NEWS FEATURE

EXTREME ATOMS

Physicists are stretching, stripping and contorting atoms to new and bizarre limits.

BY RICHARD VAN NOORDEN

One way to obliterate an atom is to shoot it with the planet's most powerful X-ray gun. Linda Young tried that experiment in October 2009, when she was testing the newly opened X-ray free-electron laser at the SLAC National Accelerator Laboratory in Menlo Park, California. A single pulse from the US$420-million machine packs the same energy as all the solar radiation hitting Earth at that moment, but focused down to one square centimetre. "It will destroy anything you put in front of it," says Young.

When the laser pulse slammed into the neon atoms in that experiment, it made them explode, stripping away each atom's 10 electrons within 100 femtoseconds (1 femtosecond is 10^{-15} seconds). But it was the manner of this destruction that most interested Young, who heads the X-ray science division at Argonne National Laboratory in Illinois. The X-rays first removed the atom's inner electrons, leaving the outer ones in place. For a brief moment, the neon atoms in the path of the laser became hollow.

That exotic form of neon is one of a number of strange species created by physicists intent on contorting atoms. Some teams have inflated atoms to the size of dust particles. Several research collaborations are creating anti-atoms out of antimatter. And others have loaded atomic nuclei with protons and neutrons in the quest to forge new superheavy elements. Some of the experiments aim to investigate atomic structure; others use atoms as the first steps in modelling more complicated systems. They are all descendants of the revolution in atomic theory catalysed by Danish physicist Niels Bohr 100 years ago. But Bohr would have had difficulty imagining how far scientists could go in poking and prodding atoms into such extreme forms.

ILLUSTRATIONS BY THOMAS POROSTOCKY

Hollow atoms

The atom that Bohr proposed[1] in July 1913 looked like a miniature Solar System, with electrons arranged in concentric orbits around a positively charged nucleus. In Bohr's model, electrons were point-like particles that were quantized, meaning that they could jump from one orbit to another but could not exist in between. The advent of quantum mechanics in the 1920s retained the concept of orbits but re-imagined electrons as spreading everywhere around the nucleus. The location of each electron can be described only in probabilities, in the form of a mathematical wavefunction.

Electrons furthest from the nucleus can be kicked free with the least amount of added energy, so are usually the first to be stripped away. Yet X-rays, which pack a concentrated punch, can remove more tightly bound electrons from inner orbits. A medical X-ray takes out just one of those inner electrons before another from an outer shell drops down to fill the space. But the SLAC X-ray laser is in a class by itself. The beam is so intense and focused that every 100-femtosecond pulse sends 100,000 X-ray photons flying past each square ångström of space (1 ångström is 10^{-10} metres). That allowed Young to blast away all the inner electrons of the neon atoms in her 2009 experiment[2]. When electrons from the outer shells dropped into the abandoned inner shells, the beam soon kicked those out as well.

