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ANTIMATTER | FEATURE

Illuminating antimatter

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The ALPHA collaboration has made seminal measurements of antihydrogen's spectral structure in a bid to test nature's fundamental symmetries.

Image credit: D Dominguez

The physics programme at CERN's Antiproton Decelerator (AD) is concerned with fundamental studies of the properties and behaviour of antimatter. Diverse experiments endeavour to study the basic characteristics of the antiproton (BASE, ATRAP), the spectra of antiprotonic helium (ASACUSA) and antihydrogen (ALPHA, ASACUSA, ATRAP), and gravitational effects on antimatter (GBAR, AEGIS, ALPHA-g). These innovative experiments at the AD – itself a unique facility in the world – can test fundamental symmetries such as charge–parity–time (CPT) and search for indications of physics beyond the Standard Model involving systems that have never before been studied.

Lurking in the background to all this is the baryon asymmetry problem: the mystery of what happened to all the antimatter that should have been created after the Big Bang. This mystery forces us to question whether antimatter and terrestrial matter really obey the same laws of physics. There is no guarantee that AD experiments will find any new physics, but if you can get your hands on some antimatter, it seems prudent to take a good, hard look at it.

We live in interesting times for antimatter. In addition to experiments at the AD, physicists study potential matter–antimatter asymmetries at the energy frontier at the

LHCb experiment, and search for evidence of primordial antimatter streaming through space using the AMS-02 spectrometer onboard the International Space Station. Antihelium-4 nuclei were observed for the first time at Brookhaven's Relativistic Heavy Ion Collider (RHIC) in 2011, while the LHC's ALICE collaboration observed and studied anti-deuterons and antihelium-3 nuclei in 2015. By contrast, the experiments at the AD are low-energy affairs: we are essentially dealing with antimatter at rest.

One of the unique advantages of AD physics, therefore, is that we can address antimatter using precision techniques from modern atomic and ion-trap physics. Following three decades of development in advanced experimental techniques by the low-energy antimatter community, the ALPHA collaboration has recently achieved the major goal of examining the spectrum of antihydrogen atoms for the first time. These results herald the start of a new field of inquiry that should enable some of the most precise comparisons between matter and antimatter ever attempted.

Unprecedented precision

If you want to measure something precisely, you should probably ask an atomic physicist. For example, the measured frequency of the electronic transition between the ground state and the first excited state in hydrogen (the so-called 1S–2S transition) is 2 466 061 413 187 035 (10) Hz, corresponding to an uncertainty of 4.2×10^{-15}, and the measurement is referenced directly to a cesium time standard. Sounds impressive, but, to quote a recent article in *Nature Photonics,* "Atomic clocks based on optical transitions approach uncertainties of 10^{-18}, where full frequency descriptions are far beyond the reach of the SI second". In other words, the current time standard just isn't good enough anymore, at least not for matter. For comparison, the current best value for the mass of the Higgs boson is 125.09 ± 0.24 GeV/c^2, representing an uncertainty of about 2×10^{-3}.

To be fair, scientists had already been observing hydrogen's spectrum for about 200 years by the time the Higgs was discovered. Fraunhofer is credited with mapping out absorption lines, some of which are due to hydrogen, in sunlight in 1814. From there we can trace a direct path through Kirchhoff and Bunsen (1859/1860), who associated Fraunhofer lines with emission lines from distinct elements, to Rydberg, Balmer, Lyman and ultimately to Niels Bohr, who revolutionised atomic physics with his quantum theory in 1913. It is no exaggeration to say that physicists learned modern atomic physics by studying hydrogen, and we are therefore morally obligated to subject antihydrogen to all of the analytical tools at our disposal.

Anti-atomic spectra are not the only hot topic in precision physics at the AD. In 2015 the BASE collaboration determined that the charge-to-mass ratios for the proton and antiproton agree to 69 parts per trillion (*CERN Courier* September 2015 p7). The following year, the ASACUSA experiment – which has been making precision measurements on antiprotonic helium for more than a decade – reported that the antiproton-to-electron mass ratio agrees with its proton counterpart to a level of 8×10^{-10} (*CERN Courier* December 2016 p19). One of the long term and most compelling goals of the AD programme has always been to compare the properties of hydrogen and antihydrogen to precisions like these.

