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Measurements of Properties of Antihydrogen

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The ALPHA project at the CERN AD is testing fundamental symmetries between matter and antimatter using trapped antihydrogen atoms. The spectrum of the antihydrogen atom may be compared to ordinary hydrogen where it has been measured very precisely. CPT conservation, which underpins our current theoretical framework, requires equality of the masses and charges of matter and its antimatter partners, so antihydrogen spectroscopy presents a path to precision CPT tests.

I will discuss the techniques used by ALPHA to trap more than 8000 antihydrogen atoms in 2016, and interrogate them for 600s. The 1S-2S transition in antihydrogen has been observed for the first time, and it agrees with its hydrogen counterpart within an uncertainty of 400 kHz or 0.2 ppb. The charge of the antihydrogen atom has been bounded below $0.710^{-9}e$. A value of 1420.4 0.5MHz for the hyperfine splitting has been obtained from observation of the positron spin resonance spectrum.

Keywords: Antimatter; antihydrogen; matter/antimatter symmetry.

1. Introduction

As a consequence of his formulation of a relativistic quantum mechanics, Paul Dirac predicted the existence of antimatter, unseen counterparts to the spin 1/2 particles with opposite charge but with otherwise identical properties[1]. This prediction was met with great scepticism. Experimental verification came swiftly with discovery of the positron by Carl Anderson[2], exciting great public interest. Physical theories were assumed at that time to satisfy not only Lorentz invariance, the continuous symmetry of special relativity, but also its finite symmetries of parity (P), time reversal (T), and charge conjugation (C). In this context charge conjugation was recognized as the symmetry between matter and antimatter. While it has been experimentally determined that the P and CP symmetries are broken in weak processes, there has been no observed violation of the combination CPT. It has been shown[3] that quantum field theories satisfying locality and causality and having a hermitian lagrangian must conserve CPT, so any violation would fundamentally impact our present theoretical framework. CPT invariance predicts the equality of the energy levels and decay widths in hydrogen and antihydrogen, and that the charges of matter particles and their corresponding antiparticles are equal in magnitude – this is also a consequence of gauge invariance. Our experimental program is to compare properties of hydrogen (H) and antihydrogen ($\overline{H}$) with the highest possible precision. The corresponding measurements in H are among the most accurate in experimental physics. Other talks in this session have explored the consequences of breaking CPT in more detail. This talk will cover only the CPT tests performed by the ALPHA collaboration.

2. Making and Trapping Antihydrogen

The measurements I will describe involve synthesizing antihydrogen from antiprotons ($\overline{p}$) from the CERN AD, and positrons (e+) from our accumulator, in a Penning trap, catching some of them in a magnetic trap, and then interrogating them to study the observable of interest. The trap[4], schematically shown in Fig 1 is surrounded by a silicon vertex detector (SVD) which efficiently detects the time and position of $\overline{p}$ or $\overline{H}$ annihilation vertices of on the trap electrodes. This can be detected during the interrogation, and the number surviving interrogation can also be measured by counting annihilations when the trap magnets are de-energized. We

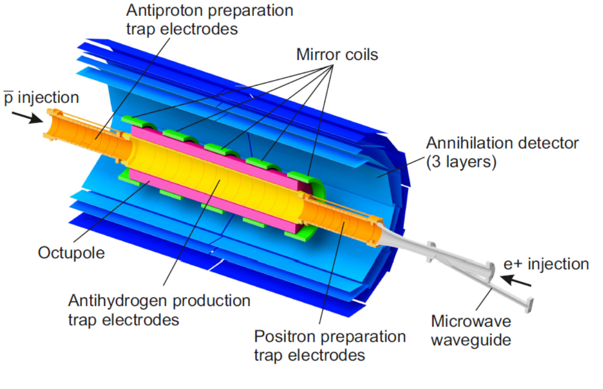

Fig. 1. Schematic of ALPHA2 atom trap. Not shown is a solenoid magnet surrounding the apparatus and producing a 1T field.

trapped our first antihydrogen in 2010, achieving a rate of 0.2 observed annihilation vertices / trial[5]. Currently 90000 $\overline{p}$ and 1.6 10^6 e^+ are mixed, producing 25000 $\overline{H}$, most of which are too energetic to trap. The improvements enabling our present 25 trapped $\overline{H}$ /trial are: a new cryostat providing a stable thermal environment, rotating wall compression in the strong drive regime coupled with evaporative cooling to produce highly reproducible e+ and $\overline{p}$ plasmas[6], slow merging of the e+ and $\overline{p}$ plasmas to synthesize $\overline{H}$, and stacking of multiple $\overline{H}$-synthesis cycles in the atom trap[7] for a single interrogation.

