Testing CPT Symmetry with Antihydrogen at ALPHA

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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 \textit{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 $7.5 \times 10^{12}$ 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

Antiproton Decelarator

Catching Trap

Faraday Cup

CT MCP

Atom Trap

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 $9 \times 10^{-20}$ GeV
- This is one of the most sensitive direct measurements of CPT symmetry

Figure from reference [3]
Hyperfine Spectrum

- We measured the $c \rightarrow b$ and $d \rightarrow a$ transitions of antihydrogen
- positron spin indicated by $\downarrow$ or $\uparrow$
- antiproton spin indicated by $\downarrow$ or $\uparrow$.

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 $5 \times 10^{-8}$
- This result is not nearly precise as the 1s-2s measurement, but observing this transition is a really important step towards laser cooling antihydrogen

Figure from reference [11]
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.
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Bibliography


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