Testing CPT Symmetry with Antihydrogen at ALPHA

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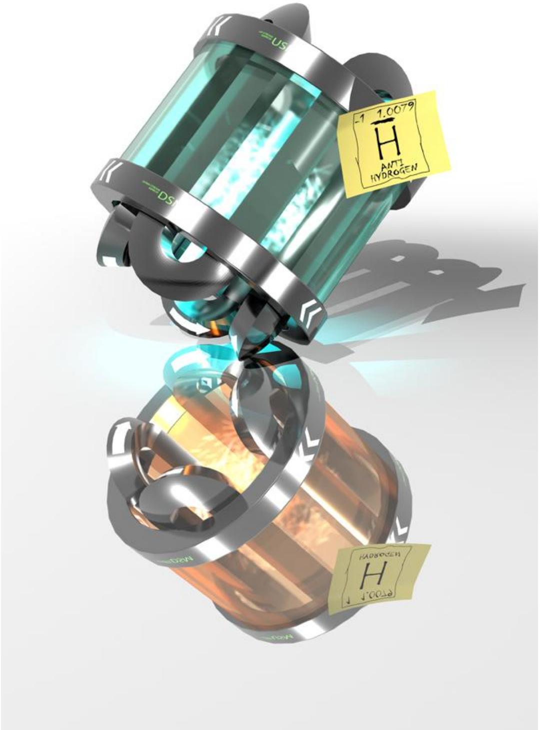
University of Oxford

Antimatter: Studying the Missing Half of the Universe

- The Standard Model predicts the universe should have nearly equal amounts of matter and antimatter, but no large quantity of antimatter has been observed
- Charge Parity Time (CPT) symmetry predicts the fundamental properties of antimatter should have the same magnitude as matter [1]
- Weak equivalence principle (WEP) predicts antimatter and matter should have the same acceleration in a gravitational field
- Precision measurements on antimatter are one way to search for CPT and WEP violation

