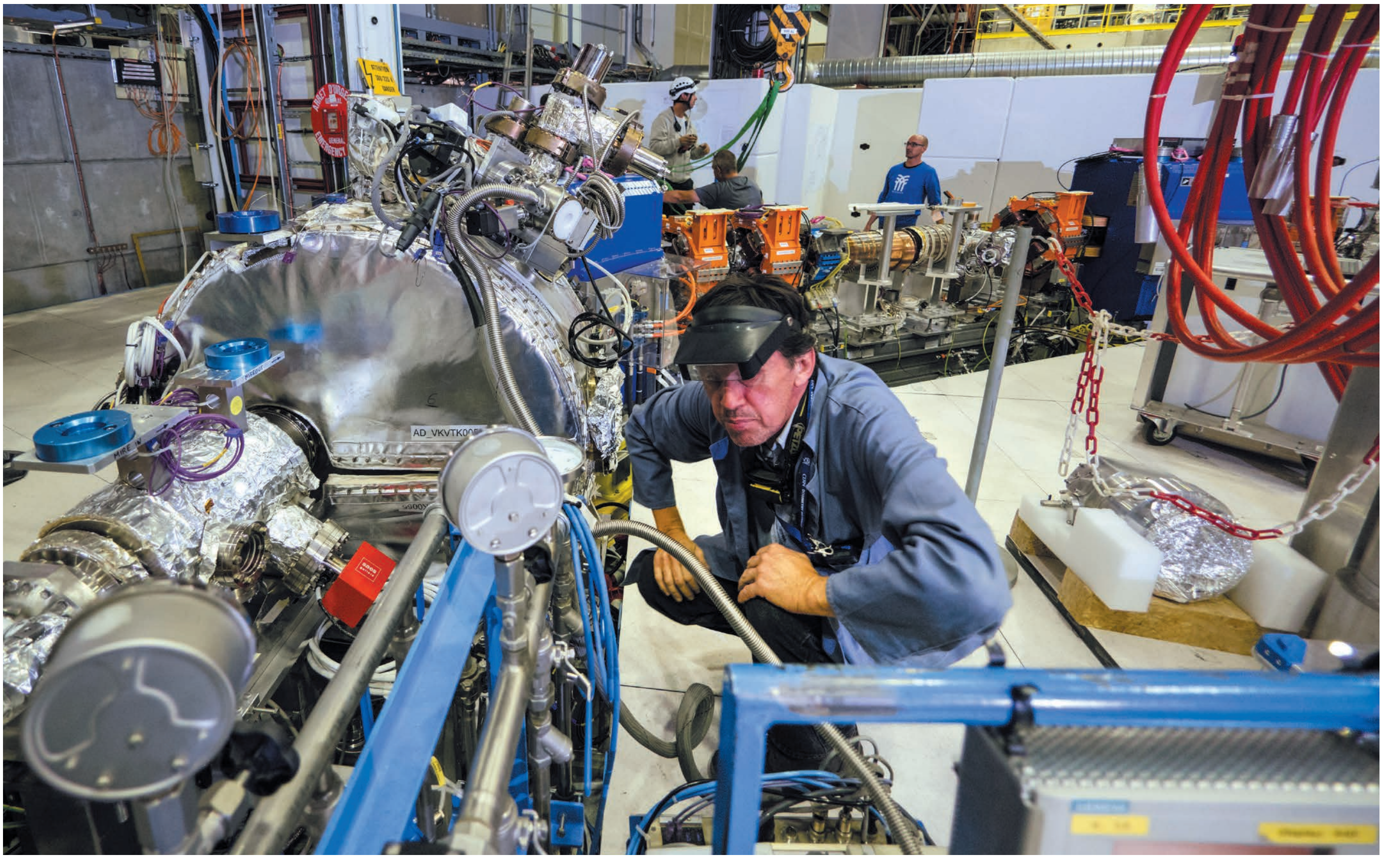


MAXIMILIEN BRICE/CERN

CERN's new antiproton decelerator, ELENA, is set to start slowing the particles down for study this year.

THE ANTIMATTER RACE

Competing experiments are hunting for new physics in the shadow of the Large Hadron Collider.

BY ELIZABETH GIBNEY

In a high-ceilinged hangar at CERN, six rival experiments are racing to understand the nature of one of the Universe's most elusive materials. They sit just metres apart. In places, they are literally on top of one another: the metallic beam of one criss-crosses another like a shopping-centre escalator, its multi-tonne concrete support hanging ominously overhead.

