Testing CPT Symmetry with Antihydrogen at ALPHA

Celeste Carruth, Ph.D.

Former student and postdoc in the ALPHA collaboration; currently a postdoc in the TIQI group at ETH Zürich

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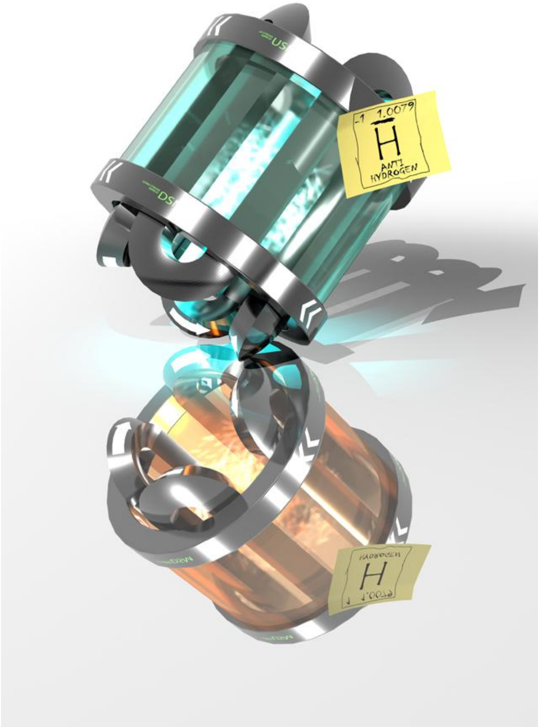
Antimatter: Why Does It Matter?

- The Standard Model predicts the universe should have nearly equal amounts of matter and antimatter, but we haven't found any large quantity of antimatter
- Charge Parity Time (CPT) symmetry predicts the fundamental properties of antimatter should have the same magnitude as matter [1], and a violation of CPT symmetry would break the standard model
- Precision measurements on antimatter are necessary in order to test CPT symmetry and try to find an explanation for the missing antimatter



