist spontaneous decay for long periods, some for up to hundreds of thousands of years.

But not for millions of years, so it's little wonder that Marinov's claim for element 122, with a half-life of at least 100 million years, raised eyebrows, if not hackles. However, it was not just the claims of a half-life that drew fire; the experimental technique was also criticised. Marinov's team ran a purified solution of natural thorium—atomic number 90, atomic mass 232—through a mass spectrometer, which measures the mass of individual atoms. Besides thorium, the team saw a handful of atoms that had much greater mass, just over 292. Marinov's team ruled out contamination and said that what they found was element 122 with 170 neutrons, or possibly element 124 with 168 neutrons.

A handful of counts in a mass spectrometer is not enough to prove the existence of such a massive atom, argues David Hinde, a nuclear physicist at the Australian National University in Canberra. Furthermore, he says: "Our extensive current understanding of nuclear physics cannot accommodate a lifetime of 100 million years for any configuration of element 122. However, if compelling evidence were found, of course we would have to look for holes in our knowledge. But the evidence is not compelling."

Marinov's experiment aside, Chowdury's and Samanta's calculations show that superheavy elements might be stable for hundreds of thousands of years, which will encourage others to keep looking for element 120 and above.

Quantum spanner

If that task was not hard enough already, quantum mechanics also throws a spanner in the works: even if a superheavy nucleus can resist spontaneous decay for hundreds of thousands of years, there is a second way it could fall apart long before then.

It's easy to picture the protons and neutrons sitting firmly in their atomic shells in precise locations, but quantum mechanics tells us things are not so clear-cut. In fact, the position of any one proton or neutron is better represented by a cloud of probable locations. And sometimes, particularly with large atoms, this cloud will move beyond the "boundary" of the nucleus. When this happens, there's a chance that a proton or neutron will escape—effectively "tunnelling" its way out.

This quantum tunnelling effect is responsible for the radioactive alpha-decay of heavy atoms, where they emit two protons and two neutrons (a helium nucleus) and slip two slots down the periodic table in the process. So while a superheavy atom might resist spontaneous decay for millennia, as Chowdury and Samanta suggest, it may nevertheless undergo alpha-decay within microseconds. This makes it extremely unlikely that we'll find stable superheavy elements in nature (see "Atomic needle in a cosmic stack", left).

Nevertheless, hope remains that it will be possible to synthesise one or more of them. One candidate that might last long enough for chemists to play with it is a potential isotope of darmstadtium, element 110, with a magical 184 neutrons. This is predicted to have a half-life of over 300 years. However, no one is close to synthesising darmstadtium with so many neutrons. The heaviest isotope created so far is still 19 neutrons short and has a half-life of just 11 seconds.

If a superheavy element does get synthesised with a long enough half-life to study its chemistry, what could we expect? Definitely something unusual. The huge positive charge of the extremely large nucleus would accelerate the electrons around it to speeds approaching the speed of light, radically skewing the element's chemical properties. This effect explains why mercury is liquid at room temperature: it weakens the bonds between atoms thus lowering the melting point. And the bigger the nucleus, the faster the electrons go and the stronger the effect. Some predictions suggest that element 114 would be a gas rather than a solid.

According to Shaughnessy, a shortage of neutron-rich nuclei beams and targets is currently the biggest practical barrier to synthesising long-lived superheavy elements. "We may get to a point where we just don't have the materials to get there, but all the theorists tell us we would be able to see something that at least lasts longer than what we have now."

If they do manage to solve the technological problems, can the researchers keep creating heavier and heavier matter? Is there an end in sight to superheavy elements? "At some point, the repulsion between the protons in the nucleus will be so high that no number of neutrons will be able to make it exist, even for a fraction of a second," says Shaughnessy.

Oganesian is more emphatic. "Of course, there is an end, as there is an end in everything," he says. But it may yet take decades of diligent effort to find the last island of stability in the turbulent sea of matter. •

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