ATRAP Progress in 2010

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ATRAP Papers 2010


Cold Antihydrogen
Aspirations Laid Out Long Ago

Goals

• Produce cold antihydrogen
• Trap cold antihydrogen
• Use accurate laser spectroscopy to compare antihydrogen and hydrogen

“For me, the most attractive way ... would be to capture the antihydrogen in a neutral particle trap ... The objective would be to then study the properties of a small number of [antihydrogen] atoms confined in the neutral trap for a long time.”

Gerald Gabrielse, 1986 Erice Lecture (shortly after first pbar trapping)

Motivations
Why Compare H and H (or P and P)?

Reality is Invariant – symmetry transformations
- P parity
- CP charge conjugation, parity
- CPT charge conjugation, parity, and time reversal

CPT Symmetry
- Particles and antiparticles have
  - same mass
  - opposite charge
  - same magnetic moment
  - same mean life
- Atom and anti-atom have
  - same structure

Looking for Surprises
- simple systems
- extremely high accuracy
- comparisons will be convincing
- reasonable effort
- FUN
Seek to Improve **Lepton** and **Baryon** CPT Tests

antihydrogen 1s-2s

unlikely dream natural linewidth in a trap

meson CPT test

$R_\infty[\bar{H}] = \frac{m[e^+] \left( \frac{q[e^+]}{q[e^-]} \right)^2 \left( \frac{q[p]}{q[p]} \right)^2 (1 + m[e^-]/M[p])}{m[e^-] \left( \frac{q[e^-]}{q[e^-]} \right)^2 (1 + m[e^+]/M[p])}$
## Comparing the CPT Tests

**Warning** – without CPT violation models it is hard to compare.

<table>
<thead>
<tr>
<th>CPT Test</th>
<th>Measurement</th>
<th>Free Gift</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accuracy</strong></td>
<td><strong>Accuracy</strong></td>
<td></td>
</tr>
<tr>
<td>$K_0 \overline{K}_0$</td>
<td>$2 \times 10^{-18}$</td>
<td>$2 \times 10^{-3}$</td>
</tr>
<tr>
<td><strong>Mesons</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e^+ e^-$</td>
<td>$2 \times 10^{-12}$</td>
<td>$2 \times 10^{-9}$</td>
</tr>
<tr>
<td><strong>Leptons</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P \overline{P}$</td>
<td>$9 \times 10^{-11}$</td>
<td>$9 \times 10^{-11}$</td>
</tr>
<tr>
<td><strong>Baryons</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3 fundamentally different types of particles

- $K_0 \overline{K}_0$, $e^+ e^-$, $P \overline{P}$

The accuracy improves with antihydrogen.
Ultimate Goal: Hydrogen 1s – 2s Spectroscopy

Many fewer antihydrogen atoms will likely be available

(Haensch, et al., Max Planck Soc., Garching)
http://www.mpq.mpg.de/~haensch/hydrogen/h.html
Spectroscopy on 1000 or Fewer Atoms Seems Possible \( \rightarrow \) 1 part in \( 10^{12} \) estimated

T. Haensch and C. Zimmerman,
Laser Spectroscopy of Hydrogen and Antihydrogen,
Ultimate Goal: Hydrogen 1s – 2s Spectroscopy

Many fewer antihydrogen atoms will likely be available.
Cold Antihydrogen
Aspirations Laid Out Long Ago

Goals

• Produce cold antihydrogen
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“For me, the most attractive way ... would be to capture the antihydrogen in a neutral particle trap ... The objective would be to then study the properties of a small number of [antihydrogen] atoms confined in the neutral trap for a long time.”

Our Community Has Come a Long Way towards Realizing this Goal
First Trap for Antiprotons – 1986

21 MeV antiprotons

1 cm

magnetic field

TRAP Collaboration at CERN
Accumulating Low Energy Antiprotons

(Developed by our TRAP Collaboration at CERN’s LEAR: 1986 - 2000)

- Slow antiprotons in matter
- Capture antiprotons in flight
- Electron cooling $\rightarrow$ 4.2 K
- $5 \times 10^{-17}$ Torr
- Stacking

Now used by 3 collaborations at the CERN AD
ATRAP, ALPHA and ASACUSA

$10^{10}$
energy reduction
"First Capture of Antiprotons in a Penning Trap: A KeV Source",
G. Gabrielse, X. Fei, K. Helmerson, S.L. Rolston, R. Tjoelker, T.A. Trainor, H. Kalinowsky,
J. Haas, and W. Kells;
Electron-Cooling of Antiprotons – in a Trap

- Antiprotons cool via collisions with electrons
- Electrons radiate away excess energy

"Cooling and Slowing of Trapped Antiprotons Below 100 meV",
Particle Physics at Low Energy