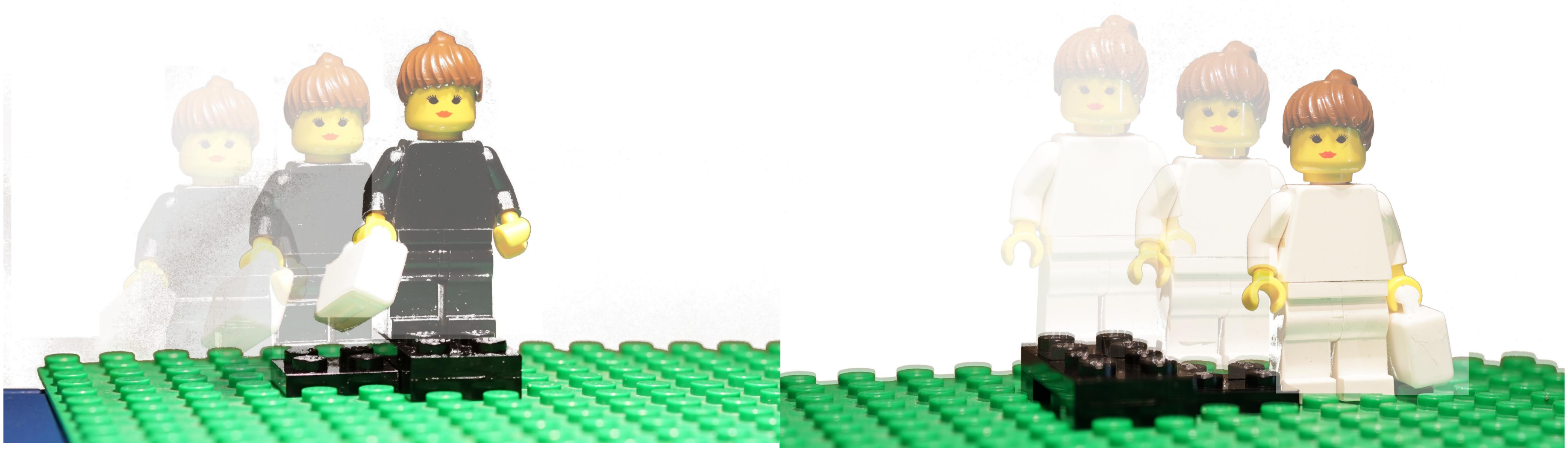


http://raman.physics.berkeley.edu/gallery.html

CPT Symmetry Transformations

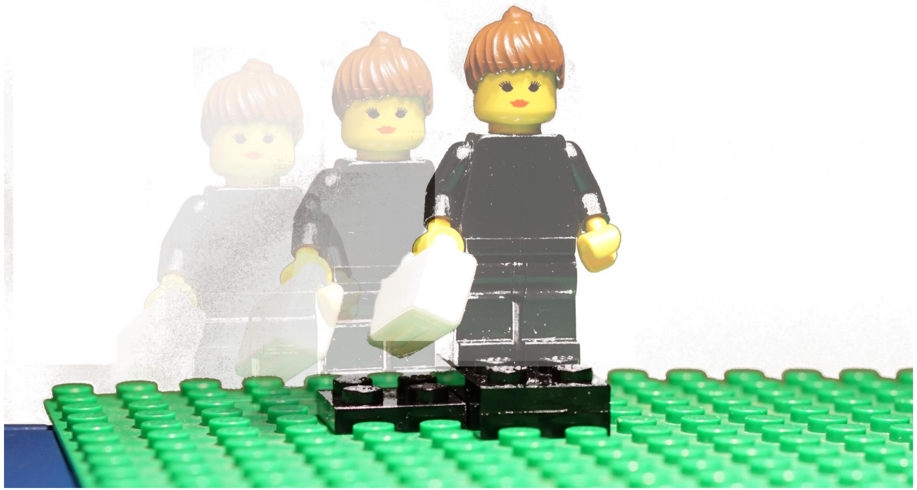
Antilinda

Linda



CPT Symmetry Transformations

Antilinda

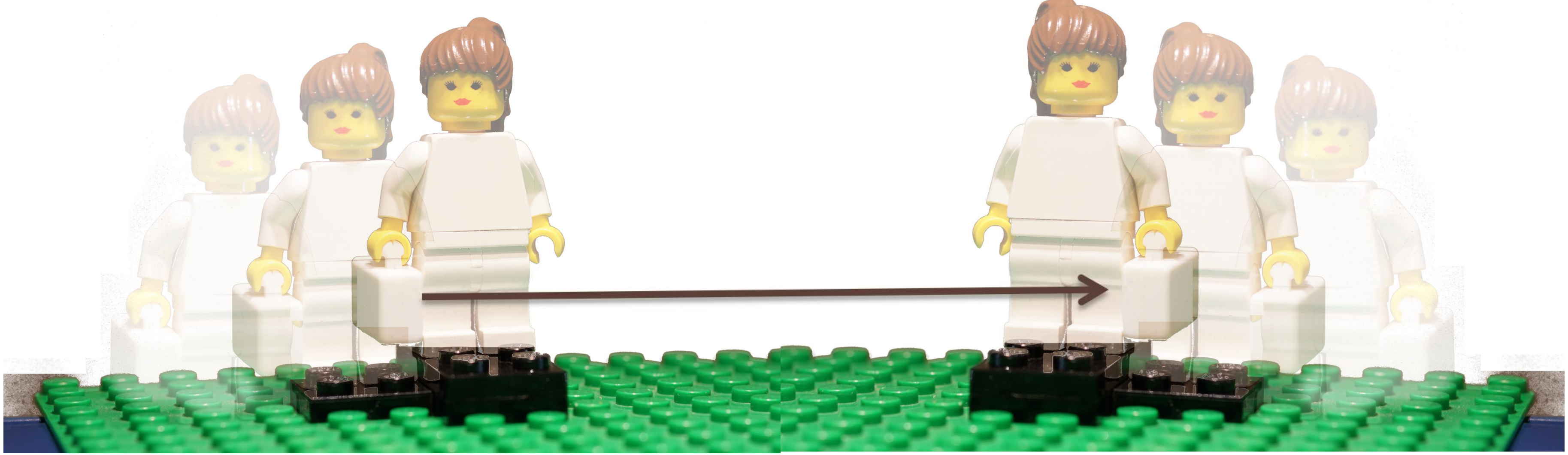


Antilinda after charge transformation (black to white)

CPT Symmetry Transformations

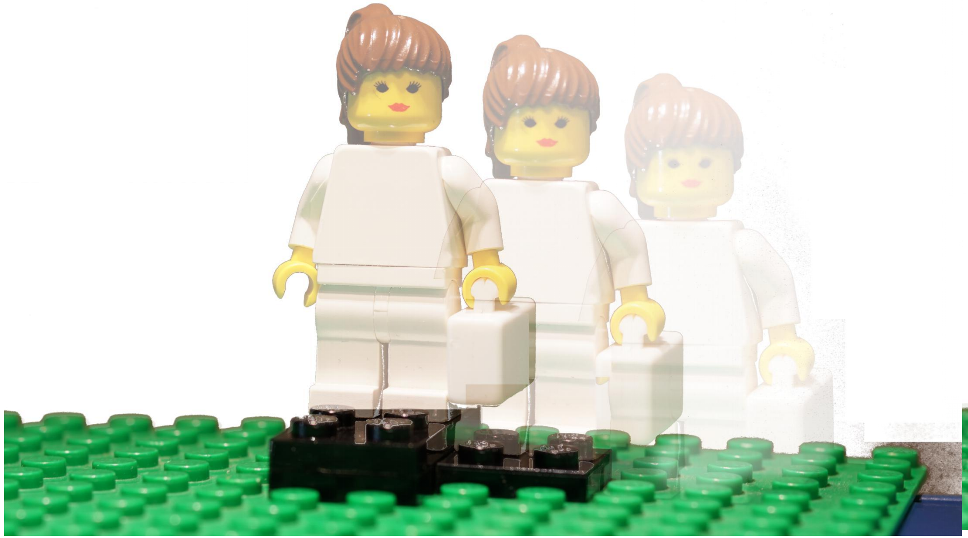
Antilinda after charge transformation

Antilinda after charge and parity transformations (left hand to right hand)



CPT Symmetry Transformations

Antilinda after C and P transformations



Antilinda after C and P transformations with time reversed

CPT Symmetry Transformations

Antilinda after CPT transformations

=

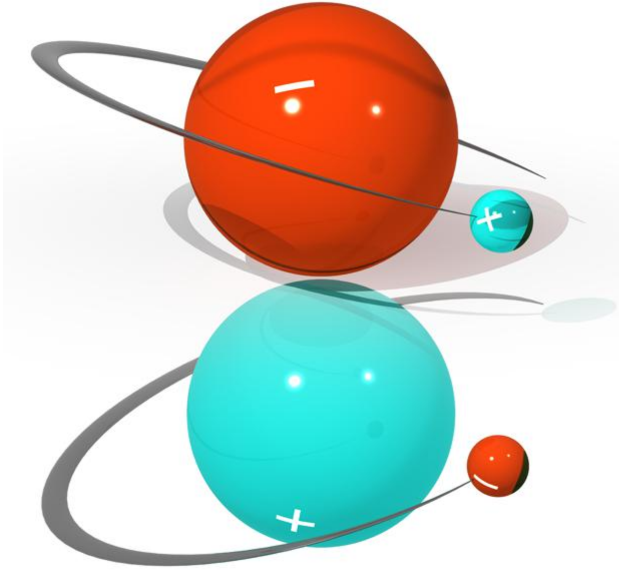
Linda

What if CPT is violated?

- CPT symmetry is required by the standard model, so an observation of CPT symmetry would break the standard model
- The standard model is accepted as the most complete and accurate physical model of particle properties and interactions
- CPT violation would require part of the standard model to be rewritten; this could lead to an explanation for the missing antimatter
- Note that CP symmetry violation, which is allowed by the standard model, could account for some of the missing antimatter
    - Up to now the observations of CP violation are at levels far too low to account for the missing antimatter

Antihydrogen

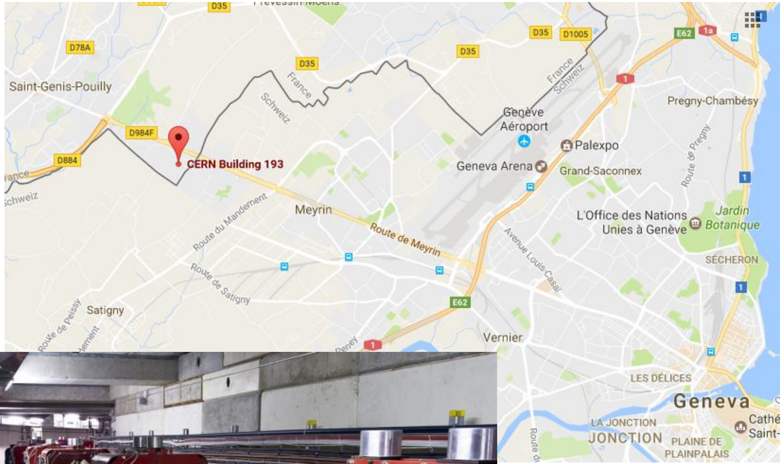
- Antimatter version of hydrogen
- Cold atoms (<0.54K) can be trapped in ALPHA's magnetic minimum well
- Long lifetime in an ultra high vacuum (10^{-13} torr or better) and cold (5K) trap makes it possible to perform precise measurements of its charge and energy levels [2, 3, 11]
- Electrically neutral: a prime candidate for measuring the gravitational behavior of antimatter