http://raman.physics.berkeley.edu/gallery.html

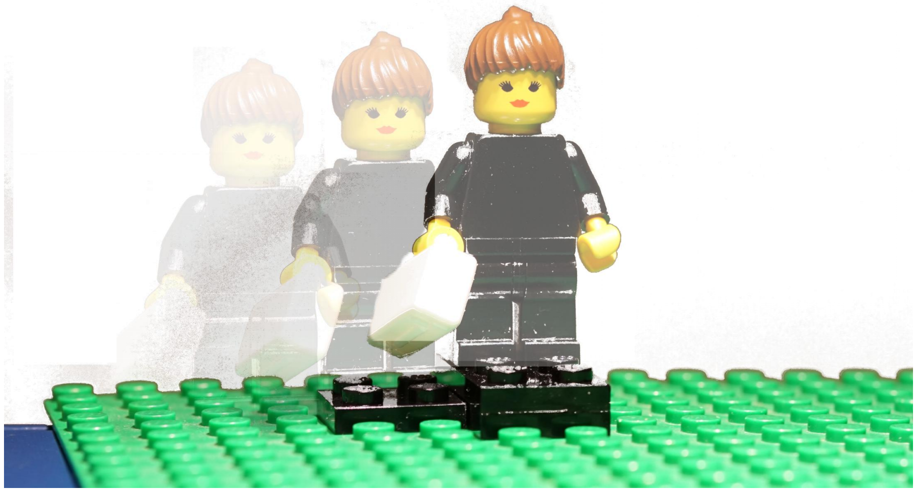
CPT Symmetry Transformations

Antilinda

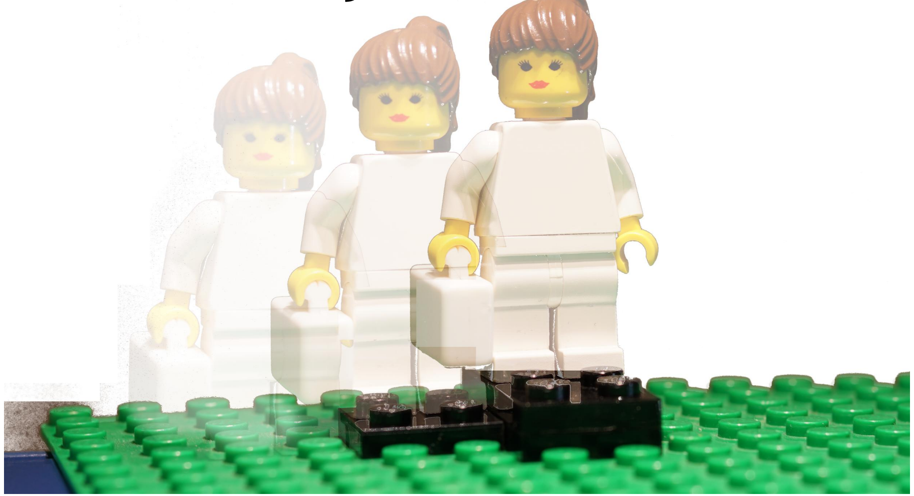
Linda

CPT Symmetry Transformations

Antilinda



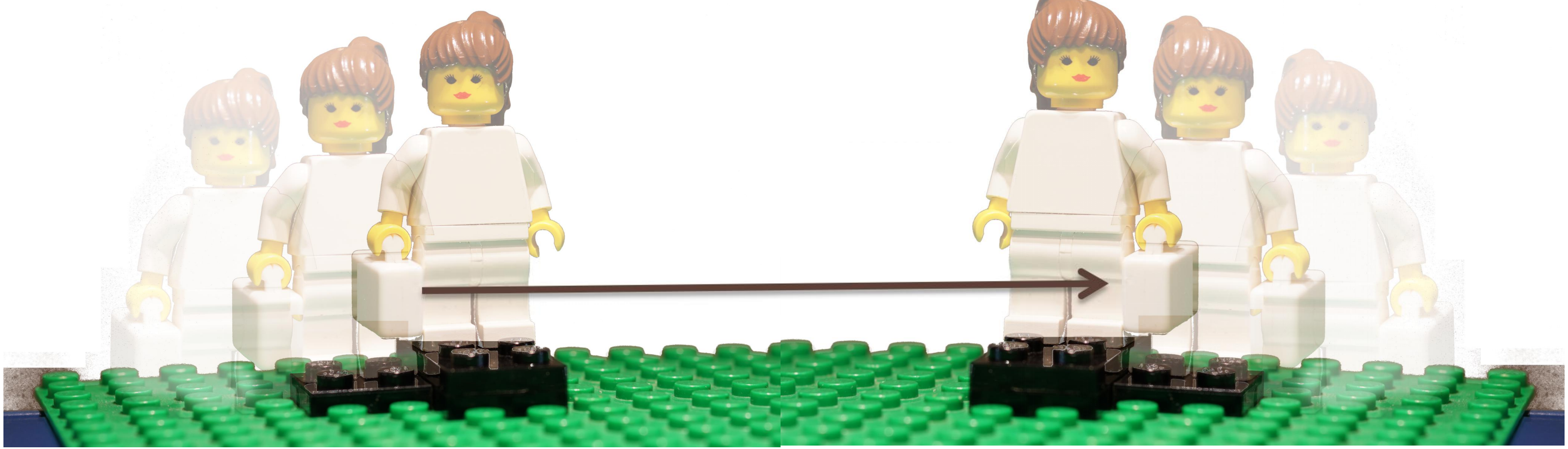
Antilinda after **charge (C)** transformation (black to white)



CPT Symmetry Transformations

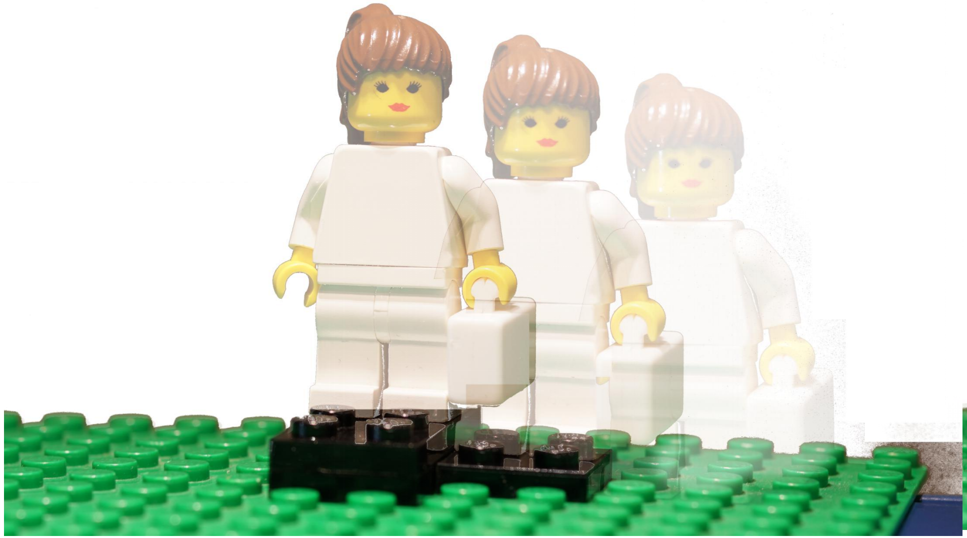
Antilinda after **C** transformation

Antilinda after **C** and **parity (P)** transformations (left hand to right hand)



CPT Symmetry Transformations

Antilinda after **C** and **P** transformations



Antilinda after C and P transformations with **time (T)** reversed

CPT Symmetry Transformations

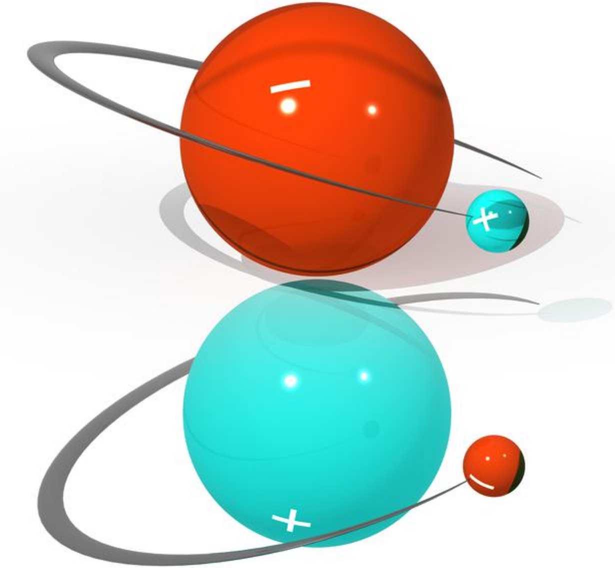
Antilinda after **CPT** transformations

=

Linda

Antihydrogen

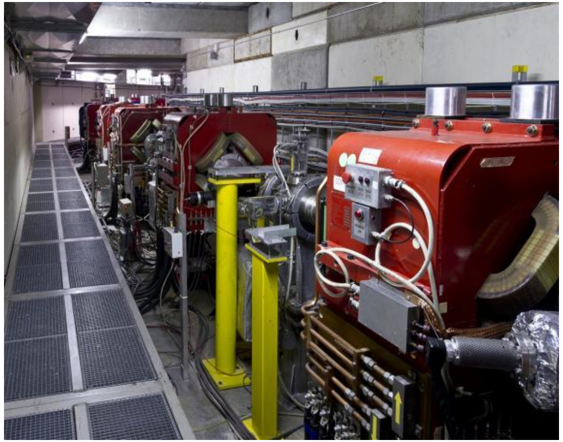
- Antimatter version of hydrogen
- Cold atoms (<0.54K) are trapped by magnetic fields in the ALPHA experiment
- An ultra high vacuum (10^{-13} torr or better) and cold (5K) trap makes it possible to trap atoms for tens of hours, and perform precise measurements of their charge and energy levels [2, 3, 11]
- Atoms are electrically neutral, and thus are a prime candidate for measuring the gravitational behavior of antimatter



http://raman.physics.berkeley.edu/gallery.html

Antiproton Decelerator

- The Antiproton Decelerator at CERN is a unique facility that prepares cold antiprotons
- Decelerates antiprotons from 3.5 GeV to 5.3 MeV
- Home to multiple international collaborations studying antiprotons, antiprotonic helium, and antihydrogen
- Approximately 7.5×10^{12} antiprotons are decelerated in the AD every year
- Science fiction fact-check: If all the antiprotons decelerated in a year happened to annihilate at the same time, the energy wouldn't be enough to boil a cup of water.



