# Second CERN Group Produces Cold Atoms of Antihydrogen

**A new experiment, by CERN's ATRAP collaboration, introduces a technique for determining the quantum state in which antihydrogen atoms are formed.**

Two collatorations at CERN have been pursuing a long-term goal: to make precision tests of how an atom of antimatter might differ from its ordinary-matter counterpart. An antihydrogen atom (consisting of a positron bound to an antiproton) might, for example, fall at a slightly different rate than a hydrogen atom. Or the lowest-lying states of the positron might have slightly different energies than those of the electron in hydrogen. If a precision test indicated that either hypothesis were true, it would shatter a very basic tenet of physics. Different rates of fall would challenge predictions of general relativity, and different energy levels would violate the invariance of physics under the simultaneous operations of charge conjugation, time reversal, and parity inversion.

To conduct such precision tests, of course, one must first form cold atoms of antihydrogen—not an easy task. A step in this direction was the demonstration by CERN's ATRAP collaboration that antiprotons could be put into the same trap (a so-called nested Penning trap[1]) as the positrons and cooled by those positrons.[2] Following that lead, a second CERN group—the ATHENA collaboration—reported in September[3] the detection of cold antihydrogen (see PHYSICS TODAY, November 2002, page 17). The ATRAP collaboration has now weighed in with its own results.[4,5]

Not only did ATRAP researchers produce and detect more antihydrogen atoms than were seen by the ATHENA team, but they used a detection method that tells them about the quantum state in which the atoms were formed. The evidence gathered by ATRAP collaborators confirmed their expectation that the $\bar{\mathrm{H}}$ atoms formed in the experiment occupy highly excited Rydberg states. The next challenge is to come up with a way to deexcite the atoms to the ground state, as required for making precision measurements.

ATRAP, which is led by Gerald Gabrielse of Harvard University, is a collaboration of researchers from Harvard, the Research Center Jülich in Germany, the Max Planck Institute for Quantum Optics in Garching, Germany, the University of Munich in Germany, and York University in Toronto, Canada.

## Detecting antihydrogen

Both CERN collaborations, working independently, used similar means to nudge the antiprotons and positrons together to form $\bar{\mathrm{H}}$ atoms, but they had very different approaches to detecting them. To make antihydrogen, each group took antiprotons from CERN's Antiproton Decelerator, further slowed them, and trapped them with a configuration of electric fields. Each group also trapped and cooled positrons from the radioactive decay of a sodium isotope. And, in each experiment, the separately trapped antiprotons and positrons were then loaded into nested Penning traps.

In such a trap, electric and magnetic fields confine the antiprotons and positrons to a cylindrical region, with separate potential wells confining the two types of particles. In general, the positrons are confined to a region in the center, along the cylinder's axis, and antiprotons bounce back and forth longitudinally through the positron cloud (see the figure on page 16). The cold positrons further cool the antiprotons (to 15 K in the ATHENA setup and to 4 K in the ATRAP experiment). As the antiprotons pass through the region of positrons, some $\bar{\mathrm{H}}$ atoms are formed.

To detect antihydrogen, ATHENA collaborators looked for the particles that emanate when an $\bar{\mathrm{H}}$ atom hits the nearest wall; upon impact, the positron and antiproton composing the antiatom annihilate their matter counterparts. The specific signature sought by ATHENA researchers was the observation of a pair of oppositely moving photons (from positron annihilation) in coincidence with the sighting of several pions (from antiproton destruction).

By contrast, the ATRAP team used an electric field to ionize any $\bar{\mathrm{H}}$ atoms that traveled some distance away from the production region along the trap axis. Such ionization presumably yielded antiprotons, which ATRAP collaborators collected and counted in what they call the ionization trap, as shown in the figure.[2]

Commenting on the different detection methods, Steven Rolston of NIST in Gaithersburg, Maryland, notes that the technique used by the ATHENA group is reminiscent of particle physics, and the detection scheme adopted by the ATRAP team is in the style of atomic physics.

Gabrielse said that he and his ATRAP colleagues made sure that they could get an antiproton in their ionization trap only if a neutral $\bar{\mathrm{H}}$ atom escaped their nested Penning trap. Any antiprotons that might have escaped the nested Penning trap should have too much energy to be stopped in the ionization trap. Indeed, the experimenters accumulated antiprotons only when positrons were present in the Penning trap. "We were elated but not surprised to see that the signal was indeed background free," Gabrielse said.

To increase the yield of $\bar{\mathrm{H}}$ atoms as a function of the number of antiprotons, ATRAP team members increased the number of times the antiprotons went back and forth through the positron region. They did that by using a radiofrequency drive to heat the antiprotons stored on either side of the 4-K positron region. They would heat first one side, then the other, in a periodic manner.

## Determining the quantum state

There are two ways in which an antiproton and a positron might combine to form an $\bar{\mathrm{H}}$ atom: In three-body recombination, an antiproton and two positrons interact to yield an antihydrogen atom and a leftover positron that carries away the extra energy and momentum. In radiative recombination, an antiproton merges with just one positron, and a photon carries off the additional energy and momentum. Three-body recombination tends to produce atoms in Rydberg states, which take a long time to cascade down to the ground state. Atoms produced by radiative recombination are formed in lower-lying states.