3. Limit on $\overline{H}$ charge from Stochastic Acceleration

The $\overline{H}$ atom offers us the ability to measure directly a small difference between the charges of its components, which is much easier than measuring the components directly. In this experiment[8] the charge is probed by applying stochastically varying potentials to the Penning electrodes, subjecting the trapped $\overline{H}'s$ to random 100V kicks. Over two days in 2015 we performed 10 runs with stochastic potentials applied during a 120s hold period, and observed 12 $\overline{H}$ annihilations when the trap magnets were de-energized at the end of the hold. These were interleaved with 10 runs having the same hold period but no applied potentials. 12 $\overline{H}$ annihilations were also observed at the end of these runs, so there is no evidence that the potentials expelled $\overline{H}'s$ from the trap.

A simple estimate of the expected energy gain of a charge Qe at the end of the hold period after N $\Delta\Phi$ volt kicks is $\sqrt{N}\Delta\Phi|Q|e$. We used $\Delta\Phi = 100V$ and $N =$ 84900 kicks, and a trap depth of 0.5K yielding an estimate of $|Q| < 1.6\ 10^{-9}$. A value of the survival probability is obtained from simulating trajectories using a detailed model of our trap and the applied stochastic potentials for a range of Q values. A Bayesian determination of the range of survival probabilities corresponding to a 1 σ variation in the data yields a bound of $|Q| < 0.7\ 10^{-9}$. This includes a systematic uncertainty for the trap model. An order-of-magnitude improvement in this bound could be obtained by increasing the hold time and using stacking and higher trapping rates.

Our bound may be used (Fig 2) together with the precise measurements of $\overline{p}He$ atomic transitions[9], the $\overline{p}$ cyclotron frequency[10], and the 1S-2S transition in positronium[11] to put a 1 σ bound of 0.7 10^{-9} on a positron charge anomaly - a factor 40 improvement. The bound on a positron mass anomaly $\frac{m_{e^-} - m_{e^+}}{m_{e^-}}$ is also improved to 20 10^{-9} .

4. Measurement of the $\overline{H}$ Hyperfine Splitting

Fig 3 shows the expected energy levels of ground state antihydrogen in a magnetic field. Only the $|c>$ and $|d>$ levels are trapped, and driving the $|c> \rightarrow |b>$ and $|d> \rightarrow |a>$ transitions with microwave radiation expels the $\overline{H}$ from the trap. Our 2012 proof-of-principle measurement of these $\overline{H}$ positron spin resonances (PSR)[12]

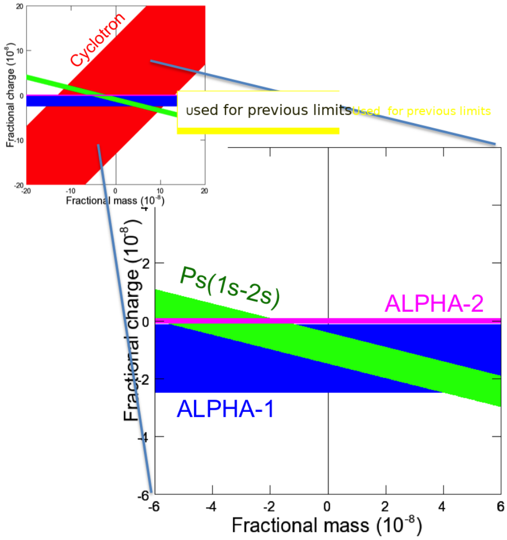

Fig. 2. Bounds on the positron mass and charge anomalies. Previous bounds came from the overlap of cylotron frequency and positronium 1S-2S measurements.

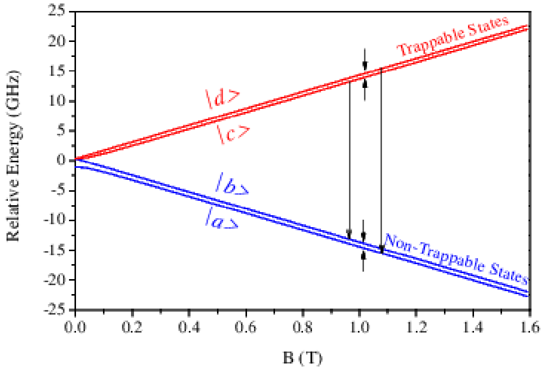

Fig. 3. Ground state antihydrogen energy levels in a magnetic field. The ALPHA field is 1T, and we drive the $|c >\rightarrow |b >$ and $|d >\rightarrow |a >$ transitions.

with 100 MHz precision was limited by our knowledge and control of the magnetic fields in our apparatus. The improvements in our ability to measure and control the fields, together with the increased trapping rate allowing measurement of both transitions in a single trial has enabled us to measure the lineshapes of these resonances in the same field, subject only to short-term drifts[13]. The inhomogeneous trap field produces an asymmetric lineshape with a sharply defined onset at the field minimum. The frequency difference between the two onsets represents the ground state hyperfine splitting is independent of the field strength and the number of anti-atoms trapped. The field at trap center measured daily to 0.3mT from electron

