

Antihydrogen gives way to spectroscopic study

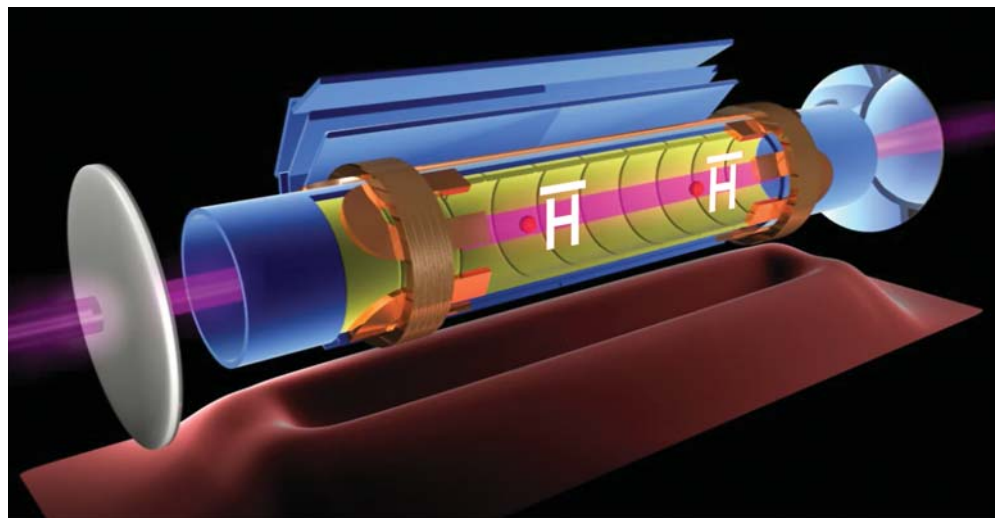
For the first time, researchers have probed the energy difference between two orbital states of an antimatter atom.

The observable universe contains almost no antimatter. Some naturally occurring radioactive isotopes decay via positron emission, and positrons and antiprotons are present in some high-energy environments, such as the particle showers produced by cosmic rays. But otherwise, matter is overwhelmingly dominant as the stuff of the natural world.

That's a puzzle. According to the laws of physics as we understand them, particles and their antiparticles should behave identically, except for a difference in sign for discrete properties such as charge. They should have been produced in identical numbers in the first moments after the Big Bang. The particle-antiparticle pairs should all have annihilated, and the universe should have been left with no matter or antimatter at all.

It wouldn't have taken much of a matter-antimatter imbalance in the primordial universe to produce the matter we see today. One extra proton per billion proton-antiproton pairs would have sufficed. But even that tiny excess is currently unexplainable. (See the article by Helen Quinn, *PHYSICS TODAY*, February 2003, page 30.)

The preponderance of matter over antimatter doesn't strictly require that matter and antimatter have some difference other than sign. But if laboratory experiments could detect such a difference, no matter how slight, it could be a crucial step in helping theorists to understand the asymmetry of the early universe. Toward that end, for the past 30 years several research groups at CERN have been working to trap and study atoms of antihydrogen. (See the Quick Study by Gerald Gabrielse, *PHYSICS TODAY*, March 2010, page 68.) A main goal of that research is to perform precision spectroscopic measurements to compare the atomic structure of antihydrogen with the known structure of hydrogen.



Now one of the CERN teams, the ALPHA collaboration, has achieved the first spectroscopic success: observing the transition between antihydrogen's 1s and 2s states.¹ Although the results reveal no difference yet between antihydrogen and hydrogen, the ALPHA researchers hope that their experimental precision, currently 200 parts per trillion, will greatly improve in the coming months.

Catching antiatoms

The standard technique for atomic spectroscopy—exciting atoms with a laser and detecting the photons they emit—is typically performed on samples of around 10^{12} atoms. For most ordinary matter, those samples are easy to come by. For example, more than 6×10^{22} hydrogen atoms can be extracted from a single milliliter of water.

Antimatter atoms are far more precious because of both the scarcity of their component particles and the difficulty of producing and handling them. CERN's Antiproton Decelerator, the source of all the facility's antihydrogen nuclei, produces just 3×10^7 antiprotons every 100 s. Those particles must be manipulated without the help of containers, tubes, nozzles, or cryostats made of matter.

The raw antiprotons, though decelerated, still travel at about 7% of the speed of light. To slow them further, the ALPHA team directs the antiparticle beam at a thin foil of aluminum. More

FIGURE 1. THE ALPHA-2 APPARATUS for trapping and spectroscopically probing atoms of antihydrogen. An array of coils and electrodes produces an inhomogeneous magnetic field that creates the potential-energy profile shown in dark red beneath the cylinder. The laser beam (pink), amplified by high-reflectivity mirrors, passes through the cylindrical trap. (Courtesy of Jeffrey Hangst.)

than 99% of the antiparticles are lost in the process, but those that survive annihilation and are scattered to a low enough energy can be combined with positrons collected from radioactive decay to produce antihydrogen. The procedure yields about 25 000 atoms per trial.

