Antihydrogen studies in ALPHA

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Abstract. The ALPHA experiment studies antihydrogen as a means to investigate the symmetry of matter and antimatter. Spectroscopic studies of the anti-atom hold the promise of the most precise direct comparisons of matter and antimatter possible. ALPHA was the first to trap antihydrogen in a magnetic trap, allowing the first ever detection of atomic transitions in an anti-atom. More recently, through stochastic heating, we have also been able to put a new limit on the charge neutrality of antihydrogen. ALPHA is currently preparing to perform the first laser-spectroscopy of antihydrogen, hoping to excite the 2s state using a two-photon transition from the 1s state. We discuss the recent results as well as the key developments that led to these successes and discuss how we are preparing to perform the first laser-spectroscopy. We will also discuss plans to use our novel technique for gravitational tests on antihydrogen for a direct measurement of the sign of the gravitational force on antihydrogen.

1. Introduction

Antihydrogen, the bound state of an antiproton and a positron, is a promising test-bed for high precision comparisons of matter and antimatter and thus for testing fundamental symmetries. However, a fundamental experimental challenge is that antihydrogen has to be made in the laboratory starting from high energy antiprotons, but high precision measurements require low energies and ultimately trapping due to the low quantities available. The neutral nature of antihydrogen makes it difficult to trap and manipulate, but is also the reason why it holds the potential for gravitational measurements, and for the use of high precision atomic spectroscopy techniques for comparisons of matter and antimatter. In recent years the ALPHA experiment has noted a number of breakthroughs that are helping pave the way for such comparisons. These include the trapping and holding of antihydrogen for extended periods [1, 2], the first observed of atomic transitions in the from of a positron spin-flip (hyperfine transition) in the ground state [3], demonstration of a novel technique for studying the effects of gravity [4] and measurements of the charge neutrality of antihydrogen [5]. These feats have put ALPHA at the lead of the

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field of antihydrogen physics and we present here some of the highlights as well as upcoming challenges for continuing from these successes.

2. Synthesising and trapping antihydrogen

Antihydrogen is now synthesised and trapped in an upgraded version of the original ALPHA apparatus that has been operational since 2013. Figure 1 shows an overview of the setup. The spin-flip and gravitational results below were performed using the previous version of ALPHA, which for the purposes of this discussion, was mostly identical. The upgrade has served to separate out the antiproton manipulations at keV energies in preparation for the ELENA ring [6]and as a means to allow laser-access to the antihydrogen trapping volume as discussed in Ref. [7].