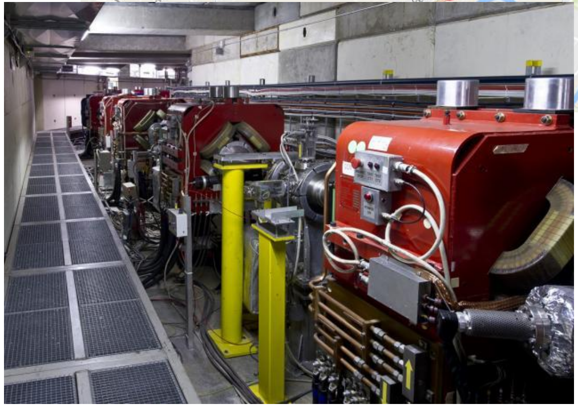


http://raman.physics.berkeley.edu/gallery.html

Antiproton Decelerator

- Antiproton Decelerator is a unique facility that prepares cold antiprotons
- Located near Geneva, Switzerland
- 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, in about 150,000 bunches every two minutes





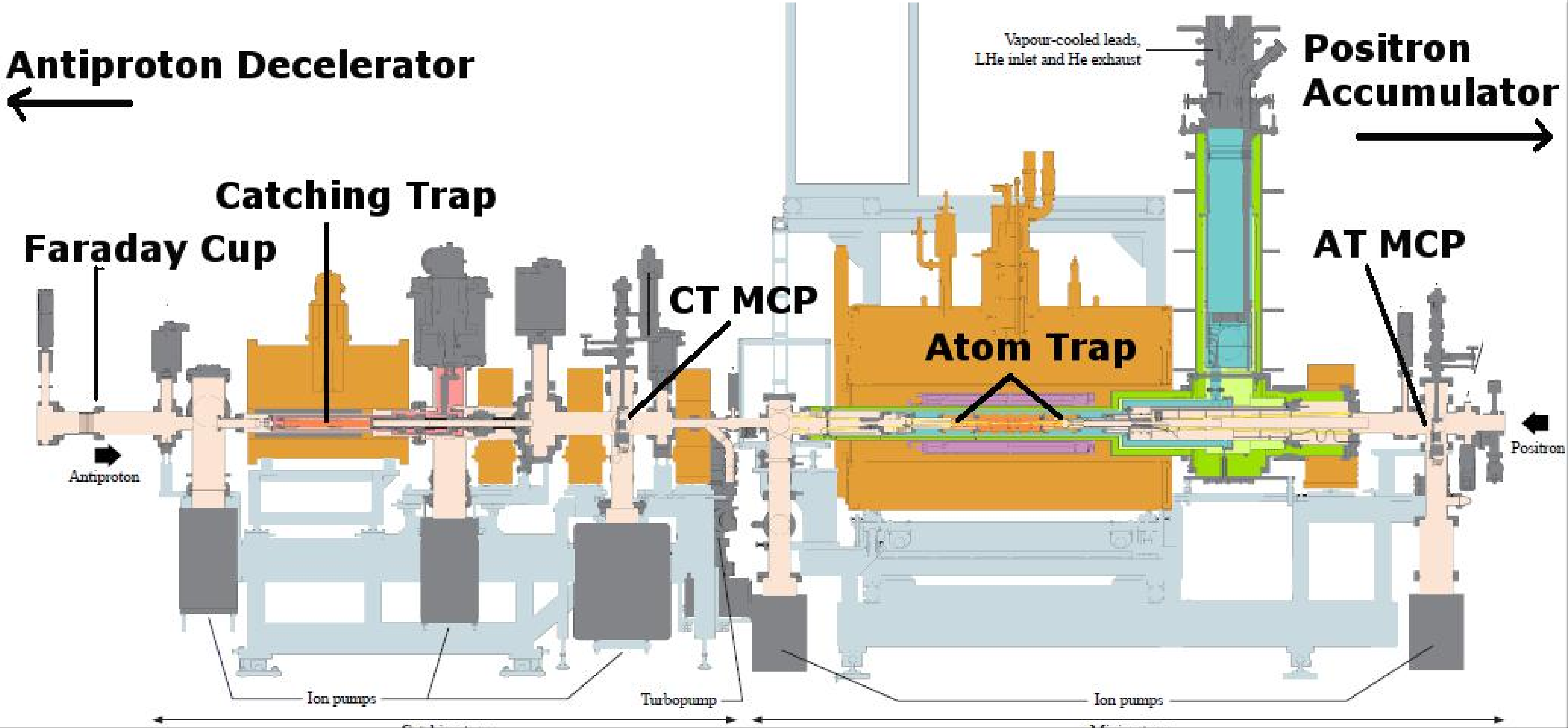
The ALPHA Experiment

- 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

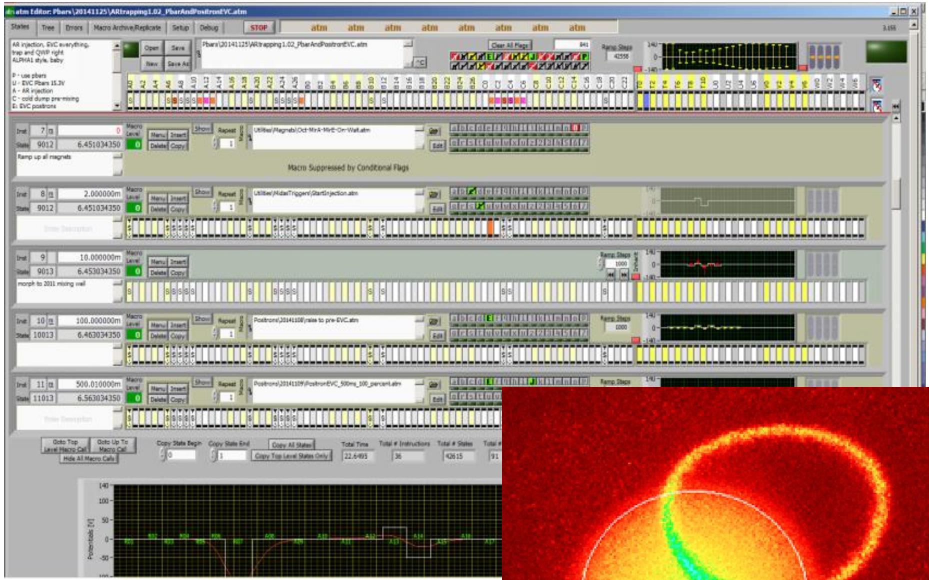


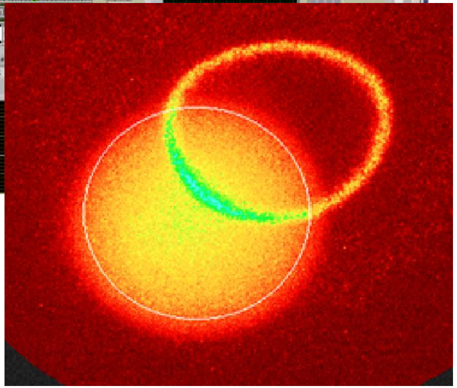
Trapping Antihydrogen

- 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

The “Sequencer”