And that's the easy part. "Making cold antihydrogen, so we can trap it, is really hard," says Jeffrey Hangst, the ALPHA collaboration spokesperson. The atoms are charge neutral, so trapping them electromagnetically relies on their magnetic moment. In an inhomogeneous magnetic field, some of the atoms are drawn toward regions of lower field, so the team's magnetic trap, with low field in the middle and high field around the edges, serves to confine the atoms—provided their energies are lower than 0.5 K. In ALPHA's first successful trapping of antihydrogen in 2010, the researchers trapped just 38 atoms across 335 trials, and they held onto each trapped atom for a fraction of a second.² They've since

refined the experiment to trap an average of 14 atoms per trial and hold them for many minutes.

Small-sample spectroscopy

The 2010 experiment was focused on trapping, not spectroscopy. So in addition to improving their trapping rates, the ALPHA researchers had to rebuild their apparatus to accommodate a laser beam. The new setup, called ALPHA-2, is depicted in figure 1. To make the most of the small antihydrogen samples, the laser power is amplified by an optical cavity bounded by high-reflectivity mirrors placed outside the trapping region. About 1 W of laser power circulates through the region where the atoms are trapped.

The coils and electrodes of the magnetic trap leave no room for optical detectors, and a 14-atom sample wouldn't offer much of an optical-emission signal anyway. Happily, the trapped antihydrogen lends itself to an alternative spectroscopic method that works well for small numbers of atoms. When one of the atoms is excited by the laser, it doesn't always return directly to its original state. Sometimes it absorbs an additional photon and is ionized, and sometimes it returns to a spin-flipped version of the ground state. In either of those cases, the magnetic trap no longer confines it. The bare antiproton or spin-flipped atom drifts into the wall of the apparatus, is annihilated, and produces an easily detectable signal. At the end of the trial, the trap is turned off so the remaining atoms can also be counted.

The researchers probed the transition between antihydrogen's ground, or $1s$, state and its first excited state, $2s$. The excitation's long lifetime—about an eighth of a second—gives the excited-state atoms plenty of time to absorb another photon before decaying back to the ground state. The lifetime arises because the transition is forbidden for a single photon. So rather than tuning their laser to 121 nm, corresponding to the full energy of the transition, the researchers used a wavelength of 243 nm and relied on atoms absorbing two photons simultaneously to make the transition. The two-photon excitation has the added advantage of increasing the measurement's precision: When the two photons arrive from opposite directions, their Doppler

shifts nearly cancel, so the spectral line is not significantly broadened by atomic motion.

Figure 2 shows a simulation of the expected results, provided that antihydrogen is just like hydrogen. When the laser is tuned to exactly the right frequency (a detuning of 0), about half the atoms should be lost from the trap during each 10-minute trial. When the laser is detuned by a few kilohertz, a slightly smaller fraction should be lost. And when the laser is detuned by 100 kHz or more in either direction, few to no atoms should be excited, so nearly all of them should remain in the trap.

With their beam time running out for 2016, the ALPHA researchers tested just two laser frequencies: one on resonance and one detuned by ~ 200 kHz, or a relative frequency difference of about 200 parts per trillion. The choice of 200 kHz was essentially arbitrary, Hangst explains, and isn't indicative of any limitation of the experimental method. "We wanted a detuning large enough that we could be sure of seeing nothing."

And nothing is what they saw. They observed 27 annihilation events during the off-resonance trials, but that number was consistent with the expected background from cosmic rays. On the other hand, the 11 on-resonance trials looked at a total of 146 atoms, 79 of which escaped the trap.

Key to unification?

The ALPHA experiment implies that if there's any fractional difference between the transition frequencies of hydrogen and antihydrogen, it's less than 2×10^{-10} . In a way, that null result is reassuring. The symmetry between particles and their antiparticles is underpinned by the theories of both quantum mechanics and general relativity, so any observed difference between matter and antimatter spectra would require major changes to most of what we think we know about the laws of physics.

The nature of those changes remains to be seen. "In the search for a new effect, it's useful to identify all possible types of signals, and indeed a general theory of all possible signals exists," says Alan Kostelecky of Indiana University Bloomington. "But until an effect is discovered, predictions from specific models shouldn't be taken too seriously."