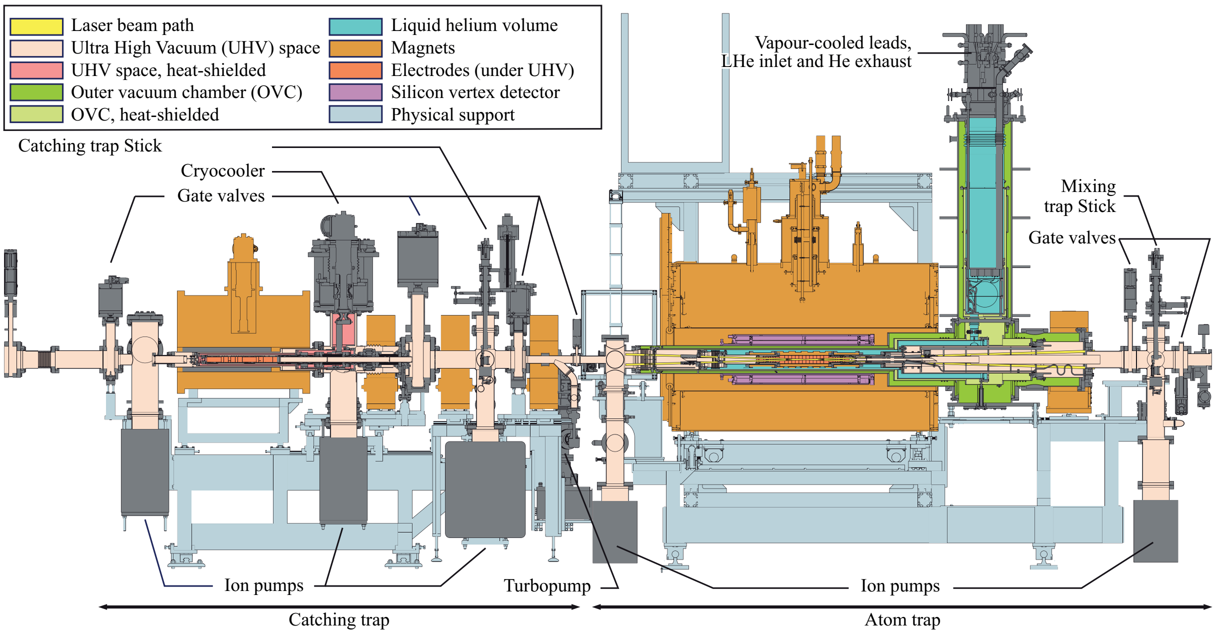

Figure 1. ALPHA setup as installed since 2013. The catching trap (left section) captures and prepares antiprotons for transfer to the atom trap (right). Positrons originate from the positron accumulator (not shown) to the right of the atom trap. There is access on the left and the right side of the atom trap for up to four lasers to enter at a grazing angle (2.34°) to the axis, paths crossing at the centre of the apparatus.

Antiprotons are sourced from the CERN antiproton decelerator (AD) at 5.3 MeV. The AD delivers a $\sim$130 ns bunch of $\sim 3\times10^7$ antiprotons every about 2 min. The antiprotons are degraded to keV energies and are dynamically trapped in a Penning-Malmberg trap. All charged-particle traps in the ALPHA apparatus are Penning-Malmberg traps where axial magnetic fields confine the particles transversely, and a large number of independently excitable co-axial cylinders provide axial electric fields that ensure axial confinement. The antiprotons are cooled to $\sim$100 K by being merged with a cloud of pre-loaded electrons that cool through the emission of cyclotron radiation towards the ambient temperature. The traps are all cooled to cryogenic temperatures (5-7 K). The antiproton plasma undergo a number of manipulations, such as being transferred from the catching trap to the atom trap (Figure 1), before eventually being injected into a plasma of cold positrons for antihydrogen formation. Positrons are sourced from a solid-neon moderated ^{22}Na source and accummulated in a Surko-type buffer gas accummulator [6]. For antihydrogen formation typically 2×10^4 antiprotons and 2×10^6 positrons are merged yielding of order 10^4 antihydrogen atoms of which on average one is trapped [3]. The depth of the magnetic-minimum neutral trap is about 50 μeV.

3. First atomic transitions

While only about one anti-atom is currently available per experiment, it can be held for long times, up to ~15 min. [2]. This allows for a long interaction time which somewhat compensates for the low number. Profiting from this we have carried out a first measurement of an atomic transition in antihydrogen using microwaves to flip the spin of the positron in the trapped ground state to an untrapped state [3]. Figure 2a shows the Breit-Rabi diagram for ground state antihydrogen, and shows how in a magnetic field, the two hyperfine ground state splits up in four, whereof two are trappable in that they are so-called low-field seekers (diamagnetic).