A word of caution is in order here. In searching for deviations from existing theories, it is tempting to use dimensionless uncertainties such as $\Delta m/m$, $\Delta f/f$ or $\Delta q/q$ (corresponding to mass, frequency or charge) to compare the merits of different types of measurements. Yet, it is of course not obvious that a hitherto unknown mechanism that breaks CPT or Lorentz invariance, or reveals some other new physics, should create an observable effect that is proportional to the mass, frequency or charge of the state being studied. An alternative approach is to consider the absolute energy scale to which a measurement is sensitive. There is good historical precedent for this in the quantum mechanics of atoms. Roughly speaking, atomic structure, fine structure, hyperfine structure and the Lamb shift reflect different energy scales describing the physical effects that became apparent as experimental techniques became more precise in the 20th century.

At the time of the construction of the AD in the late 1990s, the gold standard for tests of CPT violation was the neutral kaon system. The oft-quoted limit for the fractional difference between the masses of the neutral kaon and anti-kaon was of the order 10^{-18}. Although there are many other tests of CPT using particle/antiparticle properties, this one in particular stands out for its precision. In the most recent review of the Particle Data Group, the kaon limit is presented as an absolute mass difference of less than 4×10^{-19} GeV. Although purists of metrology will argue that nothing has actually been measured with a precision of 10^{-18} here, the AD physics programme needed a potential goal that could compete, at least in principle, with this level of precision.

The holy grail

Thus the hydrogenic 1S–2S transition became a kind of "holy grail" for antihydrogen physics. The idea was that if the transition in antihydrogen could be measured to the same precision (10^{-15}) as in hydrogen, any difference between the two transition frequencies could be determined with a precision approaching that of the kaon system. On an absolute scale, the 1S–2S transition energy is about 10.2 eV, so a precision of 10^{-15} in this value corresponds to an energy sensitivity of 10^{-14} eV (10^{-23} GeV). Other features in hydrogen such as the ground-state hyperfine splitting or the Lamb shift have even smaller energies, on the order of μeV. They are also of fundamental interest in antihydrogen and test different types of physical phenomena than the 1S–2S transition. The BASE antiproton experiment probes CPT invariance in the baryon sector at the atto-electron volt scale – 10^{-27} GeV – and recently measured the magnetic moment of the antiproton to a precision of 1.5 parts-per-billion. Amazingly, the result was better than the most precise measurement of the proton at the time.

It is sobering to reflect on the state of antihydrogen physics when the AD started operations in 2000. The experiments at CERN's Low Energy Antiproton Ring (LEAR) in 1996 and at the Accumulator at Fermilab in 1998 had detected nine and 66 relativistic atoms of antihydrogen, respectively, which were produced by interactions between a stored antiproton beam and a gas-jet target. These experiments proved the existence of antihydrogen, but they held no potential for precision measurements.

The pioneering TRAP experiment had already developed the techniques needed for stopping and trapping antiprotons from LEAR, and demonstrated the first capture of antiprotons way back in 1986. The PS200 collaboration succeeded in trapping up to a million antiprotons from LEAR, and TRAP compared the charge-to-mass ratio of protons and antiprotons to a relative precision of about 10^{-9}. However, no serious attempt had yet been made to synthesise "cold" antihydrogen by the time LEAR stopped operating in 1996.

In 2002 the ATHENA experiment won the race to produce low-energy antihydrogen and the global number of antihydrogen atoms jumped dramatically to 50,000, observed over a few weeks of data taking. This accomplishment had a dramatic effect on world awareness of the AD via the rapidly growing Internet, and it even featured on the front page of the *New York Times*. Today in ALPHA, which succeeded ATHENA in 2005, we can routinely produce about 50,000 antihydrogen atoms every four minutes.