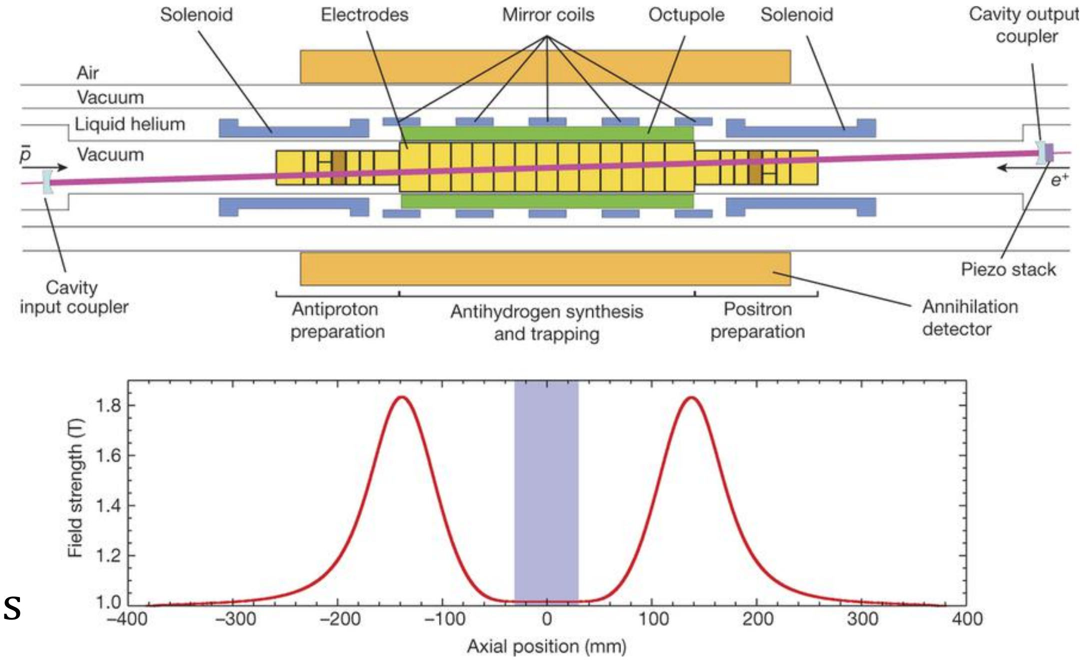
- Experiment is controlled with Labview
- The Sequencer is a labview program that controls the hardware in the apparatus
    - Programs electrode voltages
    - Turn magnets on/off
    - Trigger the camera to take pictures
    - Open gate valve for positron transfers
    - Set trigger markers for time windows we want to analyze





Trapping Antihydrogen

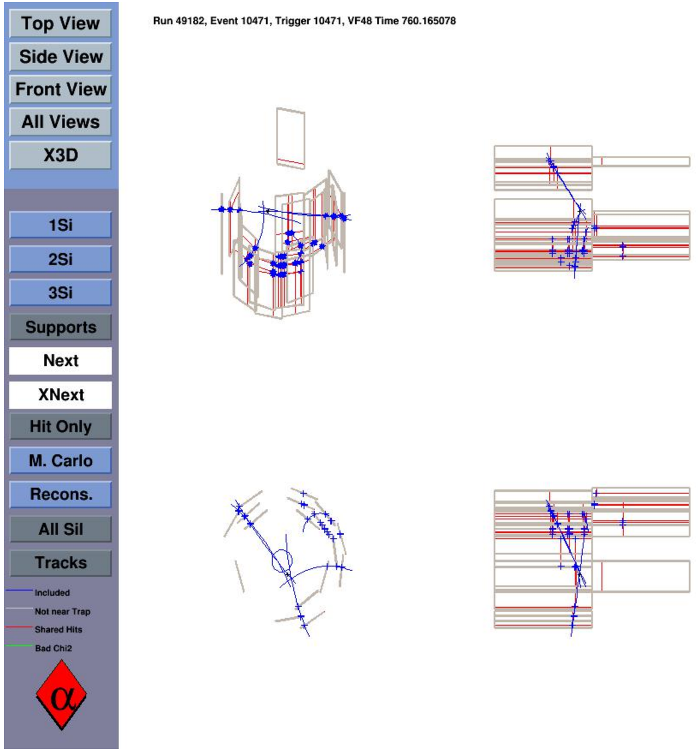
- Antiprotons and positrons are put in adjacent potential wells
- Trap magnets are energized
- Potential wells are merged together, mixing particles
- A few atoms will be cold enough to be trapped
- Can accumulate atoms with multiple trapping cycles
- Can confine for several minutes for charge or spectroscopy studies



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)



Non-Neutral Plasmas in ALPHA

- Antiproton and positron plasmas are used to make antihydrogen; electron plasmas are used to cool the antiprotons
- Controlled and reproducible parameters are necessary to optimize the trapping procedures
- The developments discussed in this presentation control the number of particles and plasma density independent of the initial conditions
- Additional developments of “smerge” and “stacking” used the stable plasmas to dramatically increase the number of antihydrogen atoms we can trap

Long-Term Stability With SDREVC

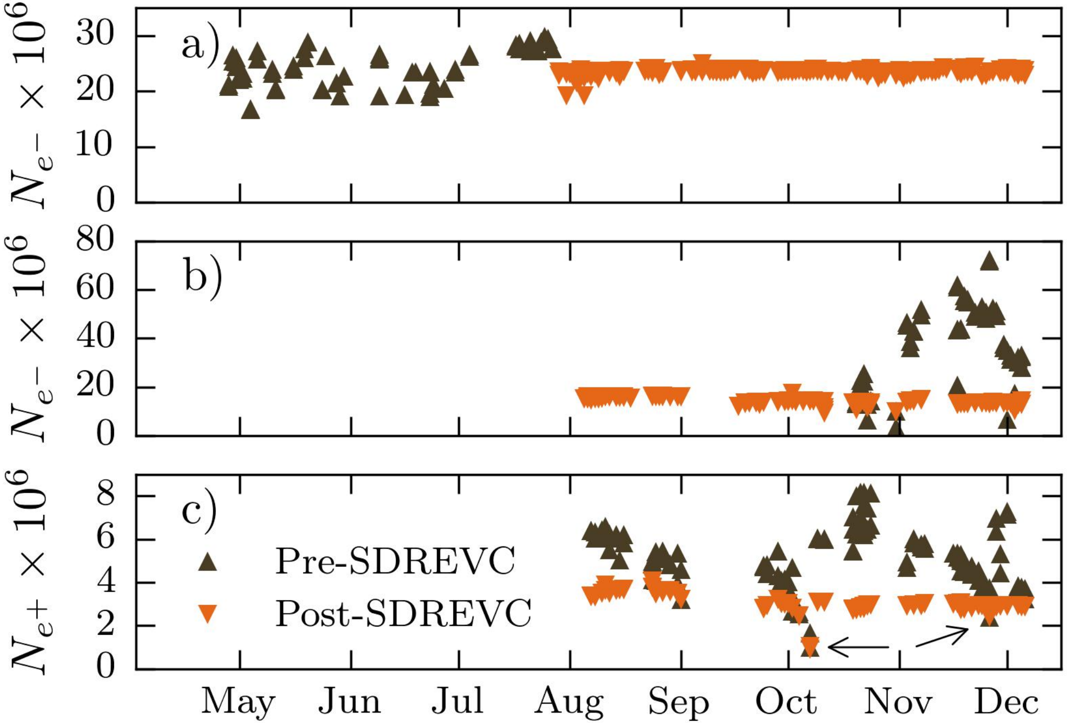


Figure from reference [6]