$2M_p c^2$

LEAR and AD

$10^{10}$

TRAP

4.2 K

0.3 meV

70 mK, lowest storage energy for any charged particles
TRAP Improved the Comparison of Antiproton and Proton by $\sim 10^6$

\[
\frac{q/m \text{ (antiproton)}}{q/m \text{ (proton)}} = -0.99999999991(9)
\]

$9 \times 10^{-11} = 90 \text{ ppt}$

**best CPT test with baryons**

100 antiprotons and protons

Two Methods Produce Slow Antihydrogen

1. In a nested Penning trap, during positron cooling of antiprotons
   Device and technique – ATRAP
   Used to produce slow antihydrogen – ATHENA and ATRAP

   Variations: Basic (ATRAP initially, ATHENA-ALPHA)
               Driven (ATRAP before 2007)
               Adiabatic well depth change (ATRAP 2007)

2. Laser-controlled resonant charge exchange
   ATRAP
Method 1: Nested Penning Trap

3-Body “Recombination”

**ANTIHYDROGEN PRODUCTION USING TRAPPED PLASMAS**

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and

W. KELLS

*Fermi National Accelerator Laboratory, Batavia, IL 60438, USA*

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We call attention to another three-body recombination

\[ p^- + e^+ + e^+ \rightarrow H + e^+ \]  \( (6) \)

which may well be more efficient for antihydrogen production by many orders of magnitude. Its cross...
Positron Cooling of Antiprotons in a Nested Penning Trap

TRAP/ATRAP Develops the Nested Penning Trap

Proposed nested trap as a way to make antihydrogen
"Antihydrogen Production Using Trapped Plasmas"
G. Gabrielse, L. Haarsma, S. Rolston and W. Kells

"Electron-Cooling of Protons in a Nested Penning Trap"
D.S. Hall, G. Gabrielse

"First Positron Cooling of Antiprotons"
ATRAP
ATRAP: Gentle Heating of Antiprotons

Why the Antihydrogen Should be Cold

Slide from ATRAP 2007 Progress Report
Chaotic Orbits $\rightarrow$ States that can be trapped

(a) Chaotic orbit representation

(b) Graph showing the standard deviation of $\rho(t)$ vs. mean $\rho(t)$ in $\mu$m

actual orbit resulting from guiding center initial conditions

$\rho > \rho_3 = \left[9r_e c^2 / \omega_c^2 \right]^{1/3} = 0.14 \, \mu$m
Congratulations to ALPHA on Observing Trapped Antihydrogen Atoms

1 atom in 9 trials reported
0.2 second storage time
more and longer being reported here

ATRAP – observed the first production of antihydrogen atoms in the fields of a Ioffe trap (PRL 2008)

Limit: Less than 20 atoms produced per trial
Thought that this limit is already too few to be useful
→ decided that we needed – more antiprotons
→ colder antiprotons

• Lowered electrode temperature to 1.2 K
• Started measuring antiproton temperatures
• Developed new pbar cooling methods
ATRAP 100 Second Loading Cycle at the AD
ATRAP II Trap Apparatus

- positrons enter
- refrigerator
- superconducting solenoid
- Ioffe trap
- laser windows
- scintillating fiber detector
- antiprotons enter

Height: 2.18 m
ATRAP’s First Antihydrogen Trap

(a)

\( \bar{p} \) cooled by electrons

10 cm

\( \bar{p} \) location for stability test

(b)

electrodes

racetrack coils

pinch coils
First Antihydrogen Production within a Penning-Ioffe Trap

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(ATRAP Collaboration)

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No antihydrogen trapped yet
• not cold enough
• not in ground state
ATRAP – observed the first production of antihydrogen atoms in the fields of a Ioffe trap (PRL 2008)

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Advances and Aspirations
Advances and Conclusions for 2010
> 10 Million Cold Pbar/Trial at ATRAP

0.4 million $\rightarrow$ 10 million
(5.4 Tesla) (1 Tesla)

3.7 Tesla
1 Tesla

better cooling

Diagram showing the relationship between accumulation time in minutes and millions of antiprotons, with a notable improvement from 0.4 million, 2002 to 10 million at 3.7 Tesla.
Pumped Helium System for Cooling Positron and Electron Traps to 1.2 K

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Colder Electrodes: 4.2 K $\rightarrow$ 1.2 K

1.2 K Penning trap electrodes

4.2 K Ioffe trap

thermal isolation bellows

thermal contact clamps

4.2 K $\bar{p}$ solenoid

4.2 K helium dewar

pumping line

impedance line (capillary system)

1 K pot

needle valve

cooling lines

Penning trap

thermal isolation bellows

thermal contact clamps
For trapping antihydrogen in a $T_0 \sim 0.5$ K Ioffe trap well
Prob. of an antihydrogen energy (in temp. units)

$$P \sim e^{-\frac{kT}{kT_0}}$$

A factor of 4 to 7 reduction in the antihydrogen energy $kT$ is important
Electron Plasma Temperature Change
Approximately Equal to the Electrode Changes
1. ATRAP cooled large enough numbers of trapped antiprotons to a low enough temperature to demonstrate for the first time the first radial separation of trapped antiprotons from the electrons used to initially cool them. This is discussed in an attached Physical Review Letter.
Centrifugal Separation of Antiprotons and Electrons


- Important for arranging efficient overlap of antiprotons and a positron plasma
- Important for understanding the heating of antiprotons when electrons are ejected

1 million antiprotons, 100 million electrons
More Advances and Conclusions for 2010

3.5 K for 3.5 million antiprotons

2. ATRAP demonstrated that temperatures as low as 3.5 K could be directly measured and realized. This is three times lower than any other directly determined antiproton temperature. It is discussed in an attached manuscript that is currently under review.