The antihydrogen atoms produced by ATHENA, and subsequently by ATRAP and ASACUSA, were not confined; they would quickly encounter normal matter in the walls of the production apparatus and annihilate. It would take until 2010 for ALPHA to show that it was possible to trap antihydrogen atoms. Although antihydrogen atoms are electrically neutral, they can be confined through the interaction of their magnetic moments with an inhomogeneous magnetic field. Using superconducting magnets, we can trap antihydrogen atoms that are created with a kinetic energy of less than 43 μeV, or about 0.5 K in temperature units.

In ALPHA's milestone 2010 experiment, we could trap on average one atom of antihydrogen every eight times we tried, with a single attempt requiring about 20 minutes. Today, in the second-generation ALPHA-2 apparatus, we trap up to 30 atoms in a procedure that takes four minutes. We have also learned how to "stack" antihydrogen atoms. In December 2017 we accumulated more than 1000 anti-atoms at once – limited only by the time available to mess about like this without measuring anything useful! It is no exaggeration to say that no one would have found this number credible in 2000 when the AD began running.

Since the first demonstration of trapped antihydrogen, we have induced quantum transitions in anti-atoms using microwaves, probed the neutrality of antihydrogen, and carried out a proof-of-principle experiment on how to study gravitation by releasing trapped antihydrogen atoms. These experiments were all performed with a trapping rate of about one atom per attempt. In 2016 we made several changes to our antihydrogen synthesis procedure that led to an increase in trapping rate of more than a factor of 10, and we also learned how to accumulate multiple shots of anti-atoms. At the same time, the laser system and internal optics necessary for exciting the 1S–2S transition were fully commissioned in the ALPHA-2 apparatus, and we were finally able to systematically search for this most sought-after spectral line in antimatter.

Antihydrogen's colours

The ALPHA-2 apparatus for producing and trapping antihydrogen is shown in figure 1. It involves various Penning traps that utilise solenoidal magnetic fields and axial electrostatic wells to confine the charged antiprotons and positrons from which antihydrogen is synthesised. Omitting 30 years of detail, we produce cold antihydrogen by gently merging trapped clouds of antiprotons and positrons that have carefully controlled size, density and temperature. The upshot is that we can combine about 100,000 antiprotons with about two million positrons to produce 50,000 antihydrogen atoms. We trap only a small fraction of these in the superconducting atom trap, which comprises an octupole for transverse confinement and two "mirror coils" for longitudinal confinement.

