AntiHydrogen Trapped

Francis Robicheaux
Auburn University

Collaborators: ALPHA
Jim Hanson, Turker Topcu, Michael Wall, Chris Norton, Christine Taylor, Michele Zhang, Jennifer Hurt, Patrick Carpenter, Patrick Donnan

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Goal

Why are we excited about holding onto atomic antimatter?

Why is it hard to do?
P = Parity

Laws of physics should(?) be same under the operation:

\[
P : \begin{pmatrix} x \\ y \\ z \end{pmatrix} \mapsto - \begin{pmatrix} x \\ y \\ z \end{pmatrix}
\]

Scalar \( a \rightarrow a \)

Example: \( P (\vec{r} \cdot \vec{r}) = (-\vec{r}) \cdot (-\vec{r}) = \vec{r} \cdot \vec{r} \)

Vector \( \vec{r} \rightarrow -\vec{r} \)

Axial Vector \( \vec{C} \rightarrow \vec{C} \)

Example: \( P (\vec{r} \times \vec{p}) = (-\vec{r}) \times (-\vec{p}) = \vec{r} \times \vec{p} \)
Classical Physics Under P

Newton’s Equations: Unchanged

\[ P \vec{F} = - \vec{F} = P (M \ddot{a}) = - M \ddot{a} \]

Maxwell’s Equations: Unchanged

Vectors: E, J

Axial Vector: B

Scalar: \( \rho_t \)

\[
\begin{align*}
\nabla \cdot \mathbf{E} &= \frac{\rho_t}{\varepsilon_0} \\
\nabla \cdot \mathbf{B} &= 0 \\
\nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\
\nabla \times \mathbf{B} &= \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}
\end{align*}
\]
Lee and Yang gave arguments for possibility of parity violation in weak decays.

C.S. Wu found signal in $\beta$ decay of $^{60}$Co by orienting magnetic moment in large magnetic field and low temperature.
CP OK!

$C = \text{Charge conjugation transformation } (Q \rightarrow -Q)$

Charge conjugation transformation and parity inversion works for $^{60}\text{Co}$. 

$\text{L}, -\mu$
CP not OK!

$K_0$ and its antiparticle mix through weak interaction to make $K_L$ and $K_S$.

$K_L$ always decays into $3 \pi$
CP = -1
$K_S$ always decays into $2 \pi$
CP = +1

$K_L$ sometimes decays into $2 \pi$. This is different CP symmetry. One phase in Standard Model. (2008 Nobel)
CPT OK?

T is the time reversal operation.
Anti-hydrogen

Hydrogen atom = 1 proton & 1 electron

Anti-hydrogen atom = 1 anti-proton & 1 positron

Don’t let the anti-matter touch matter.
Positron finds an electron, they disappear and gamma rays come out.
Antiproton finds a nucleus, antiproton “disappears” and a bunch of stuff comes out.

If you have a good vacuum, you could hold antihydrogen for a loooooooooooooong time.
H Spectroscopy

H is excited from 1s to 2s by 2 photons with $\lambda \sim 243$ nm

$f(1\text{S}-2\text{S}) = 2\,466\,061\,413\,187\,074(34)\ \text{Hz}$
ALPHA Collaboration

http://alpha.web.cern.ch/alpha
Making Antihydrogen

Movie
Production and detection of cold antihydrogen atoms


* Istituto Nazionale di Fisica Nucleare, Sezione di Genova, and ‡‡ Dipartimento di Fisica, Università di Genova, 16146 Genova, Italy
† Physik-Institut, Zürich University, CH-8057 Zürich, Switzerland
‡§ EP Division, CERN, CH-1211 Geneva 23, Switzerland
§ Dipartimento di Chimica e Fisica per l’Ingegneria e per i Materiali, Università di Brescia, 25123 Brescia, Italy
‖ Department of Physics and Astronomy, University of Aarhus, DK-8000 Aarhus, C, Denmark
†† Instituto de Física, Universidade Federal do Rio de Janeiro, Rio de Janeiro 21945-970, and Centro Federal de Educação Tecnológica do Ceará, Fortaleza 60040-531, Brazil
# Department of Physics, University of Wales Swansea, Swansea SA2 8PP, UK
☆ Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, and ** Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, 27100 Pavia, Italy
††† Department of Physics, University of Tokyo, Tokyo 113-0033, Japan
Signal