Control Plasma Parameters

- Varying the final depth of the SDREVC well allows us to select the particle number we want

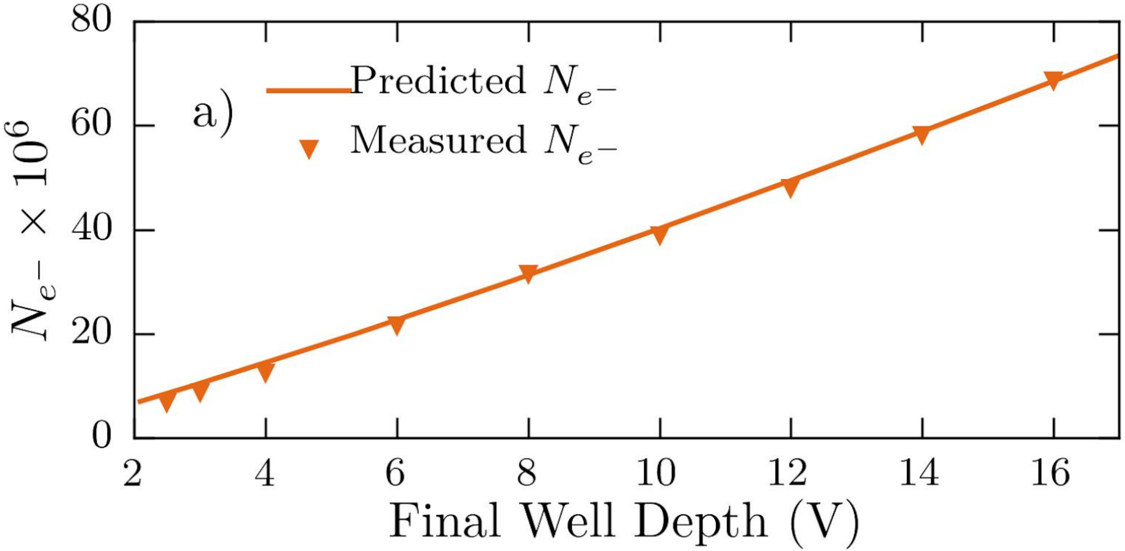
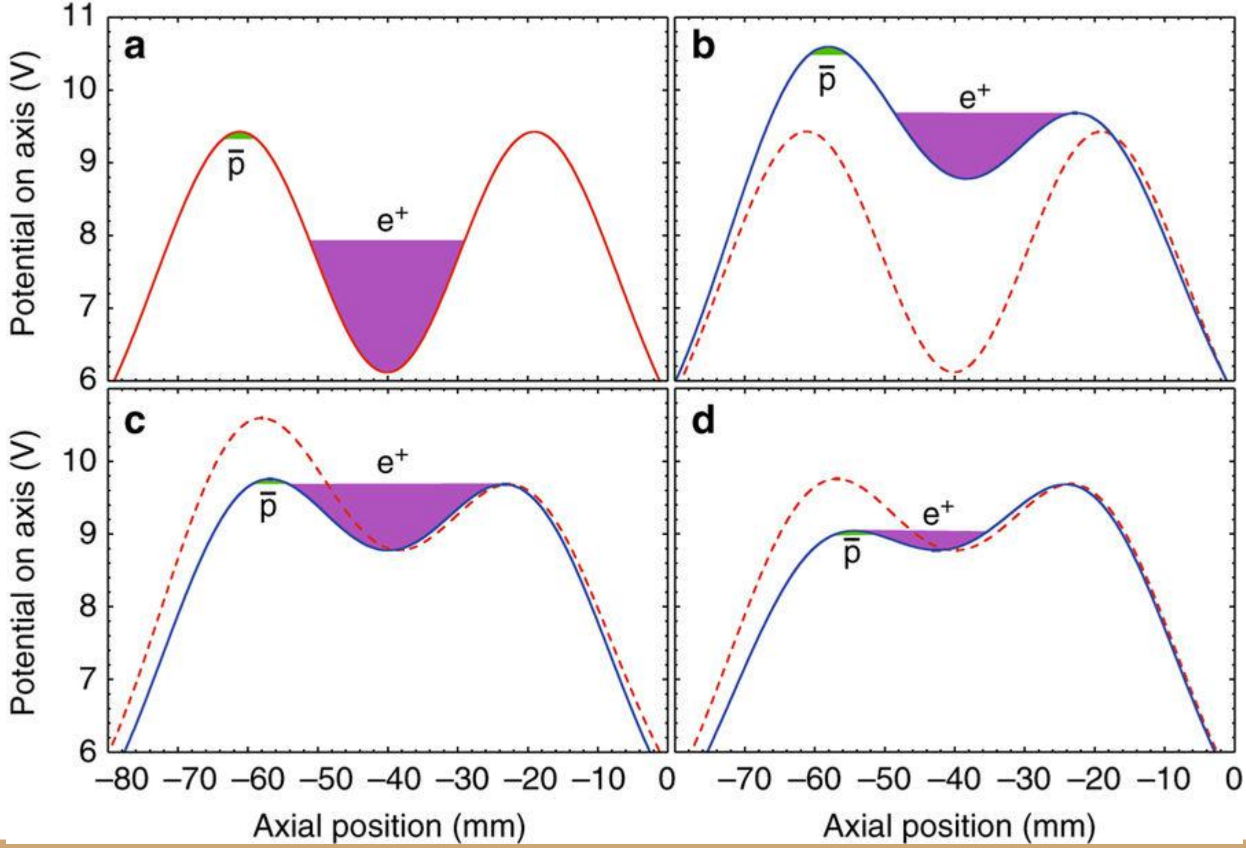


Figure from reference [6]

10-20x improvement in Antihydrogen Trapping Rate

- Used to use autoresonance
- With stable plasmas, started using these potential manipulations
- This new/old technique is called slow mixing, or "smerge" [5,11]



Antihydrogen “Stacking”

