that fluctuations in the levels of wild-type p53 are observed in nerve regeneration[12]. Thus, the authors' findings might have repercussions that reach beyond the field of cancer research to regenerative medicine. Perhaps therapies that modulate the activity of p53 will have a future role in aiding the repair or regeneration of neurons, an outcome that would make a profound difference to the lives of people who have neurodegenerative diseases or other types of nerve injury.

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Atomic physics

Fundamental symmetry tested using antihydrogen

Randolf Pohl

The breaking of a property of nature called charge–parity–time symmetry might explain the observed lack of antimatter in the Universe. Scientists have now hunted for such symmetry breaking using the antimatter atom antihydrogen. **See p.375**

One of the greatest mysteries in modern physics is why the Universe seems to contain mostly matter and almost no antimatter. This observation could be explained if a property of nature called charge–parity–time (CPT) symmetry is violated. Under CPT symmetry, the physics of particles and their antiparticles is identical. A tiny violation of CPT symmetry during the Big Bang could, in principle, be responsible for the lack of antiparticles in the Universe. On page 375, the ALPHA Collaboration[1] reports high-precision spectroscopic measurements of antihydrogen — an atom comprising an antiproton and a positron (the antiparticle of an electron). The authors find that the gaps between energy levels in antihydrogen are in excellent agreement with those measured previously in ordinary hydrogen[2–4], placing strong constraints on potential CPT violation.

Tests of CPT symmetry using individual particles — such as neutral kaons[5], positrons[6] and antiprotons[7,8] — have shown no sign of CPT violation. However, studies of antihydrogen might probe the influence of factors that were not explored in previous tests.

Hydrogen is the simplest atom, and its properties can be calculated with impressive precision. For more than a century, the study of this atom has been the driving force behind groundbreaking ideas about the structure of matter. The optical spectrum of hydrogen was measured with great accuracy in the 1880s, before being quantitatively explained in the 1910s. The structure of the atom was then at the heart of the formulation of quantum mechanics and in the generalization of this theory to relativistic (fast-moving) particles in the 1920s. And it was the unexpected discovery[9] of an energy gap between the 2S and $2P_{1/2}$ excited states of hydrogen by the physicist Willis Lamb in 1947 that motivated the development of quantum electrodynamics — the theory that describes the interactions between particles and light.

This energy gap, known as the Lamb shift, exists in both hydrogen and antihydrogen. It originates mostly from quantum fluctuations, whereby particle–antiparticle pairs spontaneously emerge in empty space and then instantly annihilate each other. However, its magnitude is subtly affected by, for example, the charge radius (the spatial extent of the charge distribution) of the proton or antiproton, the weak nuclear force and, potentially, currently unknown phenomena that could be the source of the matter–antimatter asymmetry in the Universe.

The current work was carried out using the ALPHA experiment at CERN, Europe's particle-physics laboratory near Geneva, Switzerland. A facility called the Antiproton Decelerator delivers antiprotons to this experiment, with a source of radioactive sodium providing positrons. Every few minutes, 90,000 cold trapped antiprotons and 3 million positrons are mixed in a sophisticated charged-particle trap. This process yields about 20 cold antihydrogen atoms that are then confined to a neutral-atom trap made from superconducting magnets. These antihydrogen atoms can be stored[10] for at least 60 hours, and production cycles can be repeated to obtain hundreds of such atoms.

The aim of the present study was to measure the energy differences between the 1S ground state and the $2P_{1/2}$ and $2P_{3/2}$ excited states of antihydrogen (Fig. 1). The ALPHA Collaboration used an approach called laser spectroscopy, which involved injecting pulses of laser light into the antihydrogen trap. This injection caused atoms to transition from the 1S state to the $2P_{1/2}$ or $2P_{3/2}$ state and to subsequently decay back to the 1S state. Atoms that ended up in a different magnetic substate of the 1S state from the one in which they started were expelled from the magnetic neutral-atom trap. These antihydrogen atoms then annihilated on contact with regular atoms in the walls of the ALPHA apparatus to produce particles called charged pions.

The ALPHA Collaboration plotted the number of observed charged pions as a function of the frequency of the laser light. They then used the positions of the two peaks in these plots to infer the 1S–$2P_{1/2}$ and 1S–$2P_{3/2}$ energy differences in antihydrogen.

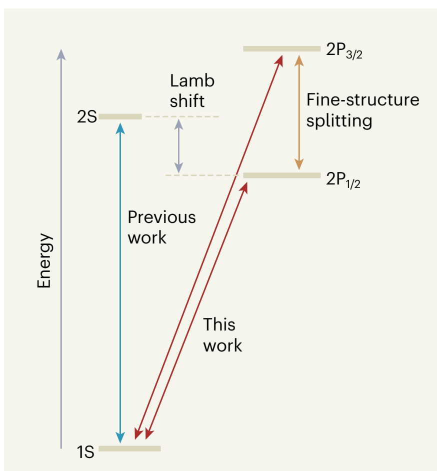

Figure 1 | Lowest-energy states of antihydrogen. The ALPHA Collaboration[1] carried out high-precision spectroscopic measurements of antihydrogen — the antimatter counterpart of hydrogen. Specifically, the team determined the energy differences between the 1S ground state and the $2P_{1/2}$ and $2P_{3/2}$ excited states of antihydrogen. They used these results to estimate the fine-structure splitting (the $2P_{1/2}$–$2P_{3/2}$ energy gap). They also combined their previous determination[11] of the energy gap between the 1S and 2S states with their current measurement of the 1S–$2P_{1/2}$ energy difference to infer the Lamb shift (the 2S–$2P_{1/2}$ energy gap). The authors found that all of these results are in agreement with the corresponding ones for ordinary hydrogen. (Drawing not to scale.)