No one knew exactly which one of those two antihydrogen production processes would dominate in the ATHENA and ATRAP experiments and hence what quantum states would be formed. To get an idea of the quantum state of the $\bar{H}$ atoms, ATRAP researchers added another feature to their experimental setup: a state-analysis region, through which an $\bar{H}$ atom must pass on its way to the ionization region, as seen in the figure.

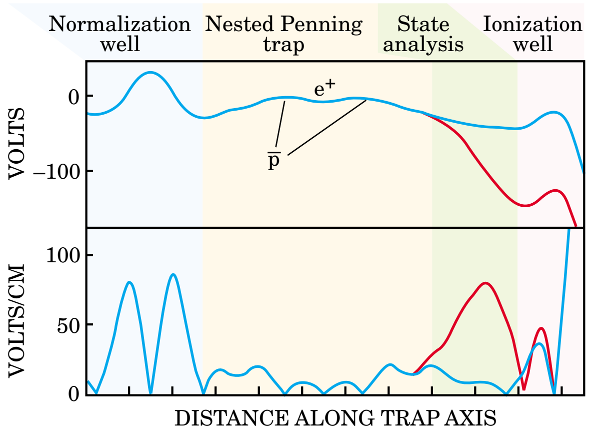
In the state-analysis region, the researchers apply an electric field, shown by the red curve, to ionize the $\bar{H}$ atoms. When ionization occurs, the resulting antiprotons will escape and the number of antiprotons snared in the ionization trap will decrease.

Gabrielse and company varied the electric field in the state-analysis region and recorded the drop in the numbers of antiprotons accumulated. They found the drop by comparing the numbers of antiprotons in the ionization trap with those in a normalization trap on the other side of the Penning trap, where there is no state-analysis region.

The strength of the field that ionizes an atom is a measure of the energy level occupied by the positron: The more tightly bound a positron, the higher the ionization field must be. Thus the observed decrease in the numbers of accumulated antiprotons is a measure of the number of $\bar{H}$ atoms with a given quantum number. It's hard to translate the measured ionization potential exactly into the principal quantum number $n$. Still, the experimenters estimate that all the atoms they formed were Rydberg atoms, with values of $n$ greater than about 50.

The ATRAP collaborators saw no evidence for lower-lying states. They found that the numbers of ionized $\bar{H}$ atoms declined as they raised the field to higher values. Beyond an electric field of 62 V/cm, they saw no further decreases. The experimenters took that as evidence that they were not seeing any tightly bound states. In future experiments, researchers might look for lower-lying antihydrogen states more directly by exciting them with a laser to states that can be ionized.

Whereas the ATRAP researchers have determined that their experiment forms Rydberg atoms, the same conclusion does not necessarily hold for the ATHENA setup, in part because ATHENA produces $\bar{H}$ atoms at higher temperatures. Rolf Landua, ATHENA's spokesman, said that his team now has evidence that three-body recombination is not the dominant process in their experiment.




**Antihydrogen detection scheme.** Blue curves indicate the electric potential (top) and field magnitude (bottom) as a function of distance along the axis of a nested Penning trap. Positrons are held by a small dip in the potential at the trap's center. The small peaks on either side of this potential dip confine antiprotons, which bounce back and forth through the positrons. If $\bar{H}$ atoms are formed, some of those that escape are stripped of their positrons by an electric field in the ionization well. These antiprotons serve as a measure of the number of $\bar{H}$ atoms formed. When an electric field applied in the state analysis region (red curves) ionizes some $\bar{H}$ atoms, fewer antiprotons are caught in the ionization well, and the drop in numbers reflects how many $\bar{H}$ bar atoms were formed in a given quantum state. The drop is found by comparison with the normalization well on the other side of the Penning trap. (Adapted from ref. 5.)

## Rydberg atoms

No one has yet calculated the properties of Rydberg atoms moving randomly in magnetic fields as high as those found in a Penning trap. However, the ATRAP team's measurements may well motivate some new calculations. One complication, says Hossein Sadeghpour of the Harvard–Smithsonian Center for Astrophysics, is that one can't separate the center-of-mass motion from the internal coordinates, as can be done with many other systems. Thomas Gallagher of the University of Virginia notes that "using field ionization as a detection technique has subtleties even without a magnetic field. Understanding it with one presents quite a challenge."

One goal of such Rydberg calculations will be to guide the experimenters as they devise techniques to bring the highly excited atoms quickly down to their ground states, where the precision experiments must be performed. Left to their own devices, Rydberg atoms tend to take a long time to decay, during which time they might be lost from their trap. Daniel Kleppner of MIT notes that, to date, those studying Rydberg atoms have been concerned with how to put them in the higher states; they now face the reverse problem.

Gabrielse said that in ATRAP's next run, which begins in June 2003, his group will try to bring the Rydberg $\bar{H}$ atoms to lower energy levels with laser deexcitation methods. He and his collaborators also hope to test ways to select specific Rydberg states. Furthermore, they also need to figure out a way to store the neutral particles.

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## References


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# Isotope Ratio Measurements Firm Up Knowledge of Earth's Formation

**New measurements on primitive meteorites suggest that Earth's core formed earlier than was previously thought.**

A complicated interplay of processes occurred 4.6 billion years ago in the early stages of the Solar System as material from the initial solar nebula condensed and collided to form aggregates, planetesimals, and eventually