Confinement of Antihydrogen for 1000 Seconds:

ALPHA Collaboration

PANIC 2011, July 25 – 29, MIT

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Motivations

• Atomic hydrogen: one of best studied systems
  – 1s-2s level: 2 466 061 102 474 851 (25) Hz \( \Delta \nu/\nu \sim 10^{-14} \)
  – Hyperfine splitting: 1 420 405 751.768 (1) Hz \( 10^{-12} \)

• Antihydrogen (anti-H): bound state of \( p\bar{b}arn \) & e+:
  produced in large quantities by ATHENA, ATRAP (2002)

• Comparison of H and anti-H: “Textbook” experiment!

• Tests of Fundamental Symmetries and Concepts:
  CPT, Quantum Field Theory, Gravity

• Trapping of antihydrogen: technical bottleneck
  \( \Rightarrow \) Initial Goal of ALPHA (est. 2005)
Antihydrogen Trapping with ALPHA

1. Prepare $3 \times 10^4$ pbars (300K; after cooling, compression, transfer), and $4 \times 10^7$ e+ (170K) \cite{4PRLs}

2. Energize magnetic trap

3. **Gently mix** pbars and e+ for 1 s \cite{Phys.Rev.Lett.2011}

4. Hbar $< 0.5$ K (50 μeV) will be trapped

5. Clear charged particles by E field

6. Anything remaining trapped **should be** neutral anti-H

7. Shutdown magnetic trap in $\sim 10$ msec by quenching magnets

8. Released anti-H hit the walls

9. Search for annihilation signatures in Si detector \cite{PLB2011}
**ALPHA Challenges**

**Characteristic energy scales:**

- Plasma energy: space charge ($\propto en_e r^2$)  
  $\approx 10$ eV
- Neutral trap depth:  
  $(\mu \Delta B) \approx 50 \mu$eV
- Need $10^{-5}$ control of plasmas to make cold enough anti-H
- ATHENA’s anti-H production was much easier!
  
  Atomic energy scale: $(m_\alpha \alpha^2)$ 10 eV  
  $\approx$ Plasma space charge 10 eV

**Detection of anti-H trapping**

- Expected event rates very low
- Statistics & backgd limited

30,000 channel 3-layer Si strips  
$\sim 0.8$ m$^2$ active area  
Liverpool + ALPHA Canada

**Position Sensitivity Essential**
ALPHA Progress since First Beam in 2006


Letters 16, 100702 Anti-H production in atom trap

More papers (2011)

Allowed “gentle mixing” of pbar & e+
Antihydrogen production via auto-resonant (AR) injection of antiprotons


AR: self-regulating feature of a driven non-linear oscillator, where oscillation amplitude can be locked by drive frequency.

Allows efficient pbar injection into e+ with very low relative energy (gentle mixing vs. 10 eV injection).
Auto-resonance

Harmonic potential
Nonlinear potential

RF drive:
Start at high freq (600 kHz)
Chirp down to lower freq

AR: Essential for trapped Hbars
Use event topology to select signal from cosmic background

Study selection criteria ("cuts"), without looking at trapping data (except on-line monitoring)

Instead use independent calibration data samples
  - Antihydrogen Sample (2.4x10^4 events); Cosmic Sample (1.3x10^5 events)

Achieved *unbiased* and *optimized* choice of cuts ("blind analysis")
  [submitted to NIM]
Event Selection Criteria

Distributions of calibration samples

Main cut variables
1. Number of tracks
2. Vertex radius
3. Linear fit residuals

Cuts optimized for expected significance (p-value)

Cosmic rejection: 99.5%
Signal acceptance: 65%

All this studied without Looking at the data
Antihydrogen Trapping

- **2009**: found 6 events after “opening the box”
  - 212 trials
  - Cosmic background rejected >5 sigma
  - (very unlikely) “mirror trapping” of bare pbars in homogenous B field could not be ruled out (recall: no e+ detected)
  - Did NOT claim anti-H trapping!