Cold Mixing
Hits on walls

Hot Mixing
Hits on gas impurities

Figure 3 Colour contour plots of the distribution (obtained by projecting into the plane perpendicular to the magnetic field) of the vertex positions of reconstructed events. 

a, Cold mixing. All reconstructed antiproton annihilation vertices from the mixing region are plotted—no crystal cuts are applied. The trap inner radius is 1.25 cm. The annihilations are centred on a slightly smaller radius, in agreement with our Monte Carlo simulations. (Some events appear to be outside of the trap radius owing to vertex reconstruction errors.) b, The same plot as above, but for hot mixing. These data are normalized to represent the same number of mixing cycles (165) as those in a.
Background-Free Observation of Cold Antihydrogen with Field-Ionization Analysis of Its States

G. Gabrielse,¹,* N. S. Bowden,¹ P. Oxley,¹ A. Speck,¹ C. H. Storry,¹ J. N. Tan,¹ M. Wessels,¹ D. Grzonka,² W. Oelert,² G. Schepers,² T. Sefzick,² J. Walz,³ H. Pittner,⁴ T. W. Hänsch,⁴,⁵ and E. A. Hessels⁶

(ATRAP Collaboration)
Three-body recombination for protons moving in a strong magnetic field

F. Robicheaux* and James D. Hanson

Department of Physics, Auburn University, Auburn, Alabama 36849-5311, USA
(Received 23 July 2003; published 27 January 2004)

Using a classical Monte Carlo method, we have computed the three-body recombination (two free electrons and a proton scattering into one free electron and a hydrogen atom: $e + e + p \rightarrow H + e$) in strong magnetic fields. The proton is allowed its full motion whereas the motion of the electron is given by the guiding center approximation. We investigate recombination for temperatures and fields similar to those used in recent ex-
Rate = C n^2 v b^5

n = density
v = (k_B T/m_e)^{1/2}
b = k e^2/k_B T

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TABLE II. Three-body recombination coefficient as a function of proton speed along the B field. B = 5.4 T, T_e = 4 K. The speed of the proton is given in units of electron thermal speed $V_0 = \sqrt{2k_B T_e/m_e} = 1.1 \times 10^4$ m/s. The energy of a proton with speed $V_z$ is also given.

<table>
<thead>
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<th>$V_z/V_0$</th>
<th>C</th>
<th>E (eV)</th>
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<td>0.000</td>
<td>0.100</td>
<td>0.00</td>
</tr>
<tr>
<td>0.167</td>
<td>0.081</td>
<td>0.04</td>
</tr>
<tr>
<td>0.333</td>
<td>0.051</td>
<td>0.14</td>
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<tr>
<td>0.500</td>
<td>0.031</td>
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<td>0.667</td>
<td>0.018</td>
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<tr>
<td>0.833</td>
<td>0.011</td>
<td>0.88</td>
</tr>
<tr>
<td>1.000</td>
<td>0.008</td>
<td>1.27</td>
</tr>
</tbody>
</table>
Simulations of antihydrogen formation

F. Robicheaux*
Department of Physics, Auburn University, Alabama 36849-5311, USA
(Received 31 October 2003; published 20 August 2004)
Results: Small BE & Fast!