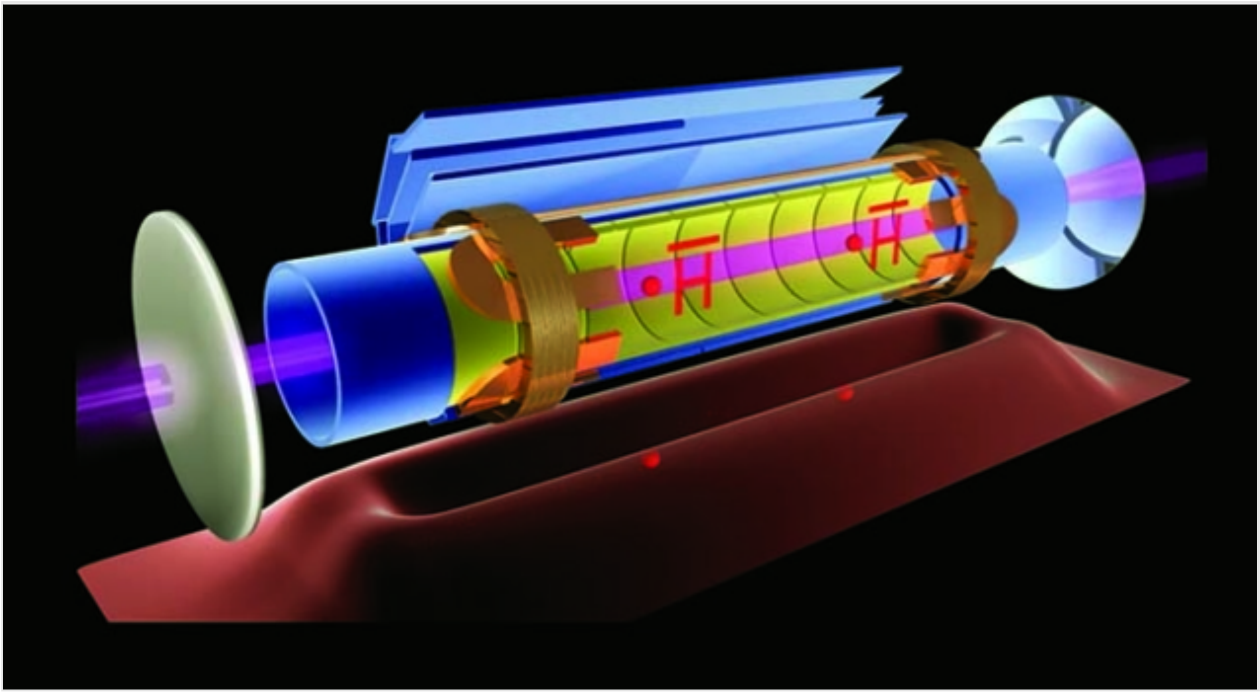

Fig. 1. A schematic cutaway of the ALPHA-2 apparatus, showing the Penning-trap electrodes (yellow), the atom-trap octupole and mirror coils (copper), and the three-layer silicon vertex detector. The mirrors for the Fabry–Pérot cavity are not to scale, and the internal diameter of the Penning-trap electrodes is about 44.5 mm. The lower part of the image illustrates the shape of the magnetic trapping potential in which antihydrogen can be confined.

Anti-atoms that are trapped can be stored for at least 1000 s, but we have yet to carefully characterise the upper limit of the storage lifetime, which depends on the quality of the vacuum. The internal components of ALPHA are cooled to 4 K by liquid helium, and antihydrogen annihilations are detected using a three-layer silicon vertex detector (SVD) surrounding the production region. The SVD senses the charged pions that result from the antiproton annihilation, and event topology is used to differentiate the latter from cosmic rays, which constitute the dominant background (figure 2).

