

## ANTI-ATOMS

## Gotcha!

Refined techniques to mix cold antiprotons and positrons in a magnetic bottle show that antihydrogen atoms can be trapped for 15 minutes — an improvement of four orders of magnitude over previous experiments.

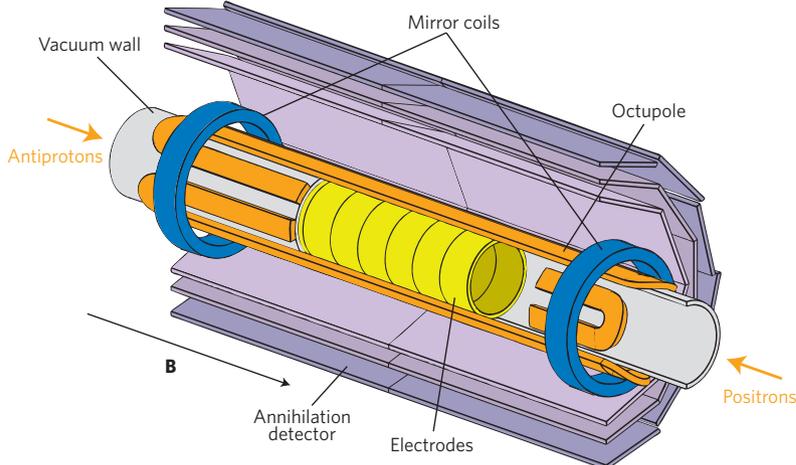
Clifford M. Surko

The quest to create, trap and study antihydrogen (a positron bound to an antiproton, the simplest stable, neutral anti-atom) is now entering its third decade. A long-term goal is to precisely compare the properties of hydrogen and its anti-atom to test certain principles, such as CPT (charge conjugation, parity and time reversal) symmetry. This could be done by optical studies to compare the electronic states of the two atoms or by microwave resonance to compare their magnetic moments. If there is a difference, this might help answer the seminal question as to why there is only matter in our Universe.

Rather than a tightly focused campaign to build and conduct one specific experiment and then take a victory lap, this effort is succeeding through a series of refinements. In the latest breakthrough, reported in *Nature Physics*<sup>1</sup>, the ALPHA collaboration, working at the Antiproton Decelerator at CERN, report trapping 309 antihydrogen atoms, with some held for longer than 15 minutes. They can now begin to improve the production of trappable anti-atoms and study their dynamics, which will be crucial for precision measurements.

The basic technique<sup>2</sup> used by the ALPHA collaboration, proposed by Jerry Gabrielse and the TRAP collaboration in the late 1980s, consists of so-called nested Penning–Malmberg traps. A set of cylindrical electrodes aligned with a uniform magnetic field **B** restricts the positrons and antiprotons from moving across the magnetic field, and electrical potentials on the electrodes confine the positrons and antiprotons in separate potential wells in the direction of **B**. The antiprotons are then forced gently through the positrons (Fig. 1).

With many subsequent improvements from ALPHA's predecessor ATHENA, TRAP's successor ATRAP, and others, the first low-energy antihydrogen atoms<sup>3,4</sup> were created by ATHENA and ATRAP in 2002. They found that when two positrons and an antiproton make a three-body collision antihydrogen atoms are formed, with the



**Figure 1** | Central features of the ALPHA collaboration's antihydrogen formation and trapping apparatus. Adapted from ref. 5.

second positron carrying away the excess (including binding) energy. Since 2002, the groups have made millions of antihydrogen atoms using this process.

In retrospect, producing antihydrogen atoms was arguably a relatively easy first step. Trapping the antihydrogen atoms to try and study them has proved difficult. The rub is that the so-called minimum-**B** configuration used to trap anti-atoms can only provide a puny trapping potential of ~0.5 kelvin, so only very cold antihydrogen atoms can be trapped. The anti-atoms formed by the three-body process in the magnetic field, called 'guiding-centre drift atoms', are initially in highly excited states and many cannot be confined by the minimum-**B** trap. Trapping is made more difficult by the fact that the electric fields of the antiproton and positron charge clouds (single-component plasmas) lead to particle heating and can rip apart the guiding-centre anti-atoms.

Following several years of attempts, in November 2010, the ALPHA collaboration reported that they had succeeded in trapping 38 antihydrogen atoms for 0.2 seconds (ref. 5). With the minimum-**B** atom trap turned on, pre-cooled antiproton

and positron plasmas are mixed to create antihydrogen atoms, and an electric field is used to clear out the remaining charged particles. The minimum-**B** trap is then turned off. The trapped antihydrogen atoms are released, exit the trap and hit the surrounding electrodes. The antiproton annihilates with a proton in the metal, producing  $\pi$  mesons. Detection of this signal demonstrates that the atoms had been trapped.

ALPHA now reports<sup>1</sup> data for over 100 atoms held for times from 0.4 to 2,000 seconds, a factor of  $10^4$  improvement in verified confinement time over last year's results. These recent results are significant in showing that some antihydrogen atoms can indeed be trapped long enough to reach the ground atomic state by radiation of photons — just the state needed for precision measurements. Longer confinement times also translate to more precise measurements of anti-atom properties.

Other important results come by virtue of ALPHA's hallmark detector system that can resolve the locations of the antiproton decays spatially and temporally. These detailed measurements can be compared with

numerical simulations of the trajectories of antihydrogen atoms to help understand the formation and trapping processes in more detail. The results are consistent with antihydrogen atoms in thermal equilibrium at the temperature of the positrons from which they were formed.