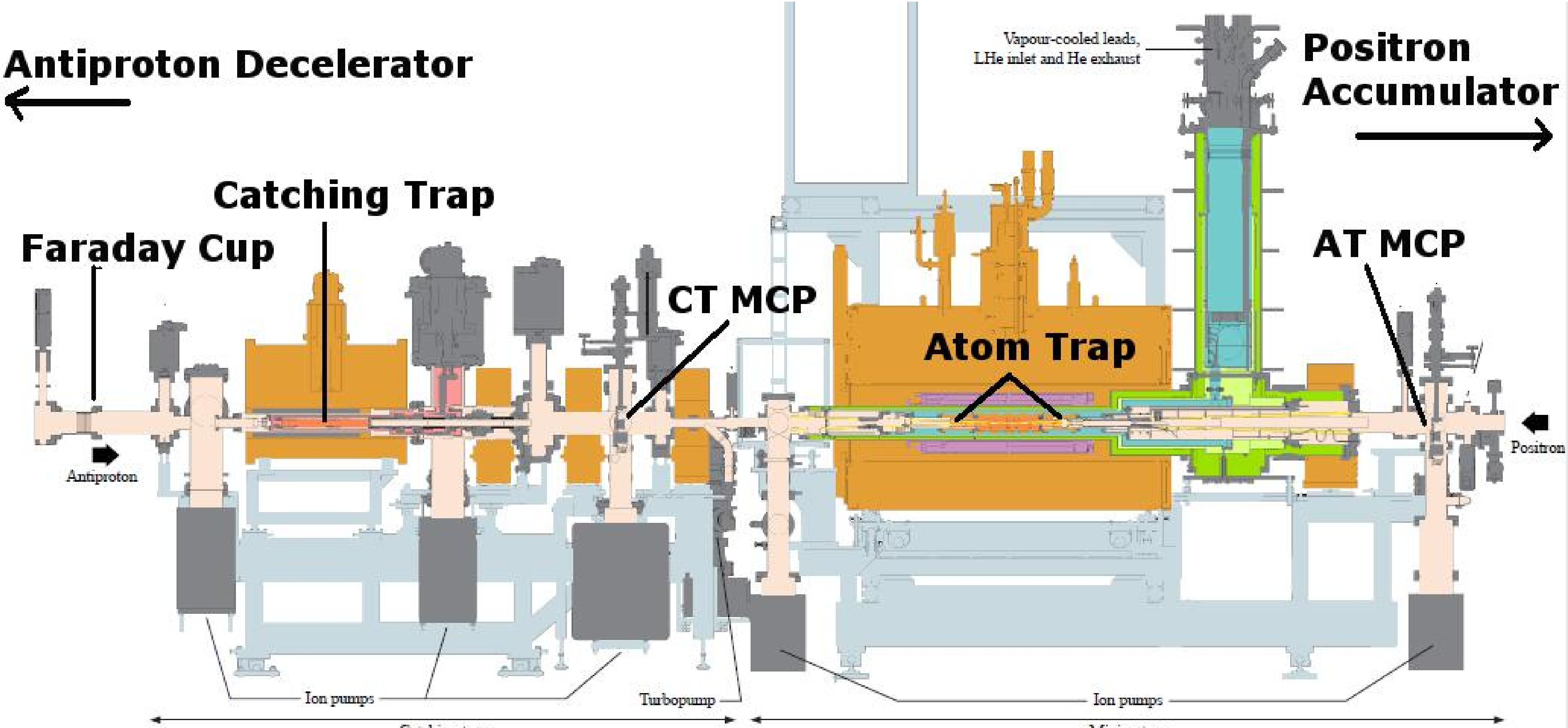
The ALPHA Experiment

- Antihydrogen Laser PHysics Apparatus (ALPHA)
- Located in the Antiproton Decelerator (AD) Hall at CERN
- Can accumulate antihydrogen atoms in the trap [10]
- First trapped antihydrogen for 1000 seconds in 2010 [4]
- In 2016 and 2017, made the first measurements of the 1S-2S spectroscopy lineshape, Lyman-alpha transition, and hyperfine spectrum of antihydrogen [3, 5, 11]

Members of the ALPHA collaboration next to the experiment
https://cds.cern.ch/record/2238961