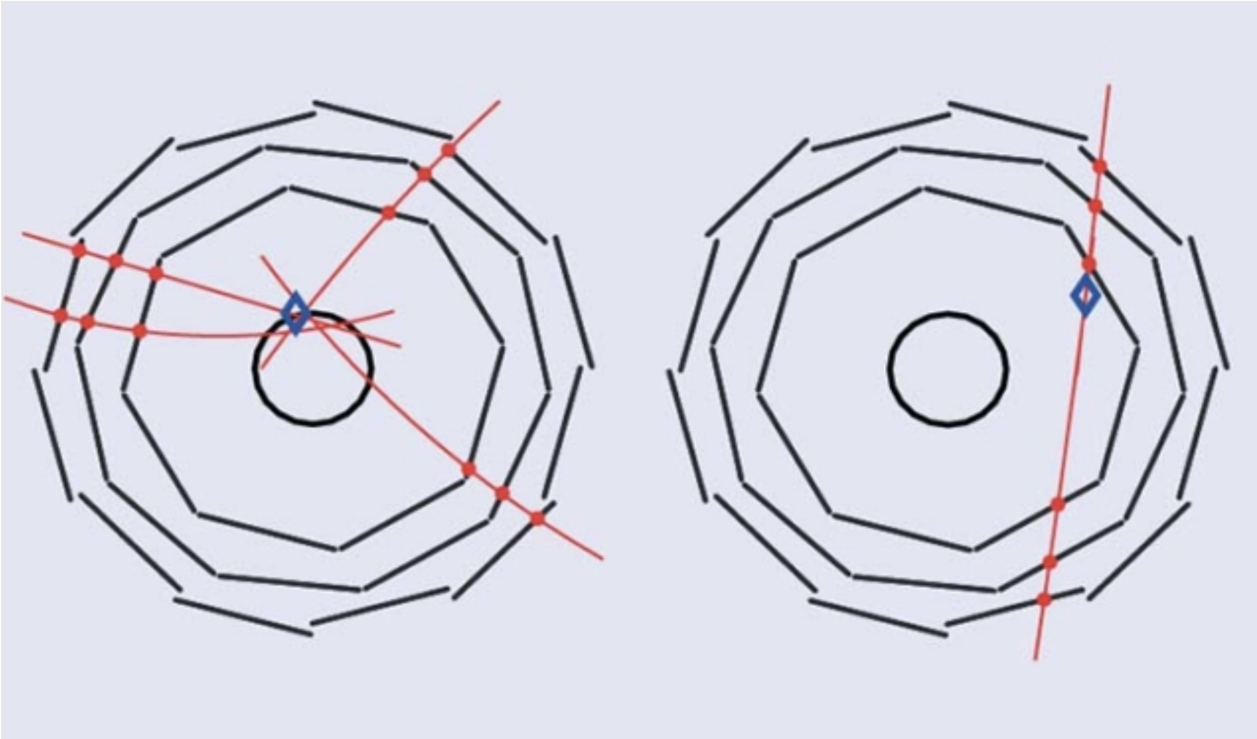

Fig. 2. The dominant background in ALPHA when searching for antihydrogen annihilations comes from cosmic rays. The left panel shows a typical topology of pion tracks resulting from an antiproton annihilation, while the right panel illustrates a typical cosmic-ray event.

A tough catch

Trapping antihydrogen is extremely challenging because the trapped, charged particles that are needed to synthesise it start out with energies measured in eV (in the case of positrons) or keV (antiprotons), whereas the atom can only be confined if it has sub-meV energy. The antihydrogen is trapped due to the interaction of its magnetic moment, which is dominated by the positron spin, with an inhomogeneous magnetic field. Even with very careful preparation of the trapped positron and antiproton clouds in a cryogenic trap, only a small fraction of the produced antiatoms are “cold” enough to be trapped. The good news is that once you have trapped them, the antiatoms stick around for long enough to perform experiments.

Compared to atomic physics with normal matter, one has to somehow make up for the dramatic reduction – at least 20 orders of magnitude – in particle number at the source. The key to this is twofold: the long interaction times available with trapped particles, and the single-atom detection sensitivity afforded by antimatter annihilation. The annihilation of an antihydrogen atom is a microscopically violent event, releasing almost 2 GeV of mass-energy that can be easily detected. This is perhaps the only good thing about working with antihydrogen: if you lose it, even just one atom of it, you know it. Conversely, the loss of a single atom of hydrogen in an equivalent experiment would go unnoticed and un-mourned if there are, say, 10^{12} remaining (a typical number for trapped hydrogen). Thus, the two experiments recently reported by ALPHA are conceptually simple: trap some antihydrogen atoms; illuminate them with electromagnetic radiation that causes the anti-atoms to be lost from the trap when the radiation is on-resonance; sit back and watch what falls out.

Let's consider first the "holy grail" (1S–2S) transition, which is excited by two, counter-propagating ultraviolet photons with a wavelength of 243 nm. The power from our Toptica 243 nm laser is enhanced in a Fabry–Pérot cavity formed by two mirrors inside the cryogenic, ultra-high vacuum system. (This cavity owes its existence to the paucity of atoms available; without the optical power buildup achieved, the experiment would not be currently possible.) The 1S–2S transition has a very narrow linewidth – this is what makes it interesting – so the laser frequency needs to be just right to excite it. The other side of the same coin is that the 2S state lives for a relatively long time, about one eighth of a second, so there can be time for an excited antihydrogen atom to absorb a third photon, which will ionise it. Stripped of its positron, the antiproton is no longer confined in the magnetic trap and is free to escape to the wall and annihilate. There is also a chance that an un-ionised 2S state atom will suffer a positron spin-flip in the decay to the ground state, in which case the atom is also lost.