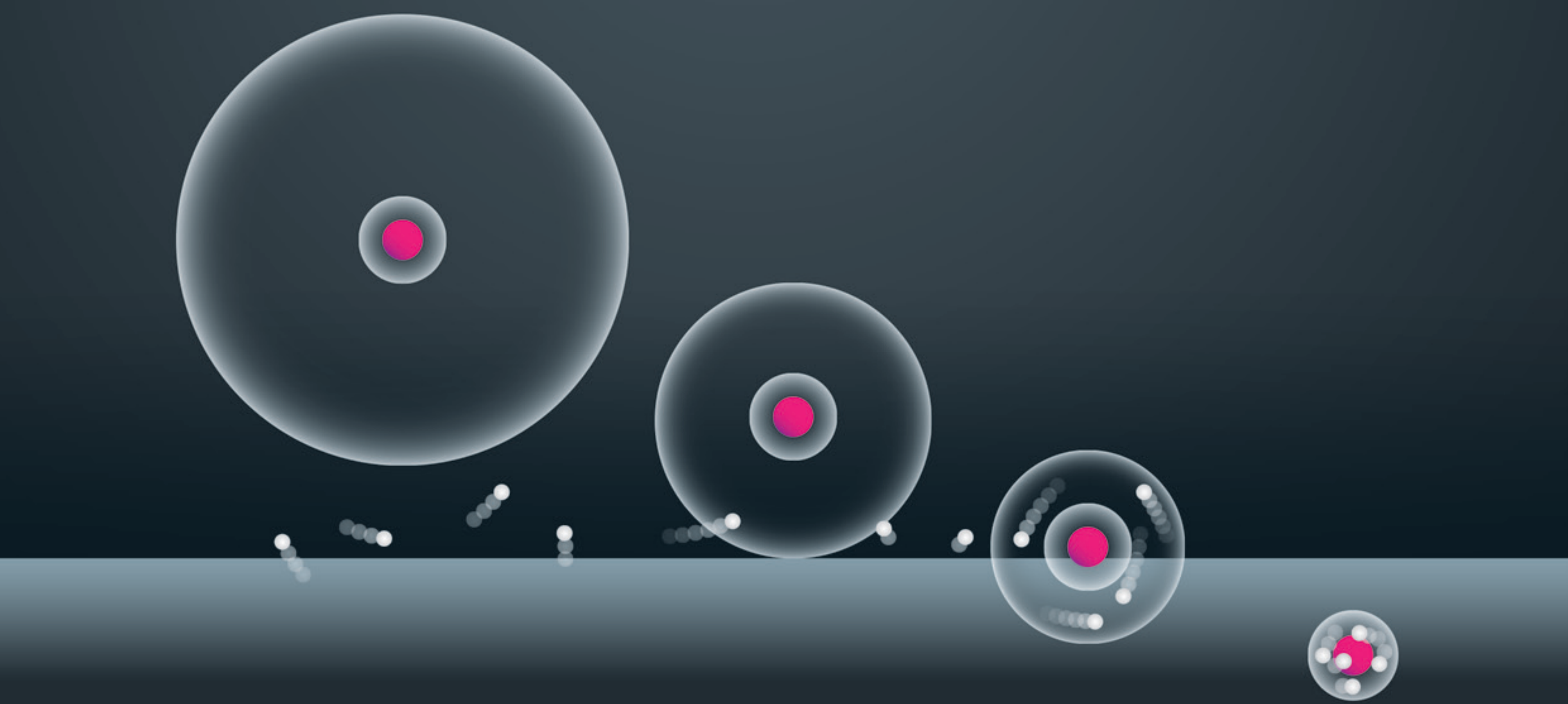
"If you tune your X-rays properly, you can pick which shell you want to empty out first," says Young. "Being able to control the inner-shell dynamics is very cool." The current record for this kind of atom-hollowing was reported last November[3] by a group at the Center for Free-electron Laser Science in Hamburg, Germany, which used the SLAC laser to strip away, from the inside out, the 36 inner electrons of a 54-electron-strong xenon atom.

Young hopes that research on hollow atoms will prove helpful when the laser is ready for one of its intended uses — creating images of biological molecules such as DNA and proteins by scattering X-rays off their atoms. Those pictures come at a price: the beam quickly destroys the molecules it is imaging. Knowing how hollow atoms form during this process may help researchers to interpret how the scattering pattern changes as a molecule explodes, Young says.

Two decades ago, several research groups made hollow atoms using a different process: first stripping almost all of the electrons from atoms, then depositing the resulting highly charged, slow-moving ions onto a surface. When the ions were a few tens of ångströms away from the surface, they attracted electrons from it, creating momentarily hollow atoms with electrons in outer but not inner shells. Those outer electrons then fell inwards, and the hollow atoms expelled a burst of energetic electrons and photons. "A hollow atom is nothing but a fireball of an enormous amount of energy," says Joachim Burgdörfer, a physicist at the Vienna University of Technology, who worked on developing the theory of the process[4].