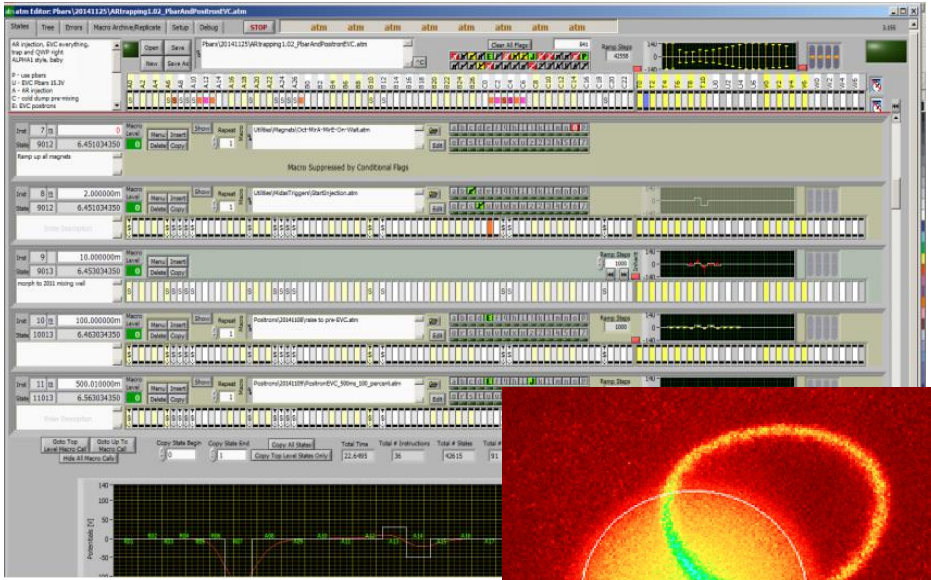
ALPHA-2 Schematic

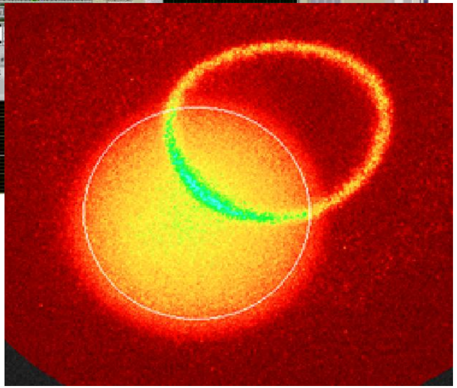
Image courtesy of Chukman So



The “Sequencer”

- Experiment is controlled with Labview
- The Sequencer is a labview program that controls the hardware in the apparatus





Long-Term Stability of Plasma Parameters

- The main part of my thesis work was to develop a method, called SDREVC, to simultaneously control the number of particles in a plasma and the plasma density, independent of its initial conditions
- After this control method was discovered and implemented, we were able to increase the number of atoms we can trap at a time by more than a factor of 10 (!)

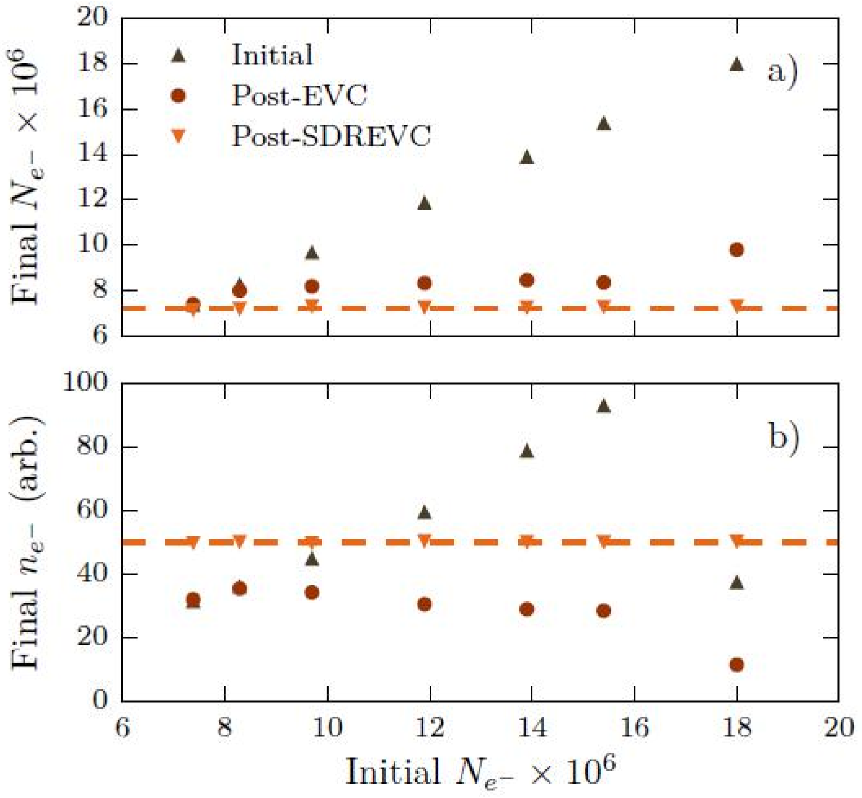


Figure from reference [6]

Making Antihydrogen

- In the catching trap:
  - Prepare electron plasma and put into a 5 kV potential well
  - Catch antiprotons in deep well
  - Cool antiproton-electron plasma in a 3T field, then kick out e- with a series of short high voltage pulses
- In the positron-end of the atom trap:
  - Transfer positrons into the far end of the atom trap, modify plasma to have a particular density and number of particles
  - Cool positrons via cyclotron radiation in a 3T field
- In the atom trap:
  - Make another electron plasma, transfer antiprotons into the atom trap and cool again
  - Cool positrons via adiabatic cooling or evaporative cooling

Making Antihydrogen

- Trap magnets are energized
- Antiprotons and positrons are put in adjacent potential wells
- Potential wells are merged together over about 1s, mixing particles and forming antihydrogen