In the actual experiment, we illuminate trapped antihydrogen atoms with a laser for about 10 minutes, then turn off the trap (in a period of 1.5 s) and use the SVD to count any remaining atoms as they escape. Also, using the SVD we can observe any antihydrogen atoms that are lost during the laser illumination. In this way, we obtain a self-consistent picture of the fate of the atoms that were initially trapped. The evidence for the laser interaction comes from comparing what happens when the laser has the "right" frequency, compared to what happens when we intentionally de-tune the laser to a frequency where no interaction is expected (for hydrogen). As a control, and to monitor the varying trapping rate, we perform the same sequence with no laser present. The whole thing can be summarised in a simple table (figure 3), which shows the results of 11 trials of each type.

	Atoms knocked out (events)	Expected background (events)	Atoms left over (events)	Expected background (events)
Laser on resonance	79 ± 8.9	28.4	67 ± 8.2	0.7
Laser off resonance	27 ± 5.2	28.4	159 ± 13	0.7
No laser	30 ± 5.5	28.4	142 ± 12	0.7

Fig. 3. The number of raw events that are used by ALPHA to measure the antihydrogen 1S–2S transition must be scaled by an overall detection efficiency to represent the actual numbers of atoms. In this table, the detection efficiencies are different for the first column (0.376) and the third column (0.688) because the algorithms used to distinguish annihilations from cosmic rays are tuned differently in order to reflect the very different observation times (600 s versus 1.5 s for each trial).

A quick glance reveals that the off-resonance and no-laser numbers are consistent with each other and with "nothing going on". In contrast, the on-resonance numbers show excess events due to atoms knocked out when the laser is on, and a dearth of events left over after the exposure. If we consider the overall inventory of antihydrogen atoms and compare the on- and off-resonance data only, we see that about 138 atoms (79–27)/0.376 have been knocked out, and 134 atoms (159–67)/0.688 are missing from the left-over sample, so our interpretation is self-consistent within the uncertainties.

This initial "go/no-go" experiment demonstrates that the transition is where we expect it to be for hydrogen and localises it to a frequency of about 400 kHz (the laser detuning for the off-resonance trials) out of 2.5×10^{15} Hz. That's a relative precision of about 2×10^{-10}, or 2×10^{-18} GeV in absolute energy units, just for showing up, and this was achieved by employing a total of just 650 or so trapped atoms. The next step is obviously to measure more frequencies around the resonance to study the shape of the spectral line, which will allow more precise determination of the resonance frequency. Note that CPT invariance requires that the shape must be identical to that expected for hydrogen in the same environment. Determination of this lineshape was the main priority for ALPHA's 2017 experimental campaign, so stay tuned.

To hyperfine splitting and beyond

A similar strategy can be used to study other transitions in antihydrogen, in particular its hyperfine splitting. With ALPHA we can drive transitions between different spin states of antihydrogen in the magnetic trap. In a magnetic field, the 1S ground state splits into four states that correspond, at high fields, to the possible alignments of the positron and antiproton spins with the field (figure 4). The upper two states can be trapped in ALPHA's magnetic trap and, using microwaves at a frequency of about 30 GHz, it is possible to resonantly drive transitions from these two states to the lower energy states, which are not trappable and are thus expelled from the trap.

