ATRAP: Context and Status

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Antihydrogen
and the Antiproton Magnetic Moment

Gerald Gabrielse
Spokesperson for TRAP and ATRAP at CERN
Leverett Professor of Physics, Harvard University
Context

CERN Pursues Fundamental Particle Physics at Whatever Energy Scale is Interesting

A Long and Noble CERN Tradition

1981 – traveled to Fermilab “TEV or bust”
1985 – different response at CERN when I went there to try to get access to LEAR antiprotons for q/m measurements and cold antihydrogen

It is exciting that there is now
• a dedicated storage ring for antihydrogen experiments
• four international collaborations
• too few antiprotons for the demand
Pursuing Fundamental Particle Physics at Whatever Energy Scale is Interesting

A Long and Noble CERN Tradition

1986 – First trapped antiprotons (TRAP)
1989 – First **electron-cooling** of trapped antiprotons (TRAP)

CERN’s AD, plus these cold methods $\rightarrow$ make antihydrogen possible
Pursuing Fundamental Particle Physics at Whatever Energy Scale is Interesting

A Long and Noble CERN Tradition

1981 – traveled to Fermilab “TEV or bust”

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LHC: $7 \text{ TeV} + 7 \text{ TeV}$

AD: $5 \text{ MeV}$

100 times More trapped antiprotons

ELENA upgrade: $0.1 \text{ MeV}$

ATRAP: $0.3 \text{ milli-eV}$

$5 \times 10^{16}$
First Physics: Compare $q/m$ for antiproton and proton to 9 parts in $10^{11}$ (could now be improved)

Current Physics: Compare antihydrogen and hydrogen (goal is a higher precision than $q/m$ measur.)

Future Physics: Compare antiproton and proton magnetic moment
First Physics: Comparing Antiproton and Proton

Best CPT test with baryons

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

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

Current Physics: Antihydrogen

Quarter century

Antihydrogen ideas (1986-1988) → realized in 2002-2010
1986 Idea: Use Cold Antiprotons to Make Cold Antihydrogen Atoms

“When antihydrogen is formed in an ion trap, the neutral atoms will no longer be confined and will thus quickly strike the trap electrodes. Resulting annihilations of the positron and antiproton could be monitored. ..."

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

2002: Antihydrogen observed by ATHENA and by ATRAP

used field ionization detection
1988 Ideas: Use Nested Penning Trap and 3-Body "Recombination"

To get opposite charges to interact

To get fast enough formation rate

Nested Penning Trap

3-Body "Recombination"

Used by ATRAP, ALPHA and ASACUSA
1988 Ideas: Use Nested Penning Trap and 3-Body “Recombination”

1996 – Protons and electrons interact in a nested Penning trap (TRAP)

2001 – Antiprotons and positrons interact in a Nested Penning Trap (TRAP)

2002 – Demonstrate that antihydrogen is produced by this method (ATRAP and ATHENA)

2010 – ASACUSA also uses these methods (with RFQ)

This method produced all slow antihydrogen to date (almost)
1986 Idea: Trap Cold Antihydrogen for Accurate Spectroscopy

“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)

Proof-of-principle demo (< 1 trapped atom per trial) – ALPHA, 2011

Need many more atoms
First Antihydrogen Production within a Penning-Ioffe Trap

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No trapped antihydrogen detected

Detection limit: < 20 atoms trapped per trial
**ATRAP** – produced and observed antihydrogen atoms in the fields of a Ioffe trap (PRL 2008)

Limit: less than 20 atoms were being trapped per trial

**ALPHA** – did similar production the following year

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**two different approaches**

**ATRAP**
Try to make more atoms

**ALPHA**
Try to detect fewer atoms
(0.1 per trial in 2010)
Nature’s Gift – trapping happens despite deexcitation through chaotic orbital motions

Chaotic Orbits $\Rightarrow$ States that can be trapped

$\rho > \rho_3 = \left[\frac{9r_ec^2}{\omega_c^2}\right]^{1/3} = 0.14 \mu m$
ATRAP – observed the first production of antihydrogen atoms within the fields of a Ioffe trap (PRL 2008)

Set limit: less than 20 atoms were being trapped per trial

ALPHA – did similar production the following year

For the next step, two different approaches:

ATRAP
Make more cold atoms

ALPHA
Detect fewer atoms
(0.1 per trial in 2010)
Colder Electrodes: 4.2 K $\to$ 1.2 K

- 4.2 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
10 Million Cold Pbar/Trial at ATRAP

0.4 million → 10 million
(5.4 Tesla) (1 Tesla)

Typical experiment trial uses a few million antiprotons
→ Need ELENA to get 10 million in a reasonable time
→ Need ELENA so that we can use more than 6 hours/day
**ATRAP ➔ More Antiprotons, Much Colder**

- Lowered electrode temperature to 1.2 K
- Started measuring antiproton temperatures
- Developed new pbar cooling methods

First antiprotons cold enough to centrifugally separate from the electrons that cool them


Two new cooling methods for antiprotons
- embedded electron cooling (almost no electrons)
- adiabatic cooling


3 million antiprotons at 3.5 K
ATRAP

Centrifugal Separation of Antiprotons and Electrons

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• 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
Embedded electron cooling
(to 31 K or 17 K)

Followed by adiabatic cooling
(to 3.5 K or below)
Compare Adiabatic and Evaporative Cooling

Compare to evaporative cooling – ALPHA (PRL 2010) starting 100 K

- 1000 times more antiprotons per trial
- 3 times lower temperature

(Need to show that these give better antihydrogen production)

Even Lower Temperatures Should be Possible

Embedded electron cooling
  - Adiabatic cooling
    - Evaporative cooling (if large particle loss is ok)
There is a Second Method to Produce Slow Antihydrogen

1. In a nested Penning trap, during positron cooling of antiprotons
   ATRAP, ALPHA, ASACUSA

2. Laser-controlled resonant charge exchange
   ATRAP
   • 200 times more atoms produced (2010-2011)
Method II: Antihydrogen Via Laser-Controlled Resonant Charge Exchange

Make Big Cs Atoms

511 nm

892 nm
We Returned to this Method in 2010

- 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

→ 500 times more positronium than in 2004 demo
→ Looks like much more antihydrogen (not yet published)

??? Detection well seems to spill the ionized antiprotons before we can count them (due to hot electrons from positronium)
   → do not yet understand
   → must detect without using detection well so far
30 million positrons

92 +/- 5% of trapped positrons form Ps
- 520 time more Ps than in demo
- 3.5 higher efficiency per positron
200 Times More Antihydrogen Made Per Trial
(compared to proof-of-principle demonstration)

Antiprotons: 5 million
Positrons: 300 million

Remains to be done in a Ioffe field
During 2011

Use much larger and much colder antiprotons for hbar production

Looking for trapped antihydrogen from laser-controlled charge exchange

Second generation Ioffe trap (with laser access)
  • Built
  • Not yet fully tested

Improving Lyman alpha laser for laser cooling antihydrogen

Comparing the antiproton and proton magnetic moments
  • Demonstrated parts in $10^{10}$ cyclotron frequency measurements long ago
  • Should be able to improve pbar/p comparison by $>10^6$
  • Using a single trapped proton to develop spin flip methods