So why now and not earlier? Experimenters have become much more adept over the years in creating, cooling and compressing antiproton and positron plasmas. Furthermore, the ALPHA collaboration used a novel auto-resonance technique to combine the antiprotons and positrons. This technique forces the antiprotons through the positron plasma very gently, creating colder, more trappable antihydrogen atoms. Less is also better: the experiments use relatively small clouds of antiprotons ( $10^4$ ) and positron plasmas ( $10^6$ ) to minimize the effects of unwanted electric fields. Both species are evaporatively cooled before mixing.

Still, there is enormous room for improvement. Only one atom is formed in every two mixing cycles, and the positron (and thus the antihydrogen) temperature is 80 times the atom-trap well depth. Learning how to create lower-energy antihydrogen atoms would be a huge advance. This might be done by further refining the present scheme, or perhaps by using another antihydrogen production scheme altogether (for example, collisions of high-Rydberg-state positronium atoms with antiprotons)<sup>6</sup>.

Another consideration is the octupole magnetic field of the ALPHA minimum-**B** atom trap. Although probably critical for anti-atom creation, it has a broad potential minimum for the anti-atoms. Some precision measurements require atoms that are localized on the magnetic axis, so perhaps an octupole trap for antihydrogen formation and initial trapping, and a quadrupole trap for long-term studies will turn out to be preferable.

In the broader picture, this paper marks great progress in the quest to compare with precision the properties of antihydrogen with that of its ordinary matter cousin. However, there may well be more twists in the road before this immensely challenging goal is achieved. □

Clifford M. Surko is in the Department of Physics, University of California at San Diego, La Jolla California 92093-0319, USA.  
e-mail: csurko@ucsd.edu

#### References

1. Andresen, G. B. *et al. Nature Phys.* **7**, 558–564 (2011).
2. Gabrielse, G. *et al. Phys. Lett. A* **129**, 38–42 (1988).
3. Amoretti, M. *et al. Nature* **419**, 456–459 (2002).
4. Gabrielse, G. *et al. Phys. Rev. Lett.* **89**, 213401 (2002).
5. Andresen, G. B. *et al. Nature* **468**, 673–677 (2010).
6. Storry, C. H. *et al. Phys. Rev. Lett.* **93**, 263401 (2004).

Published online: 5 June 2011

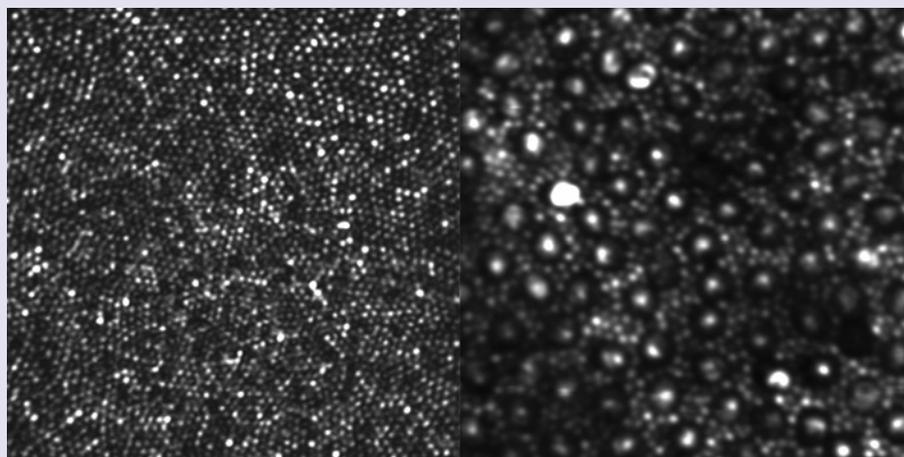
## ADAPTIVE OPTICS

# Retinal rods resolved

Although cone cells are more important for everyday vision, rod cells make up the vast majority (approximately 95%) of the photoreceptors of the human eye. Rods are much more sensitive than cones. So sensitive, in fact, that they are able to respond to individual photons, giving us the ability to see in low-light conditions. And they are responsible for detecting movement in our peripheral vision.

But, owing to their small size (around  $2\ \mu\text{m}$  in diameter) and the optical distortions introduced by other components of the eye, resolving individual rod cells in living eyes using conventional medical imaging techniques is practically impossible. This makes it difficult to diagnose the early stages of disease in these cells in order to treat them and prevent irreversible damage.

However, Alfredo Dubra and colleagues have now developed a microscope that is able to collect detailed images of the mosaic of photoreceptors in the retinas of living subjects (*Biomed. Opt. Express* **2**, 1864–1876; 2011 and *Biomed. Opt. Express* **2**, 1757–1768; 2011). It relies on a technique known as adaptive optics, pioneered by astronomers to correct for distortions introduced by the atmosphere and produce sharp images of the heavens using Earth-bound telescopes.



Their microscope — known as a confocal adaptive-optics scanning ophthalmoscope — works in three stages: scanning a focused beam of light across the subject's retina; measuring variations in the wavefront of the reflected light, which are introduced by imperfections in the lens and cornea at the front of the eye, and then correcting for these perturbations with deformable mirrors. The result is retinal images with resolutions approaching the diffraction limit for the wavelengths of light used. Both the small cones at the centre of

the retina (pictured left) and the small rods surrounding larger cones at the retina's periphery (pictured right) are clearly resolved.

Dubra *et al.* expect that this ability to routinely collect detailed images of retinal structures in a clinical setting will make it possible to diagnose retinal disease earlier, and to generate a wealth of previously inaccessible data for the development of better treatments.

ED GERSTNER