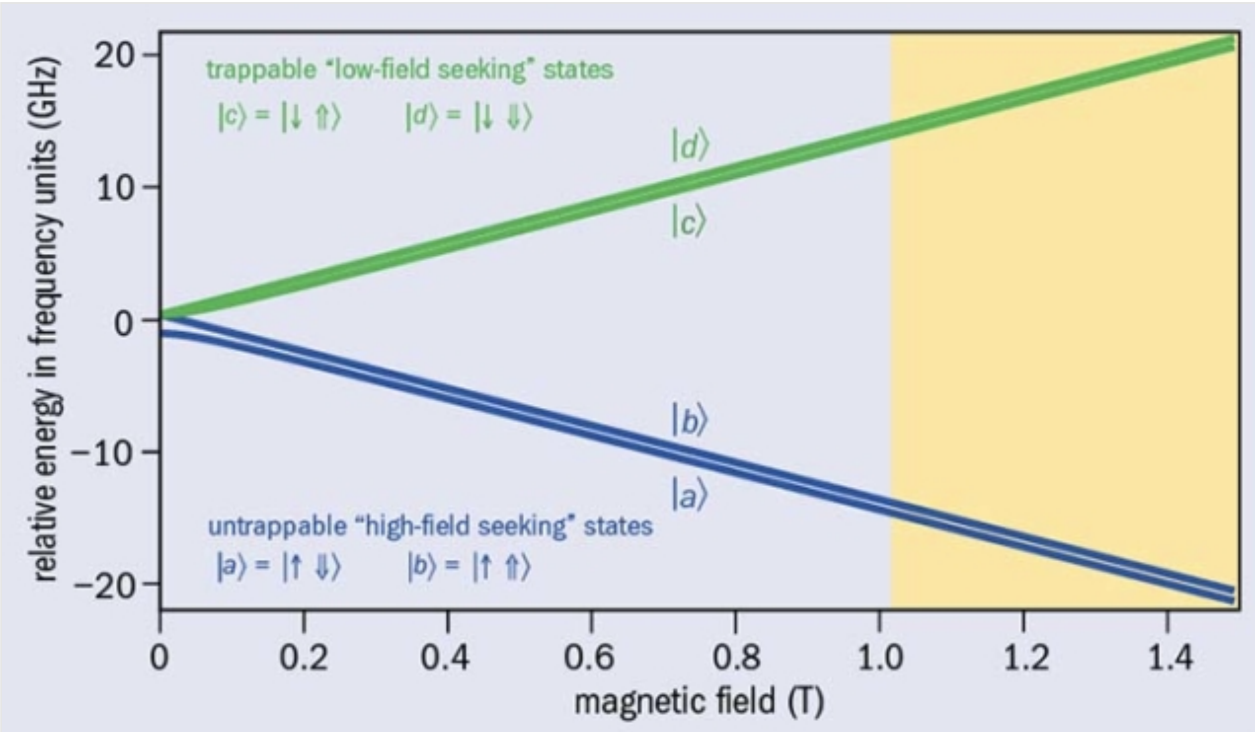

Fig. 4. A Breit–Rabi diagram showing the hyperfine energy levels of hydrogen in a magnetic field. The arrows in the state labels refer to the electron (left) and proton spin orientations, while the yellow shaded region illustrates the range of magnetic field strength in the ALPHA trap.

We concentrate on the two transitions |d⟩ → |a⟩ and |c⟩ → |b⟩, which in the ALPHA trapping field (minimum 1 T) correspond to positron spin flips. We had previously demonstrated that these transitions are observable, but in 2016 we took the next step and actually characterised the spectral shapes of the two discrete transitions in our trap. We are now able to accumulate antihydrogen atoms, scan the microwave frequency over the range corresponding to the two transitions, and watch what happens using the SVD. The result, which may be considered to be the first true antihydrogen spectrum, is shown in figure 5.

