Spectroscopy of Antihydrogen Atoms

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Background

• In 2002, ATHENA and ATRAP demonstrated the creation of untrapped antihydrogen atoms. Hundreds of millions of anti-atoms have been made to date.

• In 2010, the ALPHA collaboration at CERN demonstrated trapping of 38 antihydrogen atoms.

• Since 2010, ALPHA has trapped over 500 anti-atoms, held anti-atoms for up to 1000s, and performed the first spectroscopic and gravitational measurements on anti-atoms.

ATRAP, Background-free observation of cold antihydrogen with field-ionization analysis of its states, Phys. Rev. Lett. 89, 213401 (2002).
ALPHA, Description and first application of a new technique to measure the gravitational mass of antihydrogen, Nature Communications, 4, 1785 (2013).
Outline

• Motivation for studying antihydrogen.

• Antihydrogen trapping techniques.

• Spectroscopy of antihydrogen.

• Gravity.

• Future plans.
Why Study Antihydrogen?

• Positrons and Antiprotons have been extensively studied as isolated particles from any years:
  • At high energies in accelerators and in cosmic rays.
  • At low energies in Penning-like traps.
  • Quantities like the e/m ratio for positrons and antiprotons are well known.
• There have been few studies of the properties of complex antimatter systems.
  • There have been no studies of the properties of antihydrogen.
• There have been studies of antiprotonic helium atoms.
CPT and Antihydrogen

• CPT demands that the spectra of hydrogen and antihydrogen be absolutely identical.

• Every test to-date finds CPT holds.

• But these tests look in particular sectors or are model dependent.
  • Since we don’t know how CPT might be broken, we don’t know where to look.

CPT and Antihydrogen

• We expect antihydrogen to be spectrally identical to hydrogen…CPT demands that these spectra be absolutely identical.

• Every test to-date finds CPT holds.

• Could CPT be violated? Could the spectra of hydrogen and antihydrogen be different?
CPT and Antihydrogen

• We expect antihydrogen to be spectrally identical to hydrogen…CPT demands that these spectra be absolutely identical.
  • Every test to-date finds CPT holds.
  • Could CPT be violated?

• Physicists have been wrong before…
  • P violation---Wolfgang Pauli:¹
    "I do not believe that the Lord is a weak left-hander, and I am ready to bet a very high sum that the experiments will give symmetric results."
  • CP violation---Lev Landau:²
    "If CP is violated, I will hang myself."

• The baryogenesis problem suggests that something is wrong with our understanding of Nature. CP symmetry breaking does not seem sufficient to explain our existence.

¹Pauli in a letter to Victor Weisskopf, quoted in the Ambidextrous Universe, by Martin Gardner.
²Oral history, as related by Dima Budker.
Why Study CPT With Antihydrogen?

• Because we can...

• Using the $1s$-$2s$ transition, we can do a test which is
  • Model independent.
  • Extraordinary precise...
    • Theoretical precision of $10^{-18}$.
    • Current precision of $4 \times 10^{-15}$ with H.

Progress in fractional accuracy in H $1s$-$2s$ spectroscopy.
http://www.mpq.mpg.de/~ajh/iontraps/index.php/Research/Helium


Progress to Date

• Promise: $10^{-18}$ precision $1 \text{s}-2 \text{s}$.
• Achieved: $\sim 10^{-3}$ precision microwave spin flip.
• Experiments done on the ALPHA antihydrogen trap at CERN
Antihydrogen Trap

• Experiments are done on trapped antihydrogen atoms
• Antihydrogen has a small magnetic moment.
• Can be confined in a magnetic minimum.
  • Mirror coils to create an axial minimum.
  • Multipole (quadrupole, octupole etc.) coils to create a radial minimum.