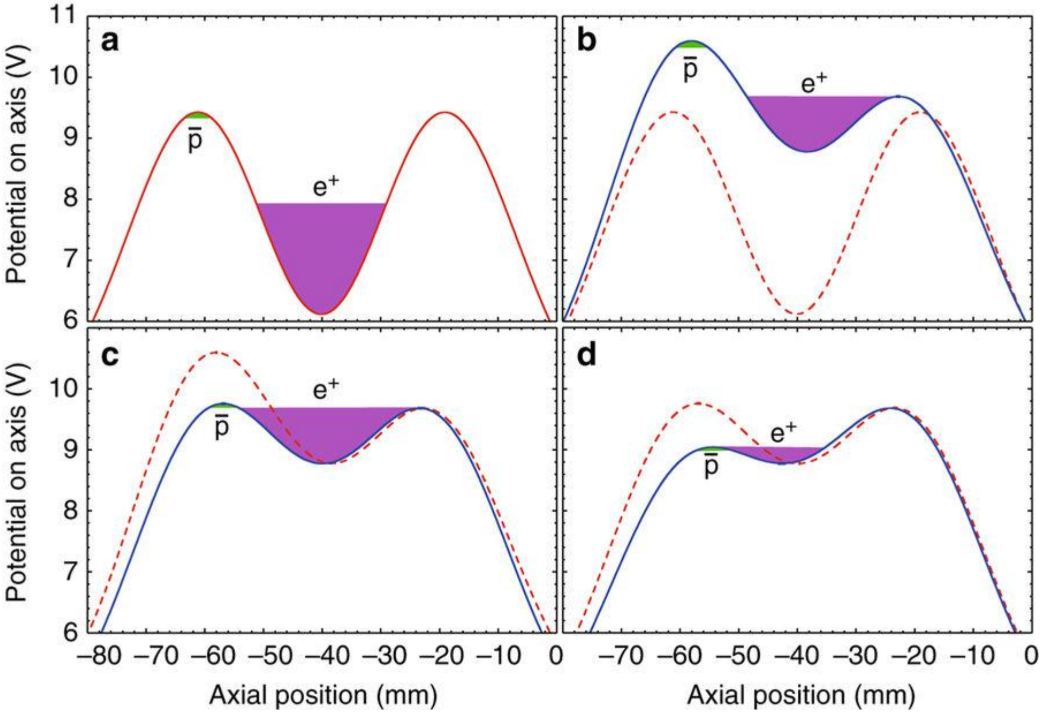
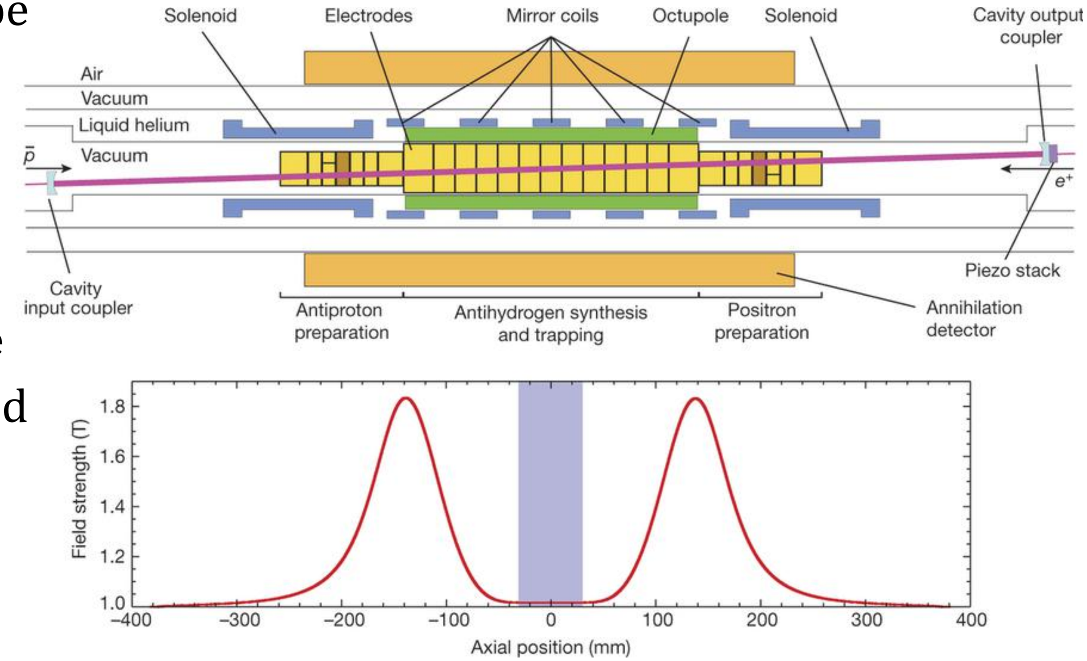


Figure from reference [10]

Trapping Antihydrogen

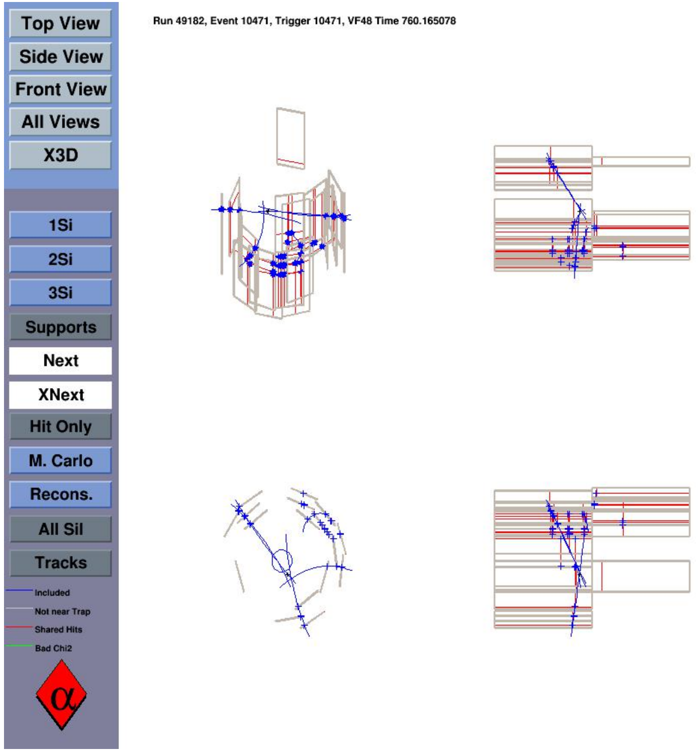
- Atoms colder than 0.54K can be trapped
- Can accumulate atoms with multiple trapping cycles
- Atoms can be trapped for several hours allowing precise measurements to be performed



http://www.nature.com/nature/journal/v541/n7638/fig_tab/nature21040_F1.html

Detecting Antihydrogen

- Antihydrogen studies require **destructively** counting the number of atoms that annihilate at different times during a measurement
- Annihilation occurs when an atom is excited into a higher-energy state, or if the trap magnets turn off.
- Antihydrogen annihilations normally produce short-lived pions
- Charged pions leave a signal in our Silicon Vertex Detector (SVD)



1S-2S Spectroscopy

- CPT predicts antihydrogen should have the same difference in energy levels as hydrogen
- In ALPHA, we use “doppler-free” spectroscopy for the 1s-2s measurements
- Excited atoms can escape the trap:
  - An additional photon can ionize the atom
  - The positron spin can flip while the atom decays back to the 1s state
- We count annihilations while the laser is on (“appearance”) and count the number of atoms remaining at the end (“disappearance”)