- Measurements on dozens of atoms provide better statistics
- While trapping 10 at a time, we developed a method to hold and accumulate additional stacks of antihydrogen atoms, passing plasmas through the trapped antihydrogen

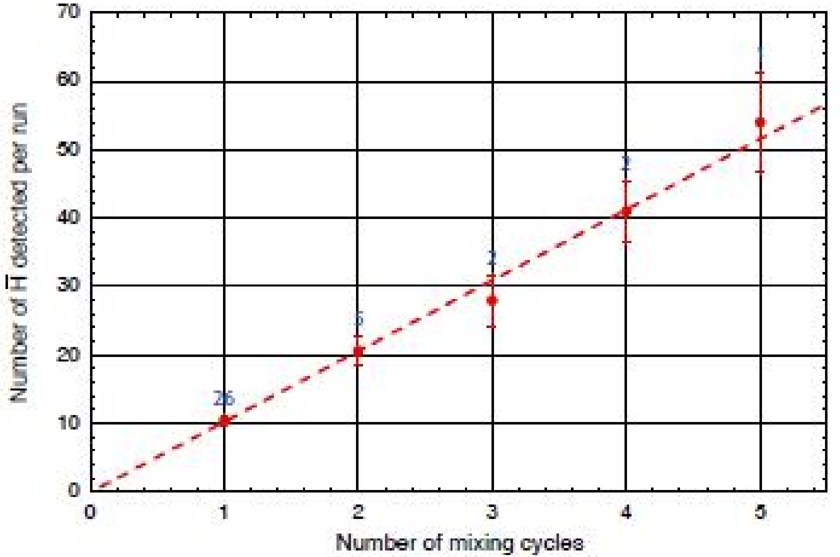


Figure from reference [10]

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")

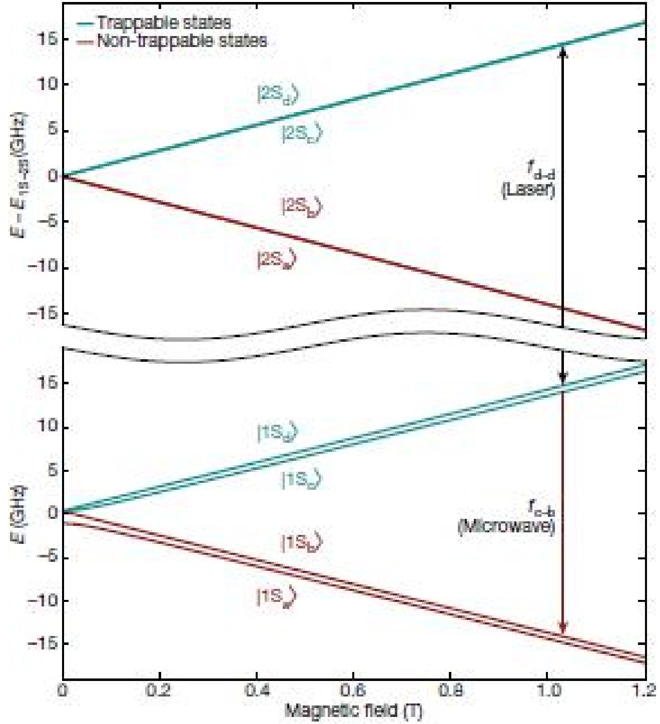


Figure from reference [3]

1S-2S Spectroscopy

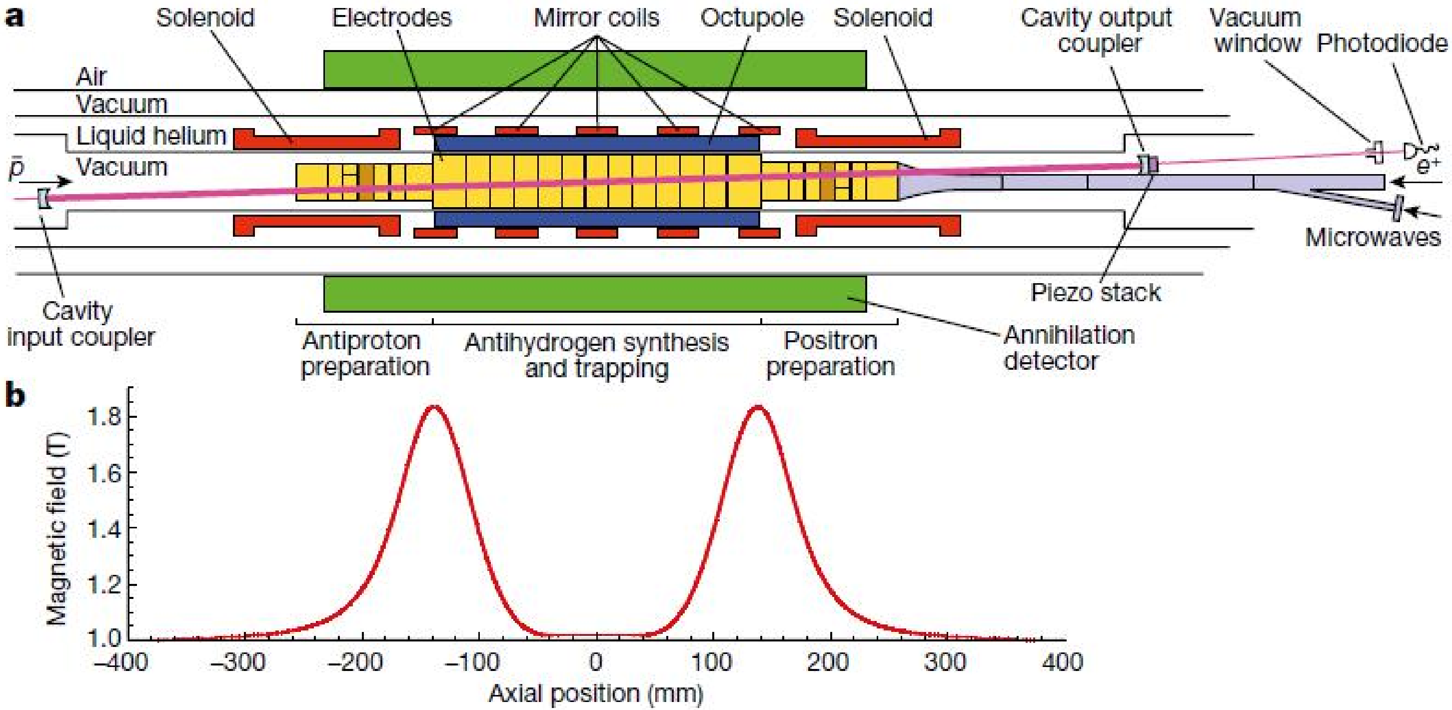


Figure from reference [3]

1S-2S Spectroscopy

- Measured value for antihydrogen:
  f(d-d) = 2,466,061,103,079.4(5 4) kHz
- Corresponding calibrated value for hydrogen in the same magnetic field:
  f(d-d) 2,466,061,103,080.3(0 6) kHz