Several research groups pursued hollow atoms in the late 1980s and 1990s, with some scientists exploring how the burst of photons from their formation might clean surfaces by removing the topmost layers without doing deeper damage. Although that procedure has been patented, it has not captured the attention of industry, says Fritz Aumayr, a physicist at the Vienna University of Technology. The closest it has come to an application so far was in 2008, when researchers invoked the process to explain how heavy ions spewed from the Sun can damage the surfaces of planets such as Mercury[5]. The ions become hollow atoms as they drop onto the planet, and release bursts of energy as they land.

This year, Aumayr published a paper[6] showing that the energy expelled from ions dropping onto carbon membranes can create nanoscale pores whose size is controlled by the strength of the ion's charge (that is, how many electrons it was missing). That might be a useful route for making nanosieves for filtering small molecules, he says, or for creating nanopores to pass DNA through for sequencing.



Giant atoms

From the perspective of an atomic nucleus, all electrons are far-flung voyagers. Whereas a nucleus measures femtometres in diameter, a bound electron typically travels 100,000 nuclear diameters away from the core. But Rydberg atoms, the colossi of the atomic world, have outer electrons so pumped with energy that they can travel 100 billion nuclear diameters — tens or hundreds of micrometres — from their nucleus. The largest Rydberg atoms even approach the size of the full stop at the end of this sentence.

Named after nineteenth-century Swedish physicist Johannes Rydberg, these giant atoms have been studied extensively since the 1970s, with the introduction of lasers that could excite electrons out to such vast distances. Like any distant traveller, the outer electron in a Rydberg system can be lonely and vulnerable. The attraction to the distant core is faint and easily disturbed by stray electromagnetic fields or collisions, so the atoms must be created in high vacuum. If carefully isolated from outside forces, such inflated atoms can be maintained for anything from a few hundredths of a second up to multiple seconds.

For Barry Dunning, a physicist at Rice University in Houston, Texas, the joy of Rydberg atoms is that they give physicists exquisite control over the motion of an electron. That is not possible with normal atoms because the electrons move much too quickly for even the fastest lasers. But the motion of an inflated electron in a Rydberg atom is much slower: it can be controlled with carefully directed nanosecond electric-field pulses, which allow researchers to herd the electron cloud by knocking it back and forth.

In 2008, researchers led by Dunning reported[7] that they had managed to squeeze the normally spread-out electron into a tight packet that briefly orbited the nucleus. Last year, they added radio waves that enabled that motion to be maintained indefinitely[8]. "It only took a century, but we recreated Bohr's atom," says Dunning proudly. His next idea is to try exciting and controlling two outer electrons at once, creating a system analogous to how Bohr might have pictured helium.

This kind of atom-stretching has some potential applications. Two gaseous atoms a few micrometres apart cannot normally affect each other. But inflate one (or both) to a Rydberg state, and the negatively charged electron clouds start to repel each other, distorting the energy levels of the atoms so that they are no longer isolated systems. Mark Saffman, a physicist at the University of Wisconsin-Madison, has used this property to make a quantum logic gate[9] — a fundamental part of a quantum computer — with lasers switching on a Rydberg interaction between two atomic quantum bits, or qubits.

He and other researchers hope next to add more atoms. A cloud of cold gas atoms might, if suitably excited, create a kind of hovering crystalline array of Rydberg interactions, says Matthew Jones, a physicist at Durham University, UK.

That approach might prove a useful model for studying the physics of 'strongly correlated' solid-state systems. These are systems, such as high-temperature superconductors, in which unusual properties emerge because particles interact strongly with their neighbours. An array of Rydberg atoms would not be a perfect model for the messy interactions in real solid-state systems, but the simplicity of the approach is a strength, says Burgdörfer. "It's a wonderful testing ground for probing many of these ideas about how strongly correlated physics actually works," he says.