"We're constantly reminded of each other," says physicist Michael Doser, who leads AEGIS, an experiment that is vying to be the first to discover how antimatter — matter's rare mirror image — responds to gravity.

Doser and his competitors have little choice but to get cosy. CERN, Europe's particle-physics laboratory near Geneva, Switzerland, boasts the world's only source of antiprotons — particles that seem identical to protons in every way except for their opposite charge and spin. The lab's Antiproton Decelerator is a ring, 182 metres around, that feeds from the same accelerators as the lab's bigger and more famous sibling, the Large Hadron Collider (LHC). Antiprotons enter the machine travelling close to the speed of light. As the name implies, the decelerator slows the particles down, providing a stream of antiprotons from which experiments must take turns to sip. All this must be done carefully; upon meeting matter, the antiparticles vanish in a puff of energy.

For decades, scientists have worked to pin down antiprotons, and the antihydrogen atoms they can be used to build, for long enough to study. The past few years have seen rapid advances: experimentalists can now control enough antiparticles to start probing antimatter in earnest and to perform increasingly precise measurements of its fundamental properties and internal structure. Jeffrey Hangst, who leads the experiment known as ALPHA, says that in principle at least, his team can now do with antihydrogen anything others do with hydrogen. "For me, this period is what I've worked towards for 25 years," he says.

The experiments have a lot riding on them: even a slight difference between the properties of matter and antimatter could explain why anything exists at all. As far as physicists know, matter and antimatter should have been created in equal amounts in the early Universe and so blasted each other into oblivion. But that didn't happen, and the origin of this fundamental imbalance remains one of the biggest mysteries in physics.

The CERN efforts are unlikely to crack the case any time soon. Antimatter has so far proved maddeningly identical to matter, and many physicists think it will remain that way, because any difference would shake the foundations of modern physics. But the six experiments, the latest in a line of investigations that began at CERN more than 30 years ago, are attracting attention as the LHC continues to draw a blank in its hunt for particles that could explain the antimatter paradox. Moreover, the teams' rapid advances in manipulating antimatter have earned them a major upgrade to the facility's antiproton factory — a cutting-edge decelerator that will start operation by the end of this year and eventually enable experiments to work with up to 100 times more particles.

The dozens of physicists working on the CERN experiments know they face a tough challenge. Antimatter is exasperating to work with, the competition between teams is intense and the odds of finding anything new seem low. But CERN's antimatter wranglers are motivated by the thrill of opening a new window on the Universe. "These are such tour de force experiments that, no matter what answer you get, you can be proud that you do this," says Hangst. There's no guarantee that antimatter will yield a major discovery. But "if you can get your hands on some", he says, "it would be completely reprehensible not to look."

THE FACT OF THE MATTER

The roots of antimatter physics can be traced to 1928, when British physicist Paul Dirac wrote an equation that described an electron moving close to the speed of light[1]. Dirac realized that there had to be both a positive and a negative solution to his equation. He later interpreted this mathematical quirk as suggestive of the existence of an anti-electron, now called a positron, and theorized that antimatter equivalents should exist for every particle.

Experimentalist Carl Anderson confirmed the positron's existence in 1932, when he found a particle that seemed like an electron except that when it travelled through a magnetic field, its trajectory bent in the opposite direction. Physicists soon realized that positrons were routinely produced in collisions: smash particles together with enough energy and some of that energy can turn into matter–antimatter pairs.

By the 1950s, researchers had begun to exploit this energy-to-particle conversion to produce antiprotons. But it took decades to find a way to make enough of them to capture and study. One motivation was the tantalizing idea that antiprotons and positrons could be paired to make antihydrogen, which could then be compared with the well-studied hydrogen atom.

Creating positrons is fairly straightforward. The particles are produced in certain types of radioactive decay, and can be readily caught with electric and magnetic fields. But the higher-mass antiproton is another story. Antiprotons can be made by slamming protons into a dense metal, but they emerge from such collisions moving too fast to be held by an electromagnetic trap.

Antimatter hunters needed a way to massively slow down, or cool, the particles. CERN's first dedicated attempt to decelerate and store antimatter began in 1982, with the Low Energy Antiproton Ring (LEAR). In 1995, the year before LEAR was slated to be shut down, a team used antiprotons from the facility to produce the first antihydrogen atoms[2].