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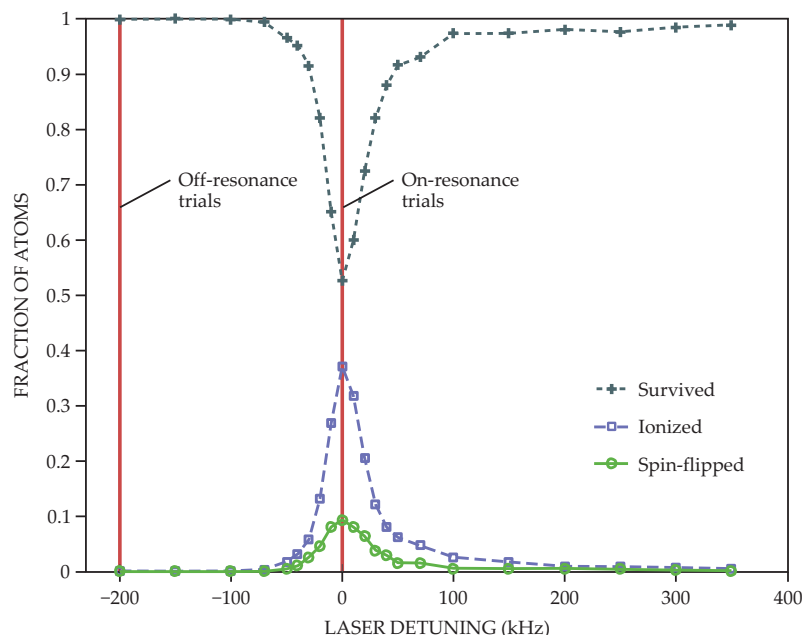
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Still, it's possible to make some educated guesses about what a matter-antimatter difference might look like. Because the revamping of quantum mechanics and general relativity could lead to unification of the two theories, one might expect the telltale spectroscopic difference to be on the natural size scale for unification effects: the ratio of the energy of elec-

troweak processes to the Planck energy, or somewhere between 10^{-17} and 10^{-23} .

It's conceivable that spectroscopic measurements could eventually chip away at that range. But that would require progress not just in antihydrogen spectroscopy but also in hydrogen spectroscopy. The latter's precision is currently around 10^{-15} .

FIGURE 2. SIMULATED RESULTS of an antihydrogen spectroscopic experiment. Atoms that are excited by the laser may be ionized or spin-flipped and thus lost from the trap. So far, the ALPHA experiment has tested two values of the laser detuning, as marked by the red lines. The results for atoms remaining in and escaping from the trap are consistent with the simulation. (Adapted from ref. 1.)

The ALPHA experiment resumes in May, and the researchers have a lot on their agenda. They want to get a detailed measurement of the $1s-2s$ transition by checking many more values of the laser detuning. They plan to explore the single-proton transition $1s-2p$, which would open the door to laser cooling of antihydrogen. And they're building a new machine to study a different open question: In the gravitational field of a planet made of matter, do antimatter atoms fall up or down?

Johanna Miller

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Supercooled water survives in no-man's-land

A "stop-motion" crystallization experiment laid bare the liquid's behavior in a temperature range that was once considered inaccessible.

Water doesn't necessarily freeze at its freezing point. A skillful experimenter who maintains the liquid free of impurities can chill it well below 0°C , or 273 K , in a metastable, supercooled state. In the 1970s chemists Austen Angell and Robin Speedy, then both at Purdue University, set out to determine just how cool water could go.¹ What they observed remains one of the biggest mysteries in thermodynamics: As their sample dipped below 250 K , its isothermal compressibility and heat capacity began to soar, indications that its density and entropy were fluctuating wildly at the molecular scale. Water seemed on the verge of some never-before-seen trans-

formation. But before the drama could play out, the sample froze.

Unable to usher the liquid below 247 K , the researchers did the next best thing: They extrapolated their data. And they concluded that whatever the mystery transformation was, it happened at 228 K , where their power-law fits predicted a singularity.

In the decades since, several possible explanations have emerged—that the fluctuations were merely precursors to crystallization, for instance, or that they signaled the existence of a theretofore unknown liquid-liquid phase transition. (See the article by Pablo Debenedetti and Gene Stanley, *PHYSICS TODAY*, June 2003,

page 40.) Speedy himself conjectured that 228 K marked the temperature at which water reached a thermodynamic bound known as a spinodal, beyond which a metastable liquid phase does not exist.²

A correct explanation, if one can be found, would do more than settle a decades-old debate. It would deepen scientists' understanding of other unusual properties of water, including the anticorrelation of entropy and volume observed at temperatures below 277 K . But the theories have proven all but impossible to scrutinize in the lab. That's because at 232 K , the so-called homogeneous nucleation temperature T_H , even pristine water will freeze—and freeze quickly. Just below that temperature, a crystalline phase spontaneously emerges in just tens of microseconds, even if no impurities are present to seed its growth.

Greg Kimmel and Bruce Kay, who have been experimenting with water for nearly two decades at Pacific Northwest National Laboratory (PNNL), knew there was little—no, nothing—they could do to slow down water's crystallization below T_H . So instead they devised a com-