These differences agree with the ones measured in ordinary hydrogen at the level of 16 parts per billion. The authors used their results to estimate the fine-structure splitting (the $2P_{1/2}$–$2P_{3/2}$ energy difference) in antihydrogen, with an uncertainty of 0.5%. This value is again in good agreement with the one for ordinary hydrogen.

In 2018, the ALPHA Collaboration measured the energy gap between the 1S and 2S states in antihydrogen[11] to one part in 10^{12}. In the current work, the authors combined this result with their measurement of the $1S$–$2P_{1/2}$ energy difference to provide an estimate of the Lamb shift in antihydrogen. This value has an uncertainty of 11% (or 3.3%, when the fine-structure splitting in ordinary hydrogen is used in the analysis).

Over the past few years, high-precision laser spectroscopy of antihydrogen has become possible, and the ALPHA Collaboration has achieved spectacular progress. An examination of several transitions in antihydrogen would enable targeted tests of CPT symmetry, quantum electrodynamics and the standard model of particle physics. For example, a measurement of the Lamb shift with an uncertainty of less than one part in 10^4 would allow the antiproton charge radius to be determined[12]. Moreover, improved measurements of the energy gap between magnetic substates in antihydrogen would provide detailed information about the magnetic structure of the antiproton[13].

The laser used for spectroscopy in the current work will, in the future, be used for cooling of antihydrogen by inducing $1S$–$2P_{1/2}$ and $1S$–$2P_{3/2}$ transitions. Such cooling would greatly improve the achievable precision in all spectroscopy experiments on antihydrogen. In addition, ultracold antihydrogen can be used to study the effect of gravity on these atoms[14]. Cold antihydrogen thus promises many cool results.

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In retrospect

30 years of the iron hypothesis of ice ages

Heather Stoll

In 1990, an oceanographer who had never worked on climate science proposed that ice-age cooling has been amplified by increased concentrations of iron in the sea — and instigated an explosion of research.

Thirty years ago this month, John Martin proposed a solution to one of the biggest mysteries of Earth's climate system: how was nearly one-third of the carbon dioxide in the atmosphere (about 200 gigatonnes of carbon) drawn into the ocean as the planet entered the most recent ice age, then stored for tens of thousands of years, and released again as the ice sheets melted? These large natural cycles in atmospheric CO_2 levels (Fig. 1a) were revealed in 1987 by an analysis of ancient air bubbles trapped in the first long ice cores taken from the Antarctic ice sheet[1]. Martin recognized that iron was a key ingredient that could have transformed the surface ocean during glacial times. His landmark iron hypothesis[2], published in *Paleoceanography*, described a feedback mechanism linking climatic changes to iron supply, ocean fertility and carbon storage in the deep ocean.

Two hundred gigatonnes is a lot of carbon to periodically withdraw from and release to the atmosphere. In the 1980s, a handful of models (see ref. 3, for example) had shown that an increase in biomass production in polar ocean regions was the most effective process for removing so much atmospheric carbon. Photosynthetic organisms in the surface ocean convert CO_2 from the atmosphere into biomass, much of which is subsequently broken down into CO_2 again by other organisms and returned to the atmosphere. But part of the biomass sinks into the deep ocean, which therefore effectively serves as a large storage reservoir of dissolved CO_2. This mechanism of CO_2 removal is called the biological pump.

However, biomass production requires not only CO_2, but also other nutrients to build lipids, proteins and enzymes. Researchers were struggling to ascertain how the ocean's abundance of key nutrients, such as nitrates or phosphates, might have increased during glacial times to fuel a stronger biological pump.

Martin argued that iron is another nutrient that limits the biological pump. He suggested that the modern marine ecosystem of the Southern Ocean around Antarctica is starved of iron, and therefore relatively low in biomass, despite having abundant nitrates and phosphates. But during glacial times, strong winds over cold, sparsely vegetated continents could have transported large amounts of iron-bearing dust into this ocean (Fig. 1b). Martin reasoned that this dust could have fertilized marine ecosystems and strengthened the biological pump, so that more carbon was transferred into the deep ocean, lowering atmospheric CO_2 levels.

Around the time of publication, evidence for high dust delivery during glacial periods had just emerged from studies of deep Antarctic ice cores[4]. But there were no reliable measurements of dissolved iron in the Southern Ocean that could confirm that its surface waters are iron-starved in modern times, or data supporting the proposal that delivery of iron-rich dust would make a difference to ocean productivity. It was clear, however, that large patches of the world's ocean had much lower quantities of biomass than would be expected on the basis of the concentrations of key nutrients such as nitrates and phosphates. But many researchers argued that this was due to natural overgrazing of algae by herbivores[5].

The idea that modern algal growth is limited by iron availability had, in fact, been proposed[6] in the 1930s, but had been incorrectly discounted by oceanographers — who had measured plenty of iron in seawater samples collected from the waters around their iron ships[7]. Martin was one of the first oceanographers to implement painstaking procedures to avoid the contamination of samples and to determine that iron concentrations in the north Pacific Ocean were extremely low[7], certainly low enough to curtail biomass production.

Despite the initial scepticism that greeted the iron hypothesis, 12 separate experiments[8] were carried out between 1993 and 2005 in which around 300–3,000 kilograms of dissolved iron were injected into small patches of the Southern Ocean, the equatorial Pacific