3. Embedded electron cooling (with antiprotons greatly outnumbering the electrons used to cool them) was used to cool large numbers of antiprotons (up to $3.5 \times 10^6$) to 17 K. This is discussed in an attached manuscript that is currently under review.

4. Adiabatic cooling was used with up to $3.5 \times 10^6$ antiprotons to realize temperatures measured to be 3.5 K or lower. This is discussed in an attached manuscript that is currently under review.
Adiabatic Cooling of Antiprotons

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(ATRAP Collaboration)
(Dated: Submitted 1 Dec. 2010)

Embedded electron cooling
(to 31 K or 17 K)

Followed by adiabatic cooling
(to 3.5 K or below)
Antiproton Temperature Measurements

Examples of antiproton temperature measurements

Cooling from 31 K to 3.5 K

Temperature limit
Or measurement limit?

\[ T_f = \left( \frac{V_i}{V_f} \right)^{2/3} T_i. \]
Compare to Evaporative Cooling

ALPHA (PRL 2010) → 1000 times less antiprotons per trial (fewer trials, of course)

→ almost 3 times higher temperature

Evaporative Cooling Would do Better with a Lower Starting Temperature

Even Lower Temperatures Seem Possible

Embedded electron cooling
→ Adiabatic cooling
→ Evaporative cooling (if large particle loss is ok)
6. The technical problems with getting sufficient Cs atoms in a cryogenic environment were solved, with one Cs source used for the entire 2010 antiproton run. The instability of the antihydrogen ingredients during antihydrogen production was also solved.

7. Antihydrogen was produced by laser-controlled charge exchange with much larger numbers of trapped antiprotons and positrons than when we first demonstrated this method [7] with small numbers of antiprotons and positrons. (Tentative conclusion still under study.)

8. Large traps and large numbers of antiprotons and positrons make it difficult to use the ATRAP field ionization method for detecting antihydrogen production.
Method II: Antihydrogen Via Laser-Controlled Resonant Charge Exchange

We Returned to this Method
Only This Year -- Mixed Results

- greatly increased number of positrons and antiprotons
- better control of the positron and antiproton plasmas
- better laser systems
- Cs source lasted the whole beam run
- greatly reduced antiproton losses

Seem to be making antihydrogen in much larger amounts.

Detection well seems to spill the ionized antiprotons before we can count them (due to hot electrons from positronium) → do not yet understand
5. Despite the declining activity of our radioactive source (what was originally 52 mCi is now 17 mCi) the positron accumulation efficiency continues to increase as we learn how to better operate and tune the accumulator and transfer line. Positrons now accumulate in our accumulator at a rate of $4 \times 10^4 e^+/s/mCi$, and in the antihydrogen trap at a rate of $1.5 \times 10^4 e^+/s/mCi$. Up to $3.8 \times 10^9$ positrons have been collected in the Penning traps where antihydrogen is made though smaller numbers were typically used in 2010.
Measure the Antiproton Magnetic Moment

**Goal:** Improve accuracy by a factor of a million or more

**Challenge:** Nondestructive detection of a proton/antiproton spin flip (nuclear magneton 2000 times smaller than Bohr magneton)
Spin-off Measurement: Antiproton $g_p^- = 5.601(18)$

Make a one proton (antiproton) self-excited oscillator
→ try to detect a proton (and antiproton) spin flip

• Hard: nuclear magneton is 500 times smaller
• Experiment underway
  → Harvard
  → also Mainz and GSI (without SEO)
    (build upon bound electron g values)

→ measure proton spin frequency
→ we already accurately measure antiproton cyclotron frequencies
→ get antiproton g value
  (Improve by factor of a million or more)

detect spin flip
make spin flip
6 mm inner diameter
Self-Excitation and Feedback Cooling of an Isolated Proton

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Gabrielse
5. Objectives for 2011

The objectives for 2011 derive directly from what was accomplished in 2010.

1. Commission and use the new Ioffe trap that we have previously described to the SPSC.

2. Use the much larger number of much colder antiprotons to make antihydrogen in a nested Penning trap and see how much of it can be trapped.

3. Continue the investigation of laser-controlled charge-exchange production of antihydrogen, and see if atoms that can be trapped are being produced.