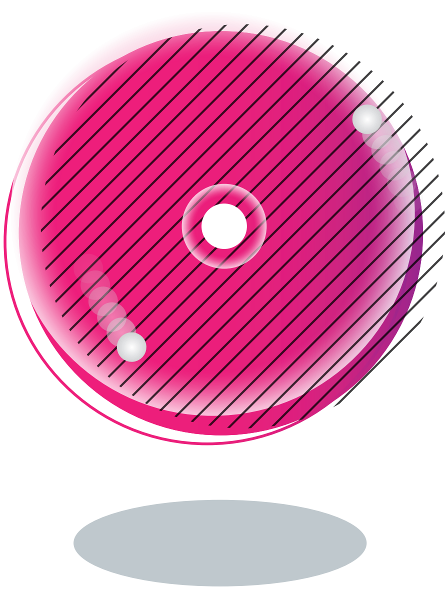
Antimatter atoms

The Large Hadron Collider at CERN, Europe's particle-physics lab near Geneva, Switzerland, currently lies in pieces, with engineers working on boosting its power. At the same time, in a side hall, an upgrade is taking place to an experiment that may allow physicists to measure the properties of atoms of antimatter.

It is a goal that researchers have been chasing since the first antihydrogen atoms were made at CERN in 1995. An antihydrogen atom consists of an antiproton and a positron, which respectively have the same mass as an ordinary proton and electron, but opposite charge. Beyond that, researchers know very little about antihydrogen. "Do matter and antimatter atoms obey the same laws of physics?" asks Jeffrey Hangst, spokesman for ALPHA, one of the collaborative efforts to make and analyse antihydrogen.

The experiments at CERN might also help to explain why there is more matter than antimatter in the visible Universe. The Big Bang should have created equal amounts of the two that would have annihilated on contact. But somehow, matter gained an advantage. Differences have been observed between the behaviour of some matter and antimatter particles, such as kaons and mesons, but these are far too small to explain the Big Bang conundrum.

To create antihydrogen atoms, researchers at CERN first make antiprotons by bombarding atoms with accelerated protons, then slow them down by passing them through metallic foil, cool them with cold electrons and trap them with electromagnetic fields. A similar trap accumulates positrons that are emitted by radioactive materials. When the clouds of charged particles are mixed, they make neutral antimatter atoms. But because these have no overall charge, in early experiments they easily escaped the electromagnetic fields



used to trap the charged antimatter particles.

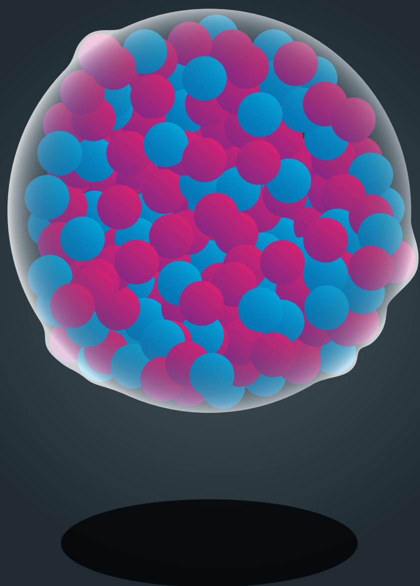
By 2002, two collaborations had been able to make as many as 50,000 atoms of antihydrogen, but the atoms quickly annihilated on the walls of their container. It took until 2010 before researchers at ALPHA showed[10] how to trap the atoms using three magnets with a combined field sufficient to restrain antihydrogen, with its tiny magnetic moment. At that time, the antimatter was held for just 170 milliseconds, and only about one atom was trapped for every eight times the group ran the 20–30 minute experiment, says Hangst. But the team has improved its equipment to trap one atom per experiment, and hold it for about 1,000 seconds.