LEAR's replacement, the Antiproton Decelerator, came online in 2000 with three experiments. Similar to its predecessor, it tames antiparticles, first by focusing them using magnets and then by slowing them using strong electric fields. Beams of electrons also exchange heat with the antiprotons, cooling but not touching them because the particle types are both negatively charged and so repel each other. The overall process slows the antiprotons to one-tenth of the speed of light. That is still too fast to work with, so each of the six experiments uses techniques to further slow and trap the antiprotons.

There is plenty of attrition along the way. Each 'shot' of 30 million antiprotons fed to an experiment starts by smashing 12 trillion protons into a target. By the time Hangst's ALPHA experiment, for example, has slowed its antiprotons enough to pair them with positrons and create antihydrogen, just 30 of the particles remain, the rest having escaped, been annihilated or been discarded because they are too fast or in the wrong condition to study. Experimenting with such tiny numbers of antiatoms is a real pain, says Hangst: "You get a whole new attitude about all the rest of physics when you have to work with this stuff."

RACE FOR THE PRIZE

Antimatter research at CERN will eventually have some competition from the Facility for Antiproton and Ion Research, a €1-billion (US$1.16-billion) international accelerator complex in Darmstadt, Germany, that will be completed around 2025. But for the moment, CERN has the monopoly on producing antiprotons slow enough to study.

Today, there are five experiments running at the antimatter facility (one, GBAR, is still being built). Each has its own way of working with antiprotons, and although some do unique experiments, they often compete to measure the same properties and independently corroborate each other's values (see 'Wrangling antimatter').

The experiments share one beam, which means that in any two-week period, just three of the five experiments get beam time, each taking their turn in an 8-hour shift. A weekly coordination meeting ensures that each experiment knows when its neighbours' magnet will be running, so as not to ruin sensitive measurements. But despite the close proximity, teams usually find out about breakthroughs made by their neighbours by reading about them in a paper. "This is built on competition, and that's good. That motivates you," says Hangst.

Today, only one of the six experiments — BASE — directly studies the antiprotons from the Antiproton Decelerator. BASE holds the particles in a Penning trap, a complex array of electric fields (which pin particles vertically) and magnetic fields (which make them orbit in a circle). The team can store antiprotons for more than a year, and has used the orbits of antiprotons in the trap to determine the particle's charge-to-mass ratio with record precision[3]. The group also uses a complex method to reveal the antiproton's magnetic moment[4] — akin to its intrinsic magnetism. The measurement involves switching individual particles rapidly between two separate traps and detecting changes caused by minuscule shifts in an oscillating microwave field. Mastering the technique has become a passion for collaboration leader Stefan Ulmer, a physicist at RIKEN in Wako, Japan. "My entire heart is in this," he says.

"THIS PERIOD IS WHAT I'VE WORKED TOWARDS FOR 25 YEARS."

Antihydrogen, which is studied by the other experiments at CERN, comes with its own challenges. Because it has a neutral charge, it is immune to electric fields, and so nearly impossible to control. Experiments must exploit the antiatoms' weak magnetic properties, restraining the particles with a 'magnetic bottle'. For the bottle to work, the magnetic fields inside must vary enormously over a tiny distance, changing by 1 tesla — the strength of a car-lifting scrapyard magnet — over just 1 millimetre. Even so, the antihydrogen atoms must have a temperature of less than 0.5 kelvin, or they will escape.

The first antihydrogen atoms, created using antiprotons on the move, lasted about 40 billionths of a second. In 2002, two experiments, ATRAP and ALPHA's predecessor ATHENA, became the first to slow antiprotons enough to make significant amounts of antihydrogen, amassing many thousands of the atoms each[5]. The major breakthrough came almost a decade after that, when the teams learnt to trap the antiatoms for minutes at a stretch[6]. They have since measured properties such as charge and mass and used laser light to probe energy levels[7]. On page 66, ALPHA reports its latest advance: the most precise measurement yet of antihydrogen's hyperfine structure, the tiny internal energy shifts caused by interactions between its antiproton and positron[8].

Together, the CERN experiments explore a range of antimatter properties, any of which could display a difference from matter. The goal

NEWS FEATURE

WRANGLING ANTIMATTER

Six experiments at the particle-physics lab CERN are on the hunt for subtle differences between the properties of antimatter and matter. All sit inside the Antiproton Decelerator, which slows antiprotons down to manipulable speeds. From there, the experiments further slow the particles and some combine them with positrons to make antihydrogen.

THE ANTIMATTER

ANTIPROTON

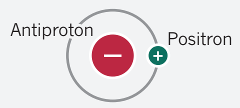
The proton's antimatter counterpart is produced in high-energy collisions and needs heavy deceleration.