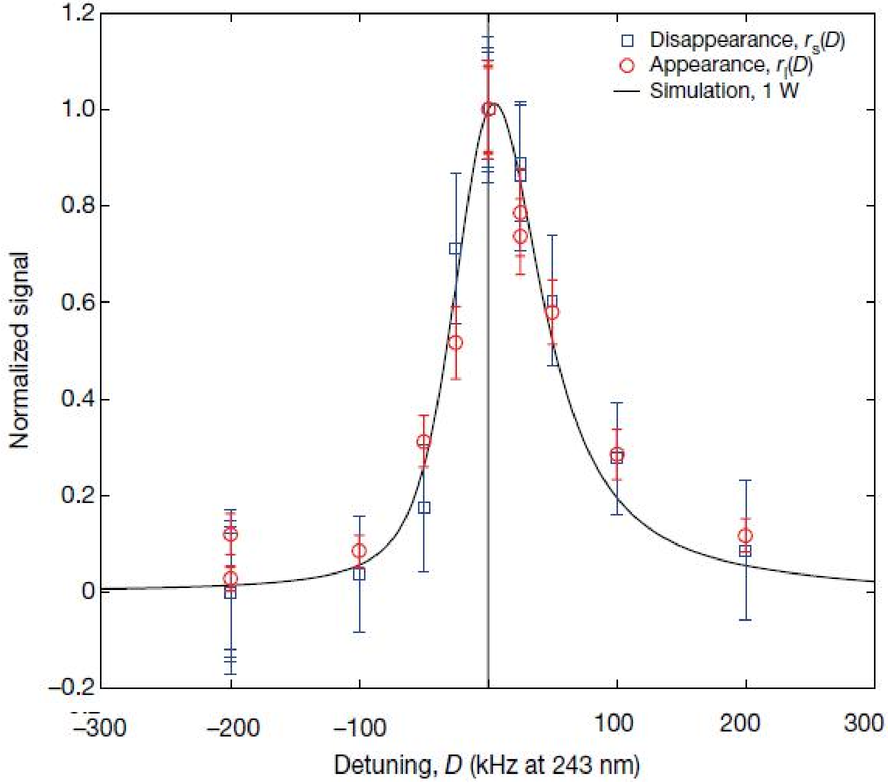


Figure from reference [3]

1S-2S Spectroscopy results

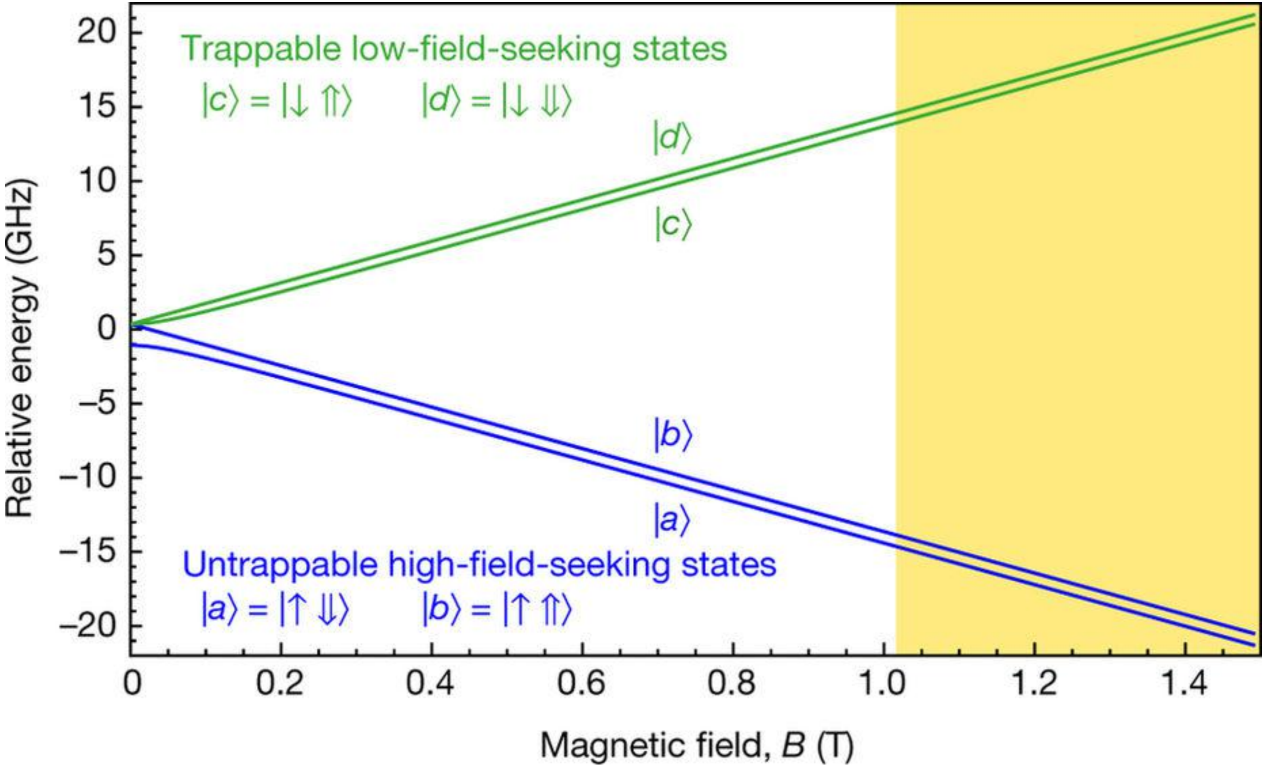
- Precision measurement to the level of a few parts per trillion corresponds to an energy sensitivity of 9×10^{-20} GeV
- This is one of the most sensitive direct measurements of CPT symmetry

Hyperfine Spectrum

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

Notation: positron spin (left; ↓ or ↑) and antiproton spin (right; ⇓ or ⇑)

Figure from reference [5]