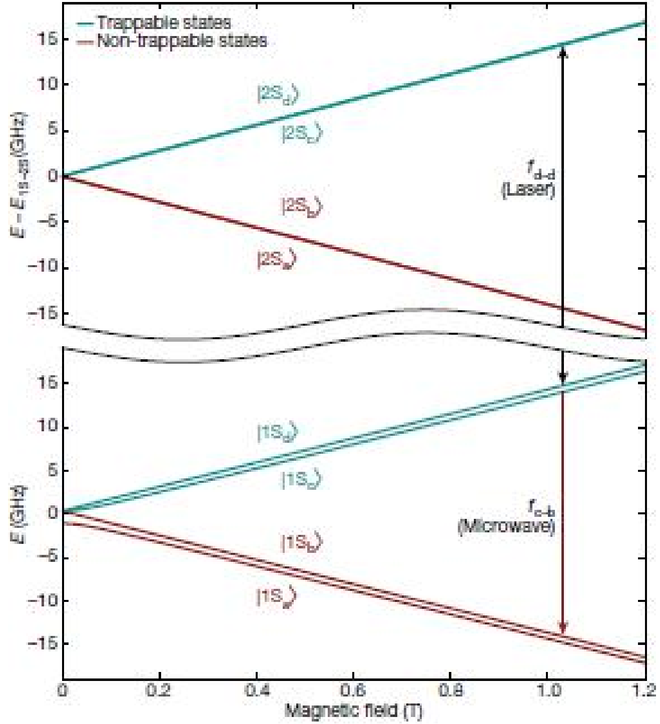


Figure from reference [3]

1S-2S Spectroscopy

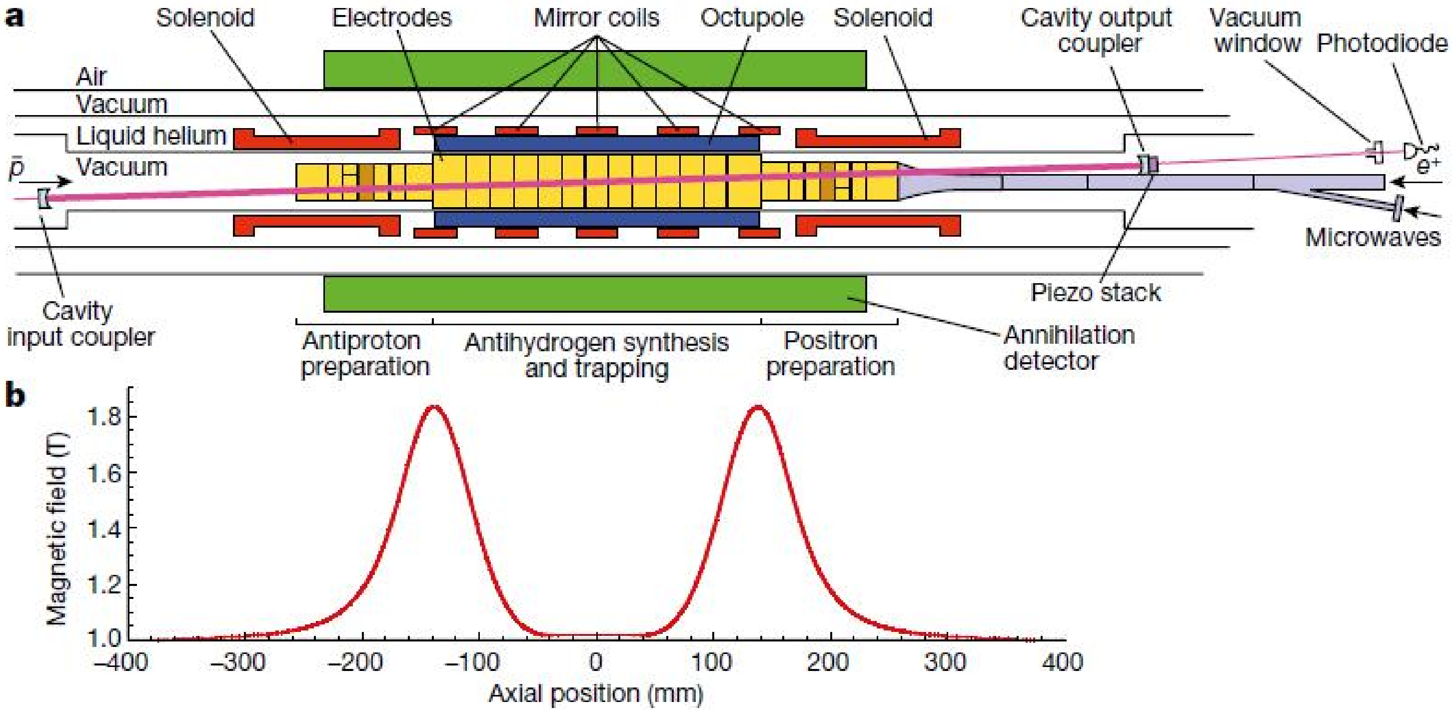


Figure from reference [3]

1S-2S Spectroscopy

- Observation: antihydrogen and hydrogen have the same 1S-2S energy level difference to ah
- Precision measurement to the level of a few parts per trillion corresponds to an energy sensitivity of 9x10^{-20} GeV
- This is one of the most sensitive direct measurements of CPT symmetry