POSITRON

This lower-mass particle, the electron's antimatter counterpart, is produced in radioactive decays.

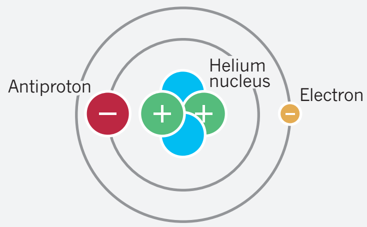
ANTIHYDROGEN

An antiproton and a positron can be combined to make antihydrogen, opening up opportunities to study new properties.

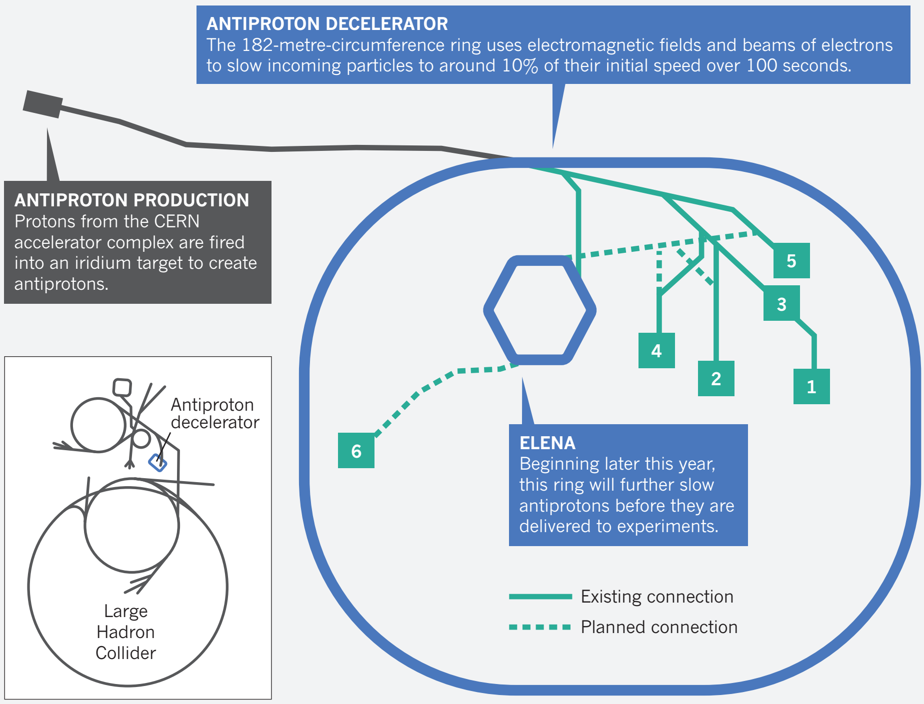


ANTIPROTONIC HELIUM

Researchers also build this exotic hybrid, in which an antiproton takes the place of an electron in a helium atom.



THE DECELERATORS



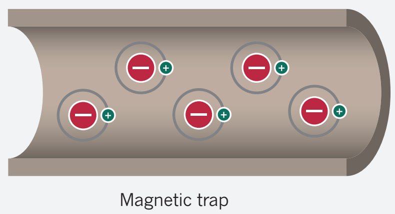
THE EXPERIMENTS

1 ALPHA

Started: 2005

Studies: Charge, spectroscopy and acceleration under gravity of antihydrogen.

How it works: Mixes antiprotons and positrons in a complex electromagnetic trap to create antihydrogen, which physicists probe with lasers.

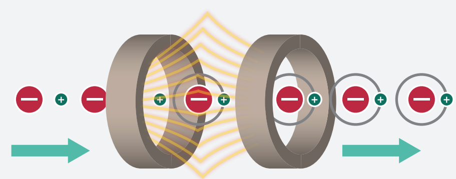


2 ASACUSA

Started: 2000

Studies: Mass of antiproton (relative to the electron), spectroscopy of antihydrogen and antiprotonic helium.

How it works: Traps antiatoms then turns them into a polarized beam, which can be probed with microwave radiation or lasers.

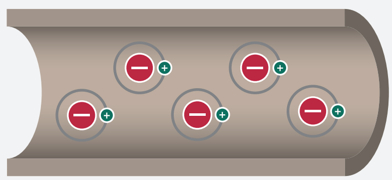


3 ATRAP

Started: 2000

Studies: Magnetic moment and charge-to-mass ratio of antiprotons; plans to study the spectroscopy of antihydrogen.