- **2010**: found 38 events
  - 335 trials
  - Improved plasma conditions

- **New control expt’s**
  - Mixing with heated e+ (suppresses anti-H production)
  - Release anti-H while applying E field: bare pbars would be deflected
  - Mirror trapped bkgd ruled out!
Annihilation time and position

Simulation for antihydrogen

Simulations for bare pbars (experimentally validated)

Position sensitivity essential!
Antihydrogen Trapped (for 172 ms)

Nature, Nov. 2010

Andrea Gutierrez
(1st yr UBC Ph.D. student) in Finnish newspaper!
Latest Results from ALPHA

Nature Phys. 7, 558 (2011)
[arXiv:1104.4982]
New Result 1: Increased trapping rates

2009: 6 events

2010 Sep: 38 events

2010 Nov: 309 events
(hard to tweak zero!)
New Result 2: Long-time confinement

- Trapping time increased from 172 ms to 1000 s:
- Nearly 4 orders of magnitude increase
Results 3: Evidence for ground state Hbars

- Precision spectroscopy requires ground state Hbars (1s state)
- All the previous observed states are excited states
  - 3 body recombination
- Our theoretical calculations
  - De-excitation to grounds state < 1 sec

- 1st evidence for G.S. Hbars!
- Will test experimentally via μ-wave spectroscopy soon
Results 4: kinetic energy of trapped Hbars

Standard simulation

- Colder Hbars come out later
- Data agree with simulated energy distribution
- Consistent with theory assuming Hbar produced at thermalized with e+ (~50 K)
- First physics information of trapped antihydrogen!
Annihilation position distribution

- Simulation: Position distribution has sensitivity to energy; but why?
- Has to do with coupling of axial and radial degrees of freedom in Hbar motion
  → Sensitivity to anisotropic temperature distributions

Trapping dynamics important for spectroscopy

Makoto Fujiwara, ALPHA
Latest ALPHA results
Nature Phys. 7, 558 (2011)
http://WWW.CERN.CH
ALPHA experiment traps antimatter atoms for 1000 seconds

Andrea Gutierrez, a PhD student from UBC, transfers liquid helium from a storage dewar into the cryostat containing the superconducting magnetic trap used by the ALPHA experiment.

In a paper published by Nature Physics, the ALPHA experiment at CERN reports that it has succeeded in trapping antimatter atoms for over 16 minutes: long enough to begin to study their properties in detail. ALPHA
Implications of long time confinement

- Still digesting the implications
- “Game changer”
  - 170 ms to 1000 s
- For spectroscopy
  - Figure of merit:
    (trapped number) x (observation time) x (laser, µ-wave power)^n
  - Reduces dramatically
    power requirements

- Laser cooling
  - Lyman alpha laser: very hard to produce
  - Atomic hydrogen laser cooled over ~15 min

- Antimatter gravity
  - At ~mK level, gravity becomes non-negligible
  - Gravity experiments becoming plausible due to long confinement

- Many other possibilities
Towards Antihydrogen Microwave Spectroscopy

Canadian-Led Initiative:
Walter Hardy (UBC), Mike Hayden (SFU)
M. Ashkezari (SFU), T. Friesen (Calgary), MCF

[Also, for Laser Spectroscopy:
Rob Thompson, T. Friesen (Calgary), MCF]
Microwave Spectroscopy (at 1 T)

- Successful microwave injection tests: Nov. 2011
- Transmission efficiency measured (e- plasma as power meter)
- Anti-H trapping with 4 W microwave injected
- Goal of this year’s run
ALPHA Status

• 2011 Run at CERN
  – May 9-Nov 21: 6.5 months

• Goals
  – First spectroscopy (via microwaves)
    Canadian initiative

• ALPHA upgrade for 2012
  – Laser access
  – Microwave resonators

• ELENA: AD upgrade just approved by CERN
  – x100 more antiprotons by 2015-2016!

• Antihydrogen: moving from “demonstration” phase to “physics” phase

• Exciting time for antihydrogen physics!
Thank you!
Merci!