Hyperfine Spectrum

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

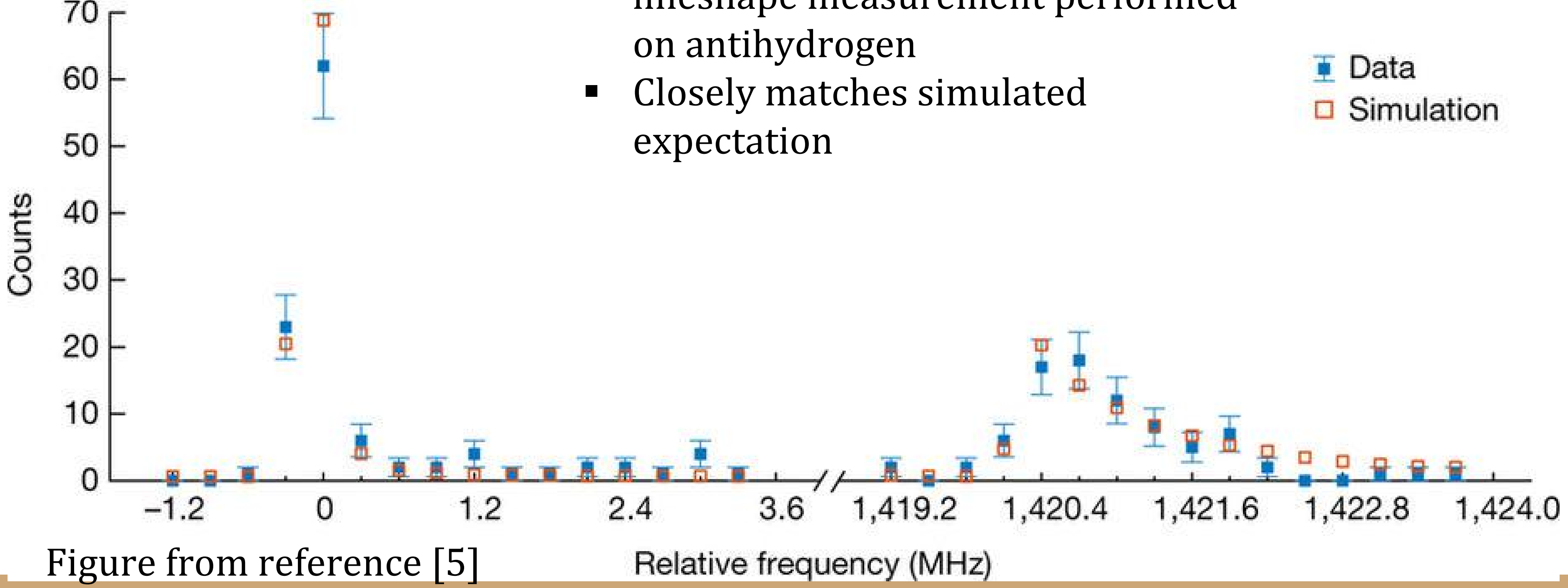


Figure from reference [5]

Lyman-alpha spectroscopy

- 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 MgF2 window and exit out the other end; a PMT measures the intensity.

Lyman-alpha spectroscopy result

- The lineshape of the detected events matched the simulation for the conditions inside the trap
- Precision is 5*10^(-8)
- This is an important step towards laser cooling antihydrogen

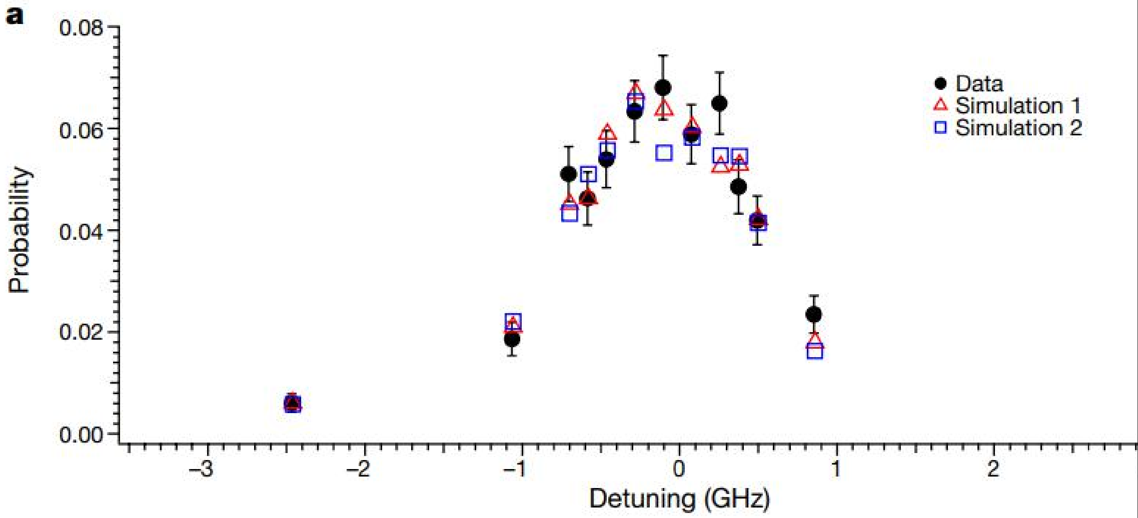


Figure from reference [11]

Summary

- The ALPHA experiment has recently made high precision measurements on antihydrogen to test CPT symmetry
- SDREVC is effective at controlling plasma density and the number of particles
- Long-term stability is achieved independent of initial conditions
- Smerge mixing method requires stable plasmas; smerge is much better than autoresonance and we achieved a ten-fold increase in the trapping rate in 2016
- Antihydrogen stacking was then developed to further increase the number of antiatoms we trap for physics experiments
- 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

Aarhus University, Denmark

University of British Columbia, Canada

University of California Berkeley, USA

University of Calgary, Canada

Imperial College London

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

Stockholm University, Sweden

Simon Fraser University, Canada `

TRIUMF, Canada

University of Wales Swansea, UK

Cockcroft Institute, UK

York University, Canada

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Bibliography

[1] "Physics with Antihydrogen", W A Bertsche, E Butler, M Charlton and N Madsen, J. Phys. B: At. Mol. Opt. Phys. 48 (2015) 232001

[2] "An Improved Limit On The Charge Of Antihydrogen From Stochastic Acceleration" M. Ahmadi et al, Nature 529, 373–376 (2016)

[3] "Characterization of the 1S-2S transition in antihydrogen"., M. Ahmadi et al. *Nature* 557, pages71–75 (2018)

[4] "Confinement of antihydrogen for 1,000 seconds" *Nature Physics* 7, 558–564 (2011) doi:10.1038/nphys2025

[5] "Observation of the hyperfine spectrum of antihydrogen" *Nature* 548, 66–69 (03 August 2017) doi:10.1038/nature23446

[6] "Enhanced Control and Reproducibility of Non-Neutral Plasmas", M. Ahmadi et al, Physical Review Letters, (2018) 120, p. 025001

[7] "Radial compression and torque-balanced steady states of single-component plasmas in Penning-Malmberg traps", J. R. Danielson and C. M. Surko, PHYSICS OF PLASMAS 13, 055706 2006

[8] "Antiproton and positron dynamics in antihydrogen production", Chukman So, PhD dissertation, University of California-Berkeley, 2014

[9] G. B. Andresen et al. (ALPHA Collaboration), Phys. Rev. Lett. 105, 013003 (2010).

[10] "Antihydrogen accumulation for fundaymental symmetry tests", M. Ahmadi et al., *Nature Communications* 8, Article number: 681 (2017) doi:10.1038/s41467-017-00760-9

[11] "Observation of the 1S–2P Lyman-α transition in antihydrogen" *Nature* 561, 211–215 (2018)

Questions?

(But now is a good time to ask the really big questions)

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