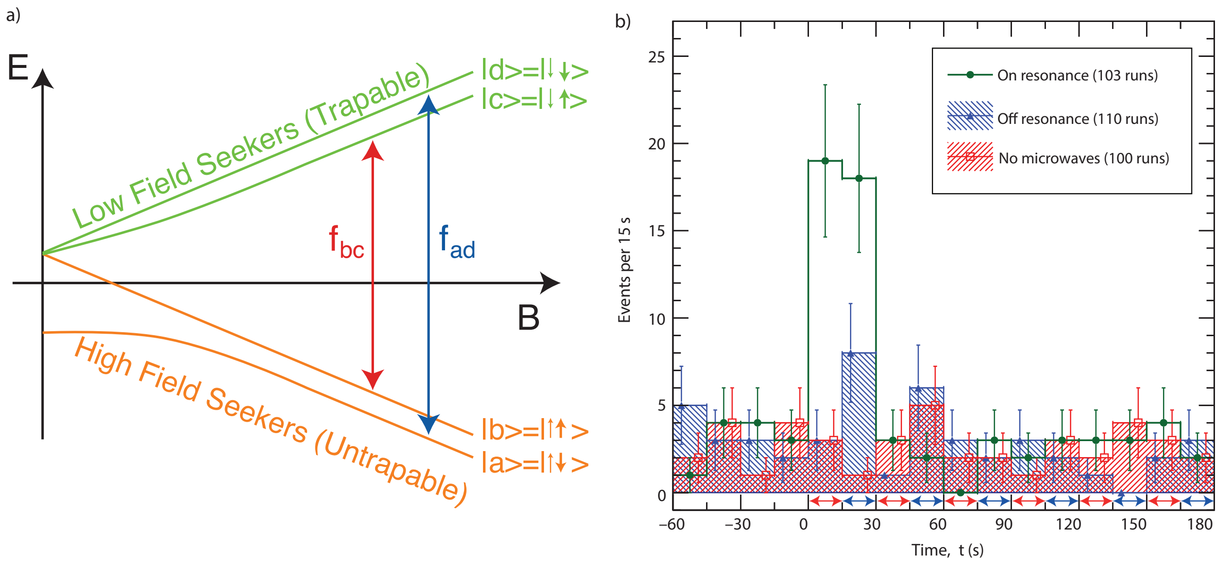

Figure 2. (a) Breit-Rabi diagram of (anti)hydrogen indicating the two transitions addressed by our experiment. The fat (thin) arrows indicate the direction of the positron (antiproton) spin relative to the external field. (b) Experimental observation of annihilations during microwave illumination. The microwave illumination starts at 0 s, and every 15 s they are shifted to address either f_{bc} or f_{ad} as illustrated. During each 15s interval the frequency is slowly swept 15 MHz, to ensure overlap with the sharp resonance peak [3].

By injecting microwaves of the frequency expected for hydrogen in our magnetic fields, we succeeded in detecting the resonant ejection of antihydrogen atoms. Figure 2b shows how we detected the appearance of annihilations during microwave illumination when the frequency was tuned to be on-resonance. On-resonance, in this case, includes a 15 MHz sweep of the microwave frequency that was around 29 GHz in order to ensure that we did not miss the transition completely, and illumination of both transitions (blue and red arrows on Figure 2) to increase statistics. In the measurement we compare on-resonance and off-resonance experiments. For the off-resonance experiments the atomic transition frequency was shifted 100 MHz up relative to nominal by increasing the magnetic field by 3.5 mT while keeping the microwave frequency constant. This means that roughly speaking the observed resonance is within 100 MHz of that expected from hydrogen, and as the frequencies observed were around 29 GHz, this corresponds to a relative precision of about 4×10^{-3}, thus marking the advent of antimatter spectroscopy.

4. Gravitational measurements

The ALPHA experiment uses a silicon strip detector to register antiproton annihilation by tracking the charged pions stemming from the annihilations. This allows reconstruction of both the position and time of the annihilation and is used to separate antiproton annihilations from cosmic rays passing through the detector. We have demonstrated how this position and time knowledge can also be used to probe the force of gravity on antihydrogen. In current experiments antihydrogen is released from the trap by essentially initiating a quench of the super-conducting trap magnets which allows the trap fields to decay with a time constant of about 9 ms. The trap is thus at about 1% of its full depth only 30 ms after the quench is initiated. This is the window during which we look for annihilations, and the cosmic ray induced background during this time is about one fake annihilation event every 700 experiments. The last antihydrogen atoms to escape while de-energising the trap are also the coldest, and those whose annihilation position is most sensitive to the influence of gravity [4]. Figure 3 shows a simulation of the release of antihydrogen from our trap with a hypothetical gravitational to inertial mass ratio of 100 and demonstrates the principle. We have done the exercise on actual data, but as the vertical extent of our trap is only 4 cm, and the experiment was not done with this test in mind, there is limited sensitivity and the result was that we could reject ratios of the gravitational to inertial mass of antihydrogen >75 at a statistical significance level of 5%, with worst-case systematic errors increasing the minimum rejection ratio to 110, and with similar bounds for negative gravitational mass.