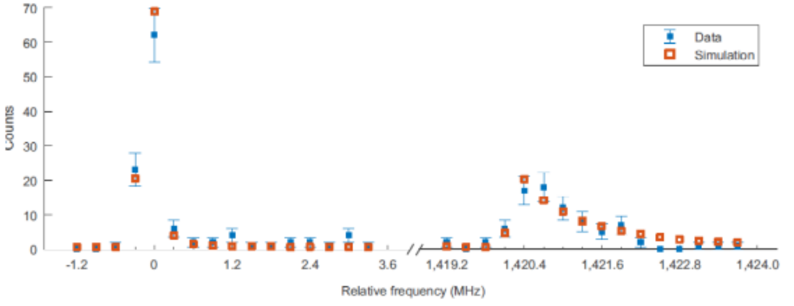

Fig. 4. Spectrum of the $|c> \to |b>/$ (lower) and $|d> \to |a>$ ground state transitions.

cyclotron resonance measurements on small electron plasmas. This also determines the microwave electric field strength at the trap center.

The run protocol consisted of irradiating 14 trapped $\overline{H}$s over the $|c> \to |b>$ transition in 16 300 kHz steps advancing every 4 s with 160 mW microwaves, scanning the $|d> \to |a>$ transition at the same rate with 320 mW microwaves, and de-energizing the trap to detect the survivng $\overline{H}$s. The results of 22 such runs taken over 3 days is shown in Fig 4. dependence of the microwave transmission through the electrode column. The lineshape is determined by the spin-flip probability and the number and trajectories of the remaining $\overline{H}$. Good agreement with a simulation using the measured microwave power and the trap dynamics can be seen. The difference in shape of the upper and lower transitions comes from the frequency dependence of transmitted microwave power. The resulting hyperfine splitting is $a/h = 1,420.4 \pm 0.5$ MHz, consistent with expectations for atomic hydrogen at the level of four parts in 10^4. There are excellent prospects for another order-of-magnitude improvement by using finer bins and better categorization of field drifts. A direct measurement of the $|d> \to |c>$ transition is potentially more precise, but radiation at that frequency is not transmitted by the electrode column. Work is proceeding on a resonator/electrode for this measurement. A complementary zero-field measurement is being pursued by the Asakusa Collaboration[14].

5. Observation of the $\overline{H}$ 1S-2S Transition

The 1S-2S transition in hydrogen has been measured to an astounding few parts in 10^{-1515}. Measuring it in antihydrogen to test CPT conservation was the original motivation for the ATRAP and ATHENA/ALPHA experiments. Performing this measurement on small numbers of trapped antihydrogen atoms instead of a cold atomic beam introduces additional challenges[16].

The ALPHA2 cryostat has access ports for four laser ports, each crossing the trap center at an angle of 2°. A particular challenge is the Fabry-Pérot buildup cavity installed within the UHV volume of the cryostat. the alignment piezzo must have sufficient adjustment under these conditions. A cavity finesse of 250 and power $> 1W$ with a linewidth $< 10kHz$ has been achieved.

The transitions of interest will excite the trapped $1S|c>$ and $|d>$ levels (Fig 3) to their corresponding 2S levels. The frequencies differ primarily because the hyperfine splitting of the 1S and 2S states are different. The trapping field is flattened using the inner three mirror coils to maximize the volume of resonance overlap with the laser beam. An $\overline{H}$ in the 2S state can be ionized by another 243nm photon, decay back to its original state, or decay via 2P mixing to a $1S|a>$ or $|b>$ state which escapes the trap and annihilates. An experimental run consisted of irradiating 10 trapped $\overline{H}$s at the $1S|d> \rightarrow 2S|d>$ hydrogen transition frequency for 300s, repeating this for the $1S|c> \rightarrow 2S|c>$ frequency, and de-energizing the trap. These were interleaved with runs with their frequencies detuned by 200kHz, and with runs with the same hold times but no laser.

Table 1. 1S-2S Resonance Yields

Series Type	Surviving Counts	Lost %	Appearance Counts	Appearance %	Power mW
Off Resonance	159	56 ±7	7	71 ±16	1100
On Resonance	67		79		1100
No Laser	142	-16±6	5	4±-8	0

Consistent resonance signals are clearly seen both during and following the laser irradiation. Within the 400kHz @121nm bound the H and $\overline{H}$ transitions have the same energy. A measurement of the lineshape with a precision goal of several ppt is currently being attempted.

6. Summary

Measurements of the $\overline{H}$ charge, hyperfine splitting and 1S-2S transition have placed more stringent limits on a difference between H and $\overline{H}$, and significantly improvement in these values is expected in the near future.

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