How it works: Studies trapped antiprotons and antihydrogen atoms, which it makes by mixing cold positrons with antiprotons.

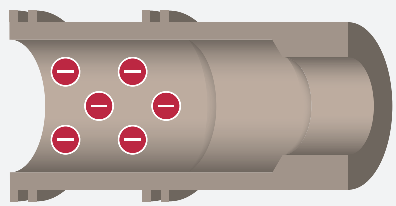


4 BASE

Started: 2014

Studies: Charge-to-mass ratio and magnetic moment of antiprotons.

How it works: Stores antiprotons in a reservoir, before observing their trajectory in a trap or shuttling particles to various traps to measure different properties.

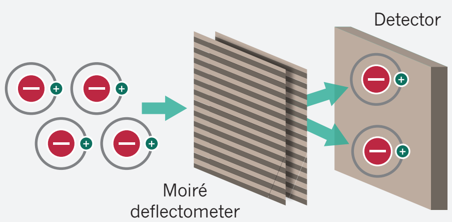


5 AEGIS

Started: 2015

Studies: Gravitational acceleration of antihydrogen atoms.

How it works: Observes the pattern produced by parallel beams of excited low-energy antihydrogen atoms as they pass through a grating.

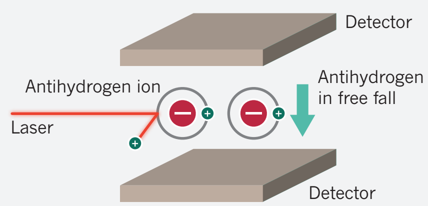


6 GBAR

Starting: 2017

Studies: Gravitational acceleration of antihydrogen atoms.

How it works: Laser-cooled beryllium ions chill antihydrogen ions containing two positrons. A laser knocks off one positron, and the antihydrogen atom free-falls under gravity.



SOURCE: CERN

for all of them is to keep shrinking the uncertainty, says antimatter veteran Masaki Hori. He leads the ASACUSA experiment, which uses lasers to study antiatoms in flight, free from the disruptive forces of traps. Last year, the team made a precise measurement of the ratio of antiproton mass to electron mass, using exotic helium atoms in which an antiproton takes the place of an electron[9]. Like other measurements so far, it showed no difference between matter and antimatter. But each result is a more stringent test of whether matter and antimatter really are exact mirror images.

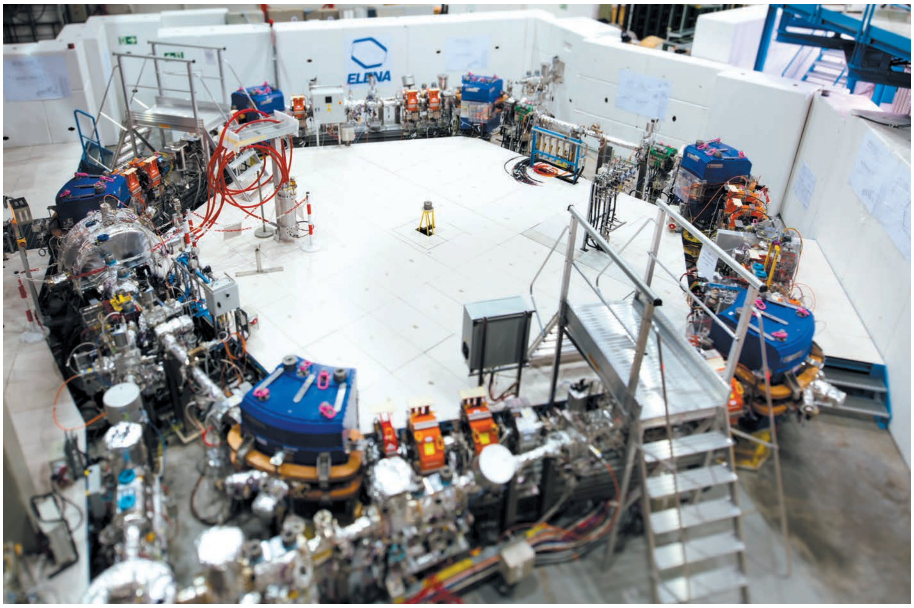
WHAT DIFFERENCE DOES IT MAKE?