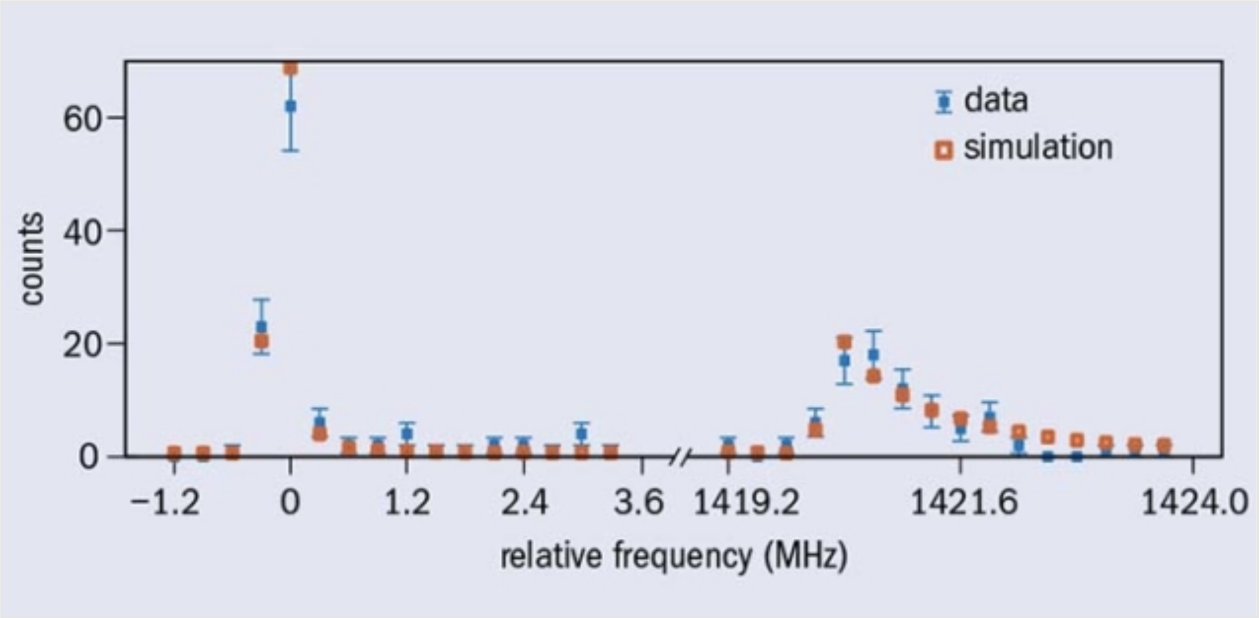

Fig. 5. The number of detected annihilation events plotted versus microwave frequency. The two spectral lines represent the *c* to *b* (left) and the *d* to a transitions (see main text and figure 4).

The difference between the onset frequencies of the two spectral lines gives us the famous ground-state hyperfine splitting (in hydrogen, the ground-state hyperfine transition is the well known "21 cm line", so beloved of radioastronomers and those searching for signs of extraterrestrial life). From figure 5 we extract a value for this splitting of 1420.4 ± 0.5 MHz, for a relative precision of 3.5×10^{-4}; the energy sensitivity is 2×10^{-18} GeV. In normal hydrogen this number has been measured to be 1420.405751768 (2) MHz – that's 1.2×10^{-12} relative precision or a shockingly small 10^{-26} GeV. ALPHA is busily improving the precision of the antihydrogen hyperfine measurement, and the ASACUSA collaboration at the AD hopes to measure the same quantity to the ppm level using a challenging antihydrogen-beam technique; an analogous experiment on hydrogen was recently reported (*CERN Courier* December 2017 p23).

The antihydrogen atom still holds many structural secrets to be explored. Near-term perspectives in ALPHA include the Lyman-alpha (1S–2P) transition, with its notoriously difficult-to-produce 121.5 nm wavelength in the vacuum ultraviolet. We are currently attempting to address this with a pulsed laser, with the ultimate goal to lasercool antihydrogen for studies in gravitation and for improved resolution in spectroscopy. To give a flavour of the pace of activities, a recent daily run meeting saw ALPHA collaborators actually debate which of the three antihydrogen transitions we should study that day, which was somewhat surreal. In the longer term, even the ground-state Lamb shift should be accessible using ALPHA's trapped antiatoms.

It is clearly "game on" for precision comparisons of matter and antimatter at the AD. It is fair to say that the facility has already exceeded its expectations, and the physics programme is in full bloom. We have some way to go before we reach hydrogen-like precision in ALPHA, but the road ahead is clear. With the commissioning of the very challenging gravity experiments GBAR, AEGIS and ALPHA-g over the next few years, and the advent of the new low-energy ELENA ring at the AD (*CERN Courier* December 2016 p16), low-energy antimatter physics at CERN promises a steady stream of groundbreaking results, and perhaps a few surprises.

Further reading

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