Force on a magnet moment from a magnetic gradient:

$$
F = \nabla (\mu \cdot B)
$$

Magnetic Field Magnitude
Antihydrogen Trap

- Octupole is a state-of-the-art superconducting magnet.
- Produces a maximum field of \(~1.54\text{T}\).
- This results in a well depth of \(~0.54\text{K}\).
- The anti-atoms cannot be quickly cooled…they have to be born, via three body recombination, in the well

\[ e^+ \]
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\(e^+\)
Antihydrogen Production Energy Scales

Energy Scales:
- Antiproton Creation Energy: 1.7 GeV
- Plasma Potential: 30 mV-10 V
- Trap Depth: 0.5 K or 40 μeV

\[
\frac{\text{Antiproton Creation Energy}}{\text{Trap Depth}} = 10^{14}
\]
\[
\frac{\text{LHC Energy Increase}}{\text{Free Protons on Creation}} = 10^8
\]
\[
\frac{\text{Plasma Potential}}{\text{Trap Depth}} = 10^3 - 10^5
\]
Antiproton Source

• Antiprotons come from the Antiproton Decelerator at CERN.

Antiproton Decelerator

CERN’s Antiproton Decelerator reduces antiproton energy to ~5MeV.

ALPHA Apparatus


Penning-Malmberg Trap
Space charge potentials are ~1eV...how do you ease the antiprotons into the positrons without them acquiring some of the space charge potential?
Antihydrogen Trapping Techniques

• Cyclotron cooling of lepton plasmas.
• Sympathetic cooling of antiprotons on electrons.
• Expansion and evaporative cooling.
• Radial compression.
• Avoiding centrifugal separation.
• Autoresonance.
• Discrimination against antiprotons.

• Plasma preparation takes about ten minutes.

Trapped Antihydrogen Synthesis Rate

- We make antihydrogen with a temperature of ~50K.
- Still...our trap depth is ~0.5K!
- We trap only the coldest antihydrogen atoms in the thermal distribution.

Approximately one anti-atom in ten thousand is potentially cold enough.
- Average mixing attempt generates ~ten thousand antihydrogen atoms.
- We should trap one antihydrogen atom in every attempt.
- Attempts take ~15 minutes.
E x B Guiding Center Antihydrogen Atoms

- Initially, the anti-atoms are highly excited \( \mathbf{E} \times \mathbf{B} \) guiding center atoms.
- Classical atoms different from Rydberg atoms…
  - The positron motion is dominated by cyclotron oscillations.
  - The positron oscillates along \( B \) in the electrostatic well made by the antiproton.
  - The positron orbits the antiprotons in the plane transverse to \( B \) because of \( \mathbf{E} \times \mathbf{B} \) drifts.


Ground State Antihydrogen Atoms

• The anti-atoms form in states equivalent to $n=40$ to 60.

• The initial decay is slow, but is fast after the anti-atoms get to $n \approx 20$.

• After 0.4s, 99.5% will have decayed to the ground state.$^1$

• Exactly how the atoms decay, and why most don’t spin flip during the decay, is not entirely understood.

• Difficult to do spectroscopy and gravity experiments on excited atoms.
  • With trapped atoms, simply wait for the atoms to decay.
  • Antihydrogen beam experiments will not necessarily make ground state beams.

How Does One Do Spectroscopy on Single Atoms?

Not by looking for emitted photons…
Microwave Spin Flip: Breit-Rabi Diagram

[Image of the Breit-Rabi diagram]

Annihilation After Spin Flip


ALPHA Vertex Imaging Detector is over 50% efficient, and locates annihilations to better than 10mm.
Driving the Spin Flip Transition

Driving the Spin Flip Transition
Microwave Spin Flip

Octupole/Mirror fields very non-uniform
Microwave Spin Flip Experiments

On Resonance

Off Resonance
(Increase Magnetic Field)

On Resonance
(Increase Magnetic Field and Microwave Drive Frequency)

### Microwave Results: Disappearance Measurements

<table>
<thead>
<tr>
<th></th>
<th>Number of Attempts</th>
<th>Detected Anti-atoms Remaining after Microwaves</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>On Resonance</td>
<td>103</td>
<td>2</td>
<td>0.02 ± 0.01</td>
</tr>
<tr>
<td>Off Resonance</td>
<td>110</td>
<td>23</td>
<td>0.21 ± 0.04</td>
</tr>
<tr>
<td>No Microwaves</td>
<td>100</td>
<td>40</td>
<td>0.40 ± 0.06</td>
</tr>
</tbody>
</table>