ALPHA is now trying to probe the properties of the anti-atoms. This year, the team reported[11] watching the tracks of hundreds of antihydrogen atoms after they were released from their magnetic cage, to test whether antimatter falls up or down under gravity. The researchers do not yet have an answer, but the experiment works in principle, says Hangst. And in the upgrade, the team is moving in some lasers, with the idea of testing next year whether antihydrogen absorbs and emits light at the same frequencies as hydrogen.

Other teams at CERN are experimenting with different aspects of antimatter, such as how antihydrogen responds to changing magnetic fields. And researchers elsewhere are looking at even more exotic atoms: Ryugo Hayano, a physicist at the University of Tokyo, leads a team studying mixed matter–antimatter atoms, such as antiprotonic helium, in which a helium nucleus is surrounded by one electron and one negatively charged antiproton, an arrangement that lasts for a few microseconds.

In the end, such experiments may not find differences between matter and antimatter that are big enough to explain why the former has prevailed over the latter. But, says Hangst, "one never knows where the new physics might show up. You just have to keep looking."

Heavy atoms



Anti-atoms are rare, but researchers working with them are swimming in data compared with those chasing superheavy atoms. In an experiment that required prodigious patience, researchers at the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt, Germany, spent almost five months last year firing titanium-50 ions — each with 22 protons and 28 neutrons — into a berkelium-249 target at the rate of about 5 trillion particles per second. The hope was that, just once or twice, two atoms would fuse to make an element with 119 protons, more than any created before.

Smashing beams of heavy atoms together has served physicists well over the past 70 years, allowing them to create increasingly heavy agglomerations of protons and neutrons, and to expand the periodic table far beyond the heaviest naturally occurring elements. The confirmed record-holder is element 116, livermorium, with 116 protons and, depending on the isotope, between 174 and 177 neutrons.

There have been claims to elements 117 and 118 too, but these have not been officially confirmed. And so far, "none of the current experiments have reported finding 119 or 120", says Christoph Düllmann, spokesman for the GSI-led collaboration — although he adds that his own team's analysis of last year's work is not quite complete.

There is a strong sense that the quest is coming to a dead end. The chance that nuclei will fuse decreases as they get heavier, because the protons and neutrons resist sticking together. Most researchers agree that beyond 120, the chance of getting two nuclei to fuse directly is vanishingly small. "So this leaves us with the question," says Düllmann, "what do we do next?"

To answer that requires an understanding of what motivates the superheavy search. Curiosity and national pride undoubtedly have a role, with politicians and scientists both looking to stamp their country's name into a new box on the periodic table. But each superheavy element is extremely short-lived, splintering in milliseconds.

Theorists have posited that some superheavy combinations of protons and neutrons will turn out to be stable for seconds, minutes or even days. This fabled 'island of stability' is thought to exist at between 114 and 126 protons, and around 184 neutrons. It is now clear that any attempt to make new superheavy elements by smashing a light particle into a heavier one will not reach the island: the isotopes spat out have too few neutrons. So researchers are changing tactics by trying to make heavier isotopes of elements that have already been created.

That is what scientists will attempt next year at the Joint Institute for Nuclear Research in Dubna, Russia. They plan to make neutron-rich isotopes of element 118 by firing beams of calcium-48 into radioactive californium-251.

The Russian team and others also want go back to the elements already made and create hundreds or thousands of atoms, rather than the handful necessary to claim a discovery. "We should set ourselves the goal of making not one or two atoms, but macroscopic quantities that we can use to study chemistry and nuclear structure in much greater detail," says Rolf-Dietmar Herzberg, a physicist at the University of Liverpool, UK. That might allow theorists to make more accurate predictions about where the island of stability lies.

But the temptation to expand the periodic table is strong. Researchers will probably turn away from head-on collisions and instead try knocking two heavy nuclei together in a glancing blow, which may stand a better chance of successfully fusing them to create new elements.

Physicists have a history of surprising themselves in their quest to create ever heavier atoms. In the early 1990s, no one thought that they could get past element 112 and then a tweak to the fusion process made it possible, says GSI team member Michael Block. "The next element is always the hardest." ■

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