Binding energy much less than expected

Speed of Hbar much larger than thermal (250 m/s) or trap depth (110 m/s).
Trapping Neutral Particles

\[ \text{PE} = - \mu \cdot \vec{B} \]

\[ \mu \cdot \vec{B} \cong \text{constant} \]

\[ \text{PE} = - \left( \mu \cdot \vec{B} \right) B(x, y, z) \]

\( \mu \) for ground state \( \sim 2/3 \) K/T
Antiparticle Trap

Trap electrodes  Detector  Liquid helium vessel.

AD vacuum  Trap vacuum

Final degrader and vacuum barrier.  Solenoid/Multipole/Mirror coils

Horizontal to Vertical scale 1 : 2
Actual Magnets: Uniform B
Actual Magnets: Octupole
Antiparticle Trap
Trapped antihydrogen


antihydrogen

cosmic
1st Trapped antiHydrogen

Simulation of antihydrogen hits
Simulation of antiproton hits

Filled symbols are experimental hits in z and time after quench (blue with right E-field, green with no E-field, red with left E-field)
Trust the pbar simulation?
Holiday Gift Idea No. 1

"Are you kidding?! It's 38 atoms of anti-hydrogen! They're priceless!"
Confinement of antihydrogen for 1,000 seconds

The ALPHA Collaboration

[Diagram of an experimental setup with labeled components: Electrodes, Vacuum wall, Cryostat wall, 3-layer Si detector, and graphs showing confinement profiles.]
t and z hit distributions

time after quench distrib.  z-hit distrib.

lines are simulations of Hbar hits
purple 10 mK, light blue 100 mK, blue 50 K (any T >> well depth), green quasi-bound
Number trapped vs delay

number of hits vs delay between mixing and magnet quench
Full z-t data/simulation compare

Antihydrogen Simulation Comparison

Antiproton Simulation Comparison

(a) Left Bias
   (b) No Bias
   (c) Right Bias

Counts

$z$ (mm)

$t$ (ms)
Do Experiments with antiH!!!

Four obvious experiments to try:
Laser spectroscopy of 1s-2s (ALPHA-II)
Microwave spectroscopy of 1s hyperfine states
Charge neutrality
Gravity

More antihydrogen useful for all experiments!!!
Cold or Small Positron Plasma?

Would you be better off trying to make your positron plasma smaller or colder? Should it be mega-dense?

Important trends:

Very cold and dense gives antiH formation before the antiprotons come into thermal equilibrium.

Wide range of parameters, the antiproton comes into thermal equilibrium with positrons before antiH formed.

Generally, cold is better…but there is another consideration.
Terrible News!

Positron plasma in B-field rotates.

Electric field parallel to B is \( \sim 0 \) inside positron plasma

\[
V \sim e \rho \frac{r^2}{(4 \varepsilon_0)}
\]

E X B drift speed \( \sim e \rho \frac{r}{(2 B \varepsilon_0)} \)

\[
\omega = \frac{v}{r} \sim e \frac{\rho}{(2 B \varepsilon_0)}
\]

The antiproton rotates with the positron plasma (same EXB drift). \textbf{The antiH will have an initial KE from thermal distribution plus the plasma rotation.}
Simulation of the formation of antihydrogen in a nested Penning trap: effect of positron density

S Jonsell¹, D P van der Werf¹, M Charlton¹ and F Robicheaux²

Radial position of where antiH formed during 0-0.1 ms, 0.4-0.5 ms, and > 1 ms

Radial drift to edge of positron plasma due to multiple formation and stripping of antiH
Fraction of antiH formed $< 1$ K

Red: evenly distributed formation of antiH
Green: formation proportional to r
Blue: formation only at the edge of the plasma

Can gain big if make positron plasma radially small
Plasmas Are Nasty

Expanding plasma has PE go to KE: gives substantial heating.

Charged plasma with cylindrical symmetry is stable. Expands slowly due to noise and slight imperfections.

Mirrors + uniform B = OK

Mirrors + octupole + uniform B = not OK

Fast expansion and heating of positrons unless radius very small. Even small plasmas are 2-4X hotter than w/out octupole.