If the experiments were to detect any difference between matter and antimatter, it would be a radical discovery. It would mean the violation of a principle called charge, parity and time reversal (CPT) symmetry. According to this principle, a mirror-image Universe that is filled with antimatter and in which time runs backwards will have the same laws of physics as our own. CPT symmetry is the backbone of theories such as relativity and quantum field theory. Breaking it would, in a way, break physics. In fact, only exotic theories predict that the antimatter experiments will find anything at all.

For this reason, the physicists at the LHC tend to view the antimatter researchers next door "with bemused attention", says Doser, who has been working on antimatter for 30 years. "They think this stuff is fun and interesting, but unlikely to lead to something new," he says. CERN theorist Urs Wiedemann seems to confirm that. He says that the experiments' ability to manipulate antimatter is "mind-boggling" and that such tests of theory are essential, but "if you ask is there a firm physics motivation that at some accuracy something new will be discovered, I think a fair statement is, 'No'".

Still, the LHC has fared little better in solving the antimatter mystery. Experiments dating back to the 1960s have shown that some physical processes, such as the decay of exotic kaon particles into more familiar ones, have tiny biases in favour of producing matter. LHC experiments have been hunting more such biases, and even a raft of as-yet-undiscovered particles whose behaviour in the early Universe could have accounted for the huge matter–antimatter imbalance that remains. There has been good reason to suspect such particles exist: they were predicted by supersymmetry, a theory that was proposed to tie up some troubling loose ends in particle physics. But no such particles have turned up in eight years of searching. Now, the simplest, most elegant versions of supersymmetry — the ones that made the idea appealing in the first place — have been largely ruled out. "Today, the LHC is looking for hypothetical particles, which may or may not be there, with very little guidance from theory. In a way, this is the same situation we're in," says Doser.

A few teams are now jumping into the next big challenge: the race to measure antimatter's acceleration under gravity. Physicists generally expect antimatter to fall just like matter. But some fringe theories predict that it has 'negative mass' — it would be repelled by, rather than attracted to, matter. Antimatter with this property might account for the effects of dark energy and dark matter, the identities of which are still unknown. But most mainstream theorists say such a Universe would be inherently unstable.



MAXIMILIEN BRICE/CERN

The ELENA antiproton decelerator began tests in late 2016.

UP IS DOWN

Measuring antihydrogen in free fall will, as ever, be a question of making it cool enough. Even the tiniest thermal fluctuations will mask the signal of a falling atom. And only neutral particles such as antihydrogen can be used, because even distant sources of electromagnetic fields can expose charged particles to forces bigger than gravity.

Next year, Hangst's group aims to use proven technology — a vertical version of its ALPHA experiment — to get a definitive determination of whether antimatter falls up or down. "Obviously I think we'll succeed first, or I wouldn't get into it," he says. But two other experiments — Doser's AEGIS and the antimatter facility's newest member, GBAR — are hot on the team's heels. Both use laser-cooling techniques to boost precision, which will enable them to pick up subtler differences between the acceleration of antimatter and matter than ALPHA currently can. AEGIS will measure the bend of a horizontal beam of antihydrogen, whereas GBAR will let its antiatoms free-fall for 20 centimetres. Both aim to bring the antiatoms' temperature down to a few thousandths of a degree above absolute zero, allowing measurements of gravitational acceleration as sensitive as 1 part in 100, and have plans to go even further.

Later this year, GBAR will be the first to benefit from ELENA, a new 25-million-Swiss-franc ($26-million), 30-metre-circumference ring that sits inside the Antiproton Decelerator and is designed to further slow the antiprotons coming from the machine. Eventually, ELENA will supply particles to all of the experiments, nearly simultaneously. The antiprotons will be slower by a factor of seven and arrive in sharper beams. Because they'll be more efficiently cooled at early stages, experiments should be able to trap more of the particles.

Now that the teams can manipulate and test antimatter, Hangst says, more and more physicists are becoming interested in the work. They even pitch ideas for experiments and values to check. And the groups are looking outwards, for ways in which their technologies could aid other areas of research. The GBAR team, for example, is working on a portable trap to carry antiprotons to a CERN experiment called ISOLDE, where they can be used to map the neutrons in unstable radioactive atoms.

Assuming a technical impasse doesn't grind progress to a halt, Doser reckons that by the end of the 2020s, physicists will be adept enough at handling antimatter to be able to replicate a range of atomic-physics feats, including constructing antimatter atomic clocks. "I see lots of ideas popping up now, and that's a sign the field is moving forward quickly," he says. "I hope CERN never kicks me out, because I've got plans for the next 30 years." ■

Elizabeth Gibney *is a senior reporter for* Nature *in London.*

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