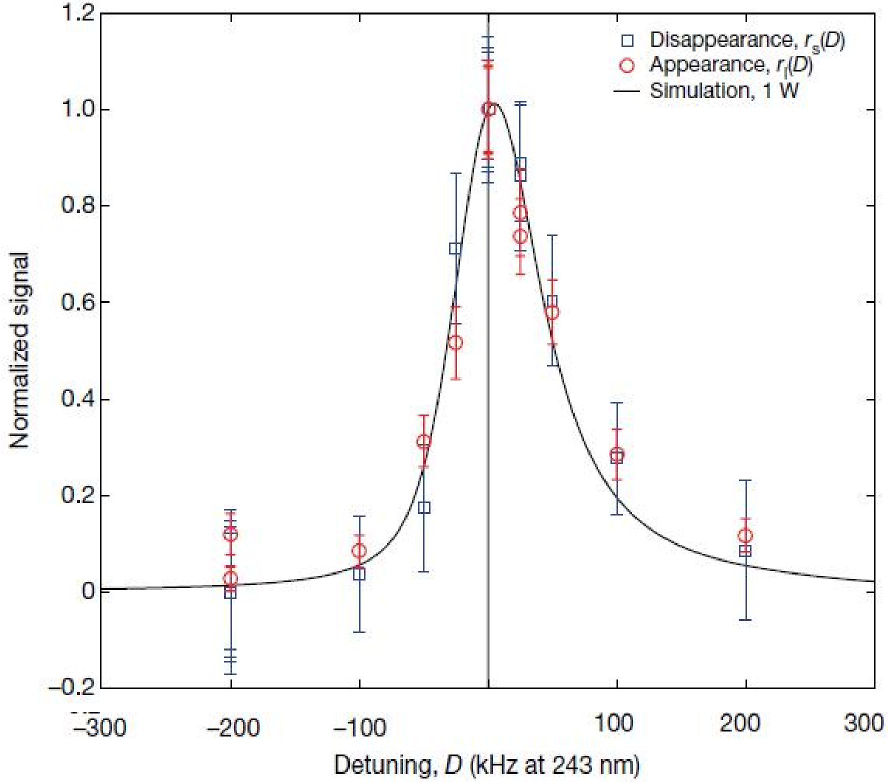


Figure from reference [3]

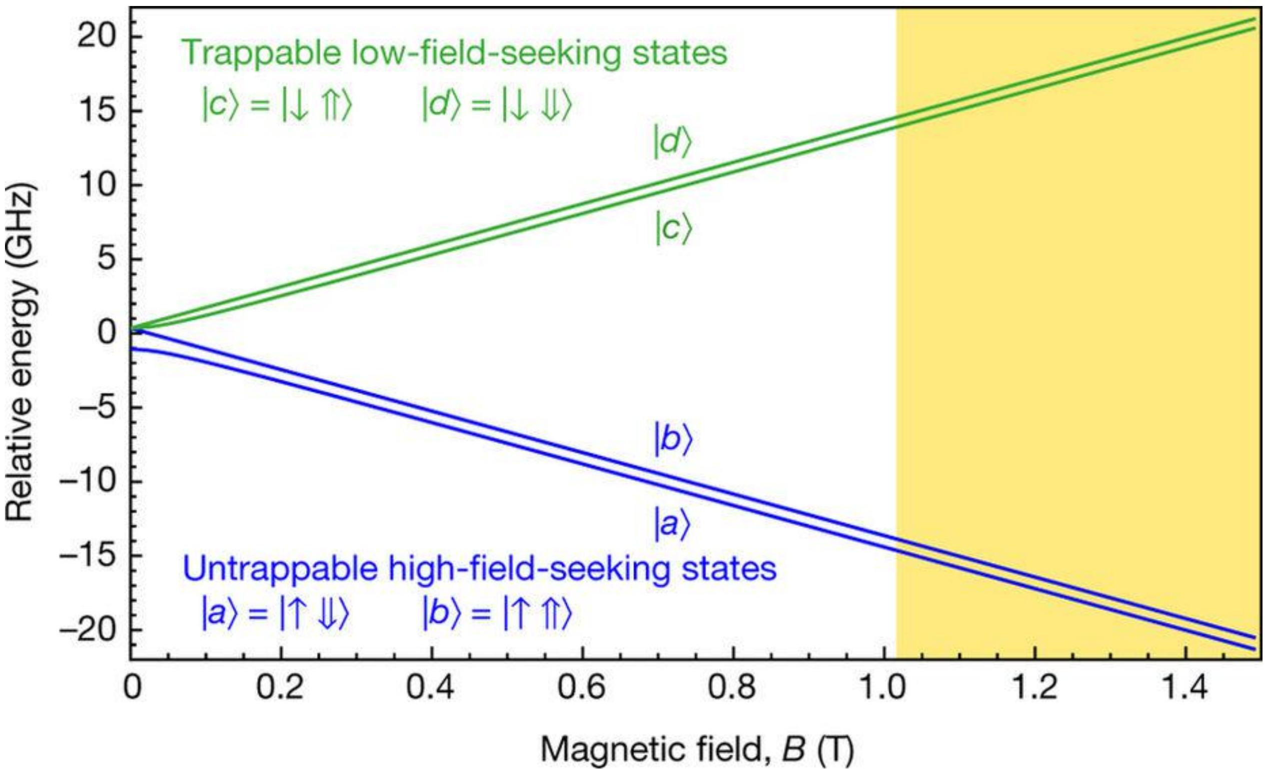
Hyperfine Spectrum

- We measured the c→b and d→a transitions of antihydrogen

- positron spin indicatedby ↓ or ↑

- antiproton spin indicated by ⇓ or ⇑.

Figure from reference [5]



Hyperfine Spectrum

- This was the first spectral lineshape measurement performed on antihydrogen
- Closely matches simulated expectation