**Off Resonance**

Microwave Results: Appearance Measurements

**Graphs and Diagrams:**

1. A graph showing the number of events per 15 seconds over time (t, s) with different resonant states labeled as follows:
   - On resonance (103 runs)
   - Off resonance (110 runs)
   - No microwaves (100 runs)

2. A graph showing events per 1.6 cm along the axial position (z, cm) with different conditions:
   - On resonance (103 runs)
   - Off resonance (110 runs)
   - No microwaves (100 runs)

**Equations and Notations:**

- $1420 \text{ MHz}$
- $f_{ad}$ and $f_{bc}$
- $15 \text{ MHz}$
- $15 \text{ s}$
- $180 \text{ s}$

**Citations:**

Cosmics

Antiproton/Antihydrogen annihilation

Cosmic “confusion” rate ~2mHz

Microwave Results: Appearance Measurements

Spin Flip Measurement Uncertainty

Drive electron cyclotron heating

Measures magnetic field to about 0.1%
Spin Flip Measurement Uncertainty

- Hyperfine splitting has a broad minimum at $H_0=0.65\,\text{T}$, corresponding to $f_0=655\,\text{MHz}$.

- Measurement of this splitting is largely independent of the magnetic field near this minimum.

1S-2S Spectroscopy
With help from an unusual funding source, we are constructing a new device, ALPHA-II.

ALPHA-II will incorporate:
- Provisions to increase the trapping rate.
- Laser access.
- A laser buildup cavity.
- Operation will recommence with antiprotons when CERN returns from its LHC upgrade.
Antimatter Gravity

• Will antimatter fall under gravity the same way that normal matter falls?
• The weak equivalence principle asserts that it will.
• There have been many indirect test of the weak equivalence principle.
• The evidence from the indirect tests is compelling, but all such indirect tests have assumptions which just might not hold.
• There have been no “free fall” tests.
Effect of Gravity on the Anti-Atom Trapping Well

\[ F = \frac{M_G}{M} = 100 \]

Trap diameter is 44.55 mm.
Antimatter Gravity

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\[ F = \frac{M_G}{M} = 100 \]

Magnet Quench Shutdown Comparison

ALPHA, Description and first application of a new technique to measure the gravitational mass of antihydrogen, Nature Comm 4, 1785 (2013).
• ALPHA would have been sensitive to gravity if gravitational interactions with antimatter were about 100 times stronger than expected.

• ALPHA's recent measurements constitute the first “free fall” measurement of gravity, albeit at a very imprecise level.

• “Proof of principle” that free fall experiments can be done on trapped anti-atoms.

• Working with Holger Müller on antimatter interferometer than could measure the gravitational force on antihydrogen to $10^{-6}$.

ALPHA, Description and first application of a new technique to measure the gravitational mass of antihydrogen, Nature Comm 4, 1785 (2013).

CPT Physics on ALPHA-II

- 1S-2S spectral comparison of hydrogen and antihydrogen.
- Hyperfine level spacing comparison.

**Graphical Content**

- **1S→2S**
  - Diagram showing the transition energies.

- **Hyperfine Splitting**
  - Diagram illustrating the magnetic field dependence of energy levels.
  - **Trappable 'low-field seeking' states**
  - **Untrappable 'high-field seeking' states**
  - Spin-flip frequencies: \( f_{\text{micro}} \), \( f_{\text{macro}} \)

- **Laser 1s-2s**
  - Pulsed
  - Initial CW
  - Improved CW \( (v/\Delta v \sim 10^{-12}) \)

- **Microwave Hyperfine**
  - Initial Positron Spin Resonance
  - Improved PSR
  - NMR + PSR \( (v/\Delta v \sim 10^{-6}) \)

- **Current H limit** \( (10^{-14}) \)
- **Longer int. time Laser Cooling**
- **Current H limit** \( (10^{-12}) \)

**Energy Precision**

- Absolute energy sensitivity (GeV)
  - \( 10^{-14} \)
  - \( 10^{-12} \)
  - \( 10^{-10} \)
  - \( 10^{-8} \)
  - \( 10^{-6} \)
  - \( 10^{-4} \)
  - \( 10^{-2} \)
  - \( 10^{-1} \)

**Potential**

- **ALPHA II Potential**