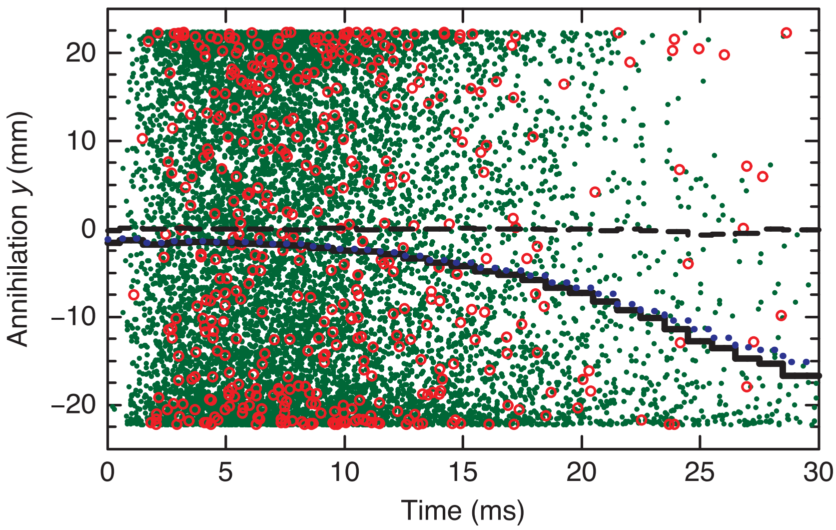

Figure 3. Simulation of annihilation locations. The times and vertical (y) annihilation locations (green dots) of 10,000 simulated antihydrogen atoms during de-energisation of the magnetic trap assuming that gravitational mass is 100 times the inertial mass. We observe a clear tendency for annihilation in the bottom half (y<0) as illustrated by the black line, that plots the average annihilation locations in 1 ms bins. The average was taken by simulating 900,000 anti-atoms of which the green dots are a sub-sample. The black dashed line shows the average for identical gravitational and inertial mass [4].

In spite of the rather wide bounds, this exercise demonstrated the potential for conducting gravity measurements starting from trapped antihydrogen, and as such has motivated us to work towards a vertical version of our setup that, using this technique, should be able to measure the gravitational acceleration of antimatter. This future upgrade is currently in the early design stages.

5. Neutrality of antihydrogen

It is supposed that antihydrogen is charge neutral. However, assuming charges are simply additive, our current knowledge of the charge of antihydrogen made from and antiproton and a positron is limited by our knowledge of the charge of the positron such that combining the two leads us to infer a bound of $|Q| \leq 25$ p.p.b. on the charge Qe of antihydrogen where e is the elementary charge. We have implemented a new technique to measure the charge of antihydrogen [5].

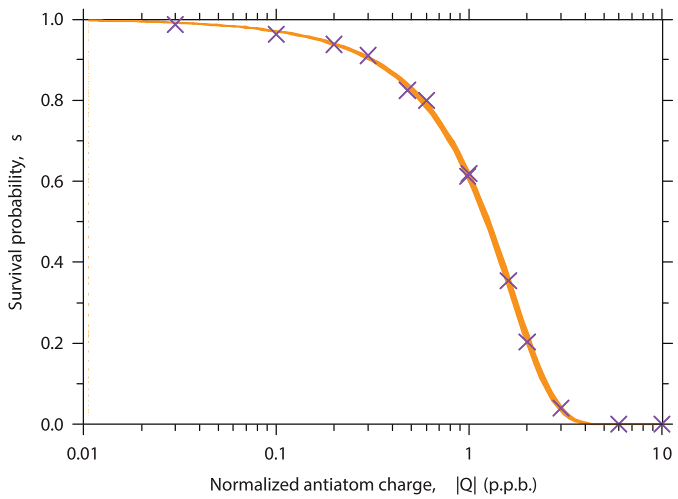

Figure 4. Simulated survival probability s as a function of $|Q|$ for the stochastic trials [5].

We apply a series of randomly timed electrical fields across our trap while holding the trapped antihydrogen inside. If antihydrogen had a charge Qe, and the average kick of each pulse is $\Delta\Phi$, such pulses will increase the kinetic energy of the antihydrogen atoms in our trap by about $|Q|e\Delta\Phi\sqrt{N}$, where N is the number of pulses. The antihydrogen would escape from the trap if it gained about the energy of the trap depth E_{well}, i.e. if

$$|Q| \leq \frac{E_{well}}{e\Delta\Phi\sqrt{N}}. \tag{1}$$

Thus by measuring if antihydrogen survives this treatment for a fixed number of kicks we can set an upper limit on its charge. The simple estimate based on the equation above does not include the averaging of the motion of the antihydrogen atoms in the neutral trap, nor the time to raise a given field and the randomness of the antihydrogen atom's position at a given time. These can all be included in a more elaborate simulation of our full apparatus and the exact responses of our electrodes etc. This simulation showed that, with our particular set of experiments, the survival probability of antihydrogen would be correlated with it's charge as depicted in Figure 4. In our measurements we did not succeed in kicking any antihydrogen atoms out of the trap in 10 trails with 12 atoms observed in total, and we concluded that the upper limit on the charge of antihydrogen was $|Q| < 0.71$ parts per billion (one standard deviation), or about 20 times improved compared to the bound based on adding the positron and antiproton charges.