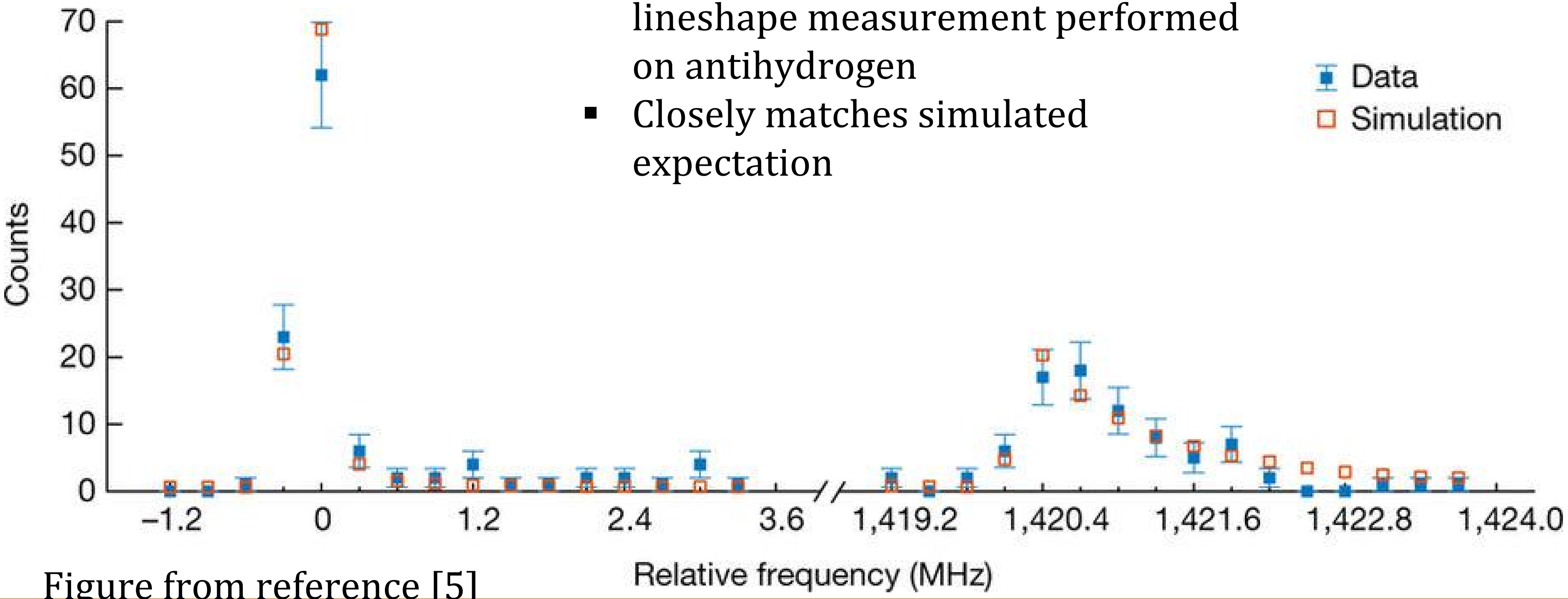


Figure from reference [5]

Lyman-alpha spectroscopy result

- 1S-2P transition
- The lineshape of the detected events matched the simulation for the conditions inside the trap
- Precision is on the order of $5x10^{-8}$
- This result is not nearly precise as the 1s-2s measurement, but obvserving this transition is a really important step towards laser cooling antihydrogen

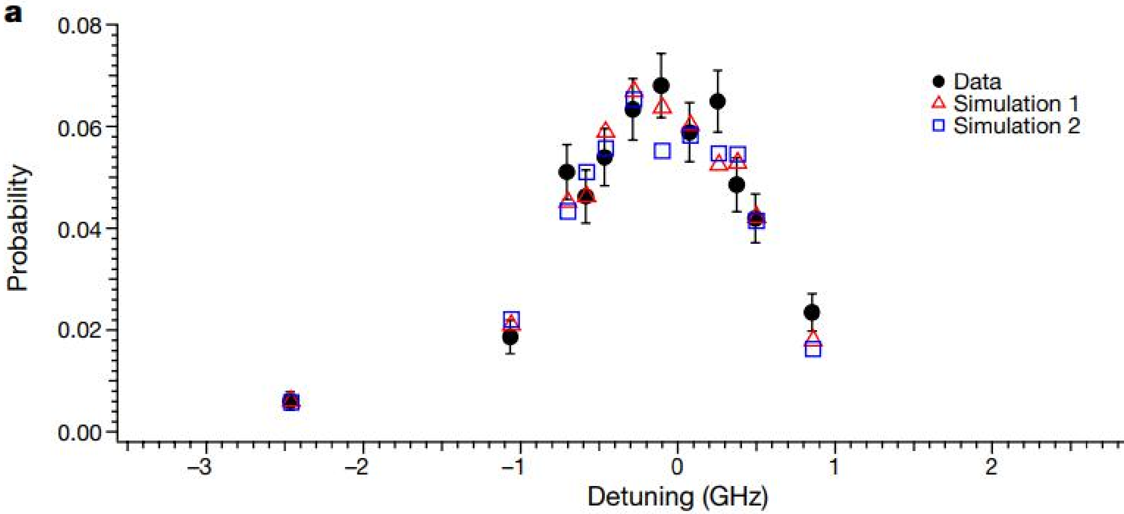


Figure from reference [11]

Summary

- The ALPHA experiment has recently made high precision measurements on antihydrogen to test CPT symmetry
- In 2016-2017 we increased our rate of trapping antihydrogen atoms by nearly a factor of 20
- We also developed a method for accumulating hundreds of antihydrogen atoms
- Several exciting new measurements have been performed to measure the 1s-2s and 1s-2p spectroscopies and the hyperfine transition
- Results are in agreement with CPT symmetry
- We need to keep searching for an explanation regarding the missing antimatter

Aarhus University, Denmark

University of British Columbia, Canada

University of California Berkeley, USA

University of Calgary, Canada

Stockholm University, Sweden

University of Liverpool, UK

University of Manchester, UK

NRCN - Nuclear Res. Center Negev, Israel

Purdue University, West Lafayette, USA

Federal University of Rio de Janeiro, Brazil

Simon Fraser University, Canada

TRIUMF, Canada

University of Wales Swansea, UK

Cockcroft Institute, UK

York University, Canada

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Got questions?

(of course you do, you're a physicist!)

Lyman-alpha spectroscopy details

- 1s-2p transition: required for directly laser-cooling antihydrogen
- Requires 121.6nm photons: these are produced by doubling the frequency of 730-nm photons created by a Toptica diode laser, then applying third harmonic generation in a high-pressure gas cell using a mixture of Kr and Ar
- Photons are produced in pulses 30ns long, have energy ~0.5nJ, and are produced at a rate of 10 Hz
- Photons enter the experiment through a MgF_2 window and exit out the other end; a PMT measures the intensity.