6. Laser-spectroscopy

The ALPHA apparatus (Figure 1) was upgraded in particular to allow laser spectroscopy of antihydrogen. It allows for up to four independent laser-paths to cross through the antihydrogen trapping region. The 1S-2S transition of interest is dipole forbidden and is therefore a two-photon transition. By illuminating with retro-reflected light the first order Doppler shift is cancelled and Doppler broadening eliminated, resulting in both a narrower line and a higher transition rate for a given power. However, as pointed out in Ref. [2] the trapped antihydrogen atoms have an energy distribution consistent with a truncated high temperature distribution. This means that the antihydrogen atoms essentially explore the full 0.4 L volume of the magnetic minimum trap. In order to ensure a transition rate high enough to be detectable we have therefore implemented an internal enhancement cavity for the 243 nm laser light needed for this transition. State-of-the art continuous wave (cw) lasers can deliver up to around 200 mW at this wavelength, but due to the unfortunate details of our experiment, in particular the only-one-atom-at-a-time, we estimate that we need around 2 W of laser light to ensure a detectable signal. The laser-setup to deliver narrow-band, SI-second-referenced laser-light and enhance it is illustrated in Figure 5. We expect to see a first measurement in 2016.

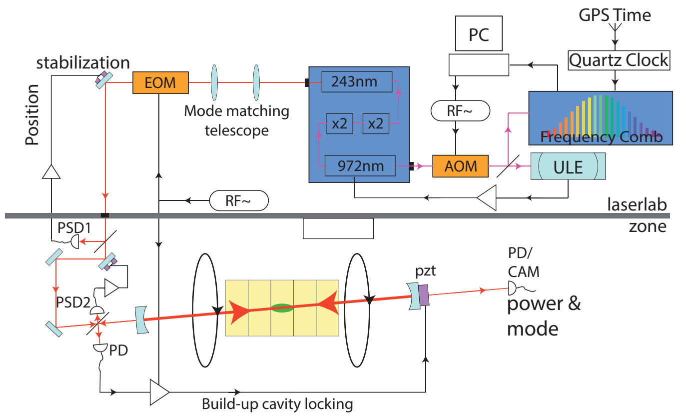

Figure 5. Laser setup for two-photon spectroscopy in ALPHA. The top part laser-setup is housed in a separate room (laserlab). The light is thus transported about 6 m from the laser setup before it enters the antihydrogen apparatus, necessitating a position-stabilisation system. The 243 nm laser light is generated in a commercial system by quadrupling a 972 nm amplified laser-diode which is locked to a commercial stable Ultra-Low-Expansion glass (ULE) cavity for stability and whose frequency is referenced, via a commercial frequency comb, to a quartz-oscillator referenced to the Global Positioning System (GPS) clock.

As pointed out above a limiting factor (but not detrimental) in these experiments is the low number of trapped anti-atoms. Fundamentally the challenge is that our trap depth is around 50 μeV, or equivalent to about 0.5 K. The antihydrogen must be made at lower energy than this depth and inside the trap to be held. We have previously demonstrated cooling of the antiprotons, carrying almost all the momentum of the antihydrogen, to around 9 K [8]. However, we observe that, upon injection into the positron plasma, they thermalise with the positrons faster than they recombine with them. It is thus, currently, the positron temperature that sets the antihydrogen temperature. In order to cool the positrons further we have made an effort to eliminate external noise and improve the cryostat, but their temperature will also be limited by magnetic field-inhomogeneities, which are intrinsic to a magnetic minimum trap, so we have started working towards active cooling using laser-cooled Beryllium ions [9]. Simulations show that this strategy holds the promise of reducing our positron temperatures to about 5 K, or about an order of magnitude lower than the temperatures at which we are currently operating. Such an improvement should result in an up to two orders of magnitude increase in the number of trapped antihydrogen, a potential game-changer for probing the anti-atoms.

7. Conclusions

We here presented the latest results of the ALPHA antihydrogen experiment and discussed some exciting upcoming directions. The ALPHA programme is concerned with comparing antihydrogen and hydrogen in all ways possible in order to help understand the fundamental asymmetry of our Universe. We discussed how we now routinely trap antihydrogen in our trap and demonstrated how this feat is a powerful platform for further experimentation, already having measured the first atomic transition, tested the neutrality of antihydrogen and demonstrated a technique for measuring the gravitational force on antihydrogen. We also discussed how we are proceeding towards laser-spectroscopy and how we plan to increase the antihydrogen trapping rates significantly.

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