Typical temperatures are ~40+ K.
An “Obvious” Problem

Anti-protons are in a plasma with electrons
Electrons cool the anti-protons & reduce $r$ (rotating wall)

Recombination with electrons around?

Positrons need to strongly outnumber the electrons near the anti-proton or TBR is strongly suppressed. FR, J. Phys. B 40, 271 (2007): electron/positron < 0.2

Also, if you try a dynamic mixing, average charge/mass will fluctuate.
Three-body recombination with mixed sign light particles

Recombination in 4 K plasma to states bound by > 16 K, for fraction of electrons: 0.0, 0.04, 0.08, 0.12, 0.16, 0.20

Lines from simple model calculation
An “Obvious” Solution

“Kick” the electrons out of the plasma.

Small electron mass means anti-protons hardly move during kick.

Heating of antiprotons on the 100-1000 K scale.
An “Obvious” Problem

Anti-protons are in a plasma, with no electrons, at a temperature more than few 100X too big for trapping.
A somewhat different case from usual evaporative cooling because of strong $B$ & coulomb scattering.

Slowly dump antiprotons out of their trapping well.
Dump antiprotons to measure $T$

Maxwell-Boltzmann tail; steeper means lower $T$

$A=1040$ K, $B=325$ K, $C=57$ K, $D=23$ K, $E=19$ K, $F=9$ K
More low energy antiprotons

Evaporative cooling means you lose antiprotons

Factor of ~100 decrease in temperature corresponds to factor of ~20 decrease in number

But!! Average r increases because evaporate antiprotons from r ~ 0.
Counterintuitive Results: Atoms

Large B-field combined with highly excited atoms can give strange result.

Microwave photons can cool center of mass motion…

Lower temperature not always better…
Cooling AntiH: Microwaves?
Cooling of Rydberg $\tilde{H}$ during radiative cascade

C L Taylor, Jingjing Zhang and F Robicheaux

Simulations performed by Michele Zhang & Christine Taylor (limited geometry tests FR)

Atoms start out in perfect circular state: $n,n-1,n-1$

Approximate non-circular states (quasi-classical rates)

Solve Newton’s equation for C.O.M. motion with random emission of photon
Antiparticle Trap
Adiabatic vs. Sudden Cooling

Initial KE = 5.4 K (~300 m/s), n = 25, perp to axis, center

Only look at atoms with final $E_{\text{com}} < 0.79$ K
Final $E_{\text{com}}$ Distribution

Initial $KE = 5.4$ K ($\sim 300$ m/s), $n = 25$, center

solid = perp, random $m > 15$; dot-dash = perp, circular

dotted = parallel, random $m > 15$; dashed = parallel, circular

Shape and # predicted from simple theory
Thermal KE = 4 K, n = 25, spheroid (2mm,15mm radii)
dash = circ; dotted = random m>15
dash-dot = initial distribution, solid = Maxwell

Fraction Trapped:
18%
16%
6%
Nice increase
Cushion
Microwave cause l,m transition at large B

Weak microwave because electric dip.

Lower l,m radiates faster

Leads to extra cooling (factor of 1.5 started at 16 K)
TBR Temperature Surprise?
Three-body recombination for electrons in a strong magnetic field: Magnetic moment

F. Robicheaux

Atoms bound by more than 32 K

Fraction with $dE/dB > 0$ and $dE/dB > 10 \, K/T$ increases with increasing positron temperature!

- 4 K positrons: 0.17, 0.035
- 8 K positrons: 0.21, 0.058
- 16 K positrons: 0.25, 0.063

Magnetic moment vs T and BE

$\mu$ proportional to $m_{<xv_y - yv_x>}$
Guiding Center Atom: $\mu$

$\mu = m_e \frac{v^2}{2} B$
$= -KE_{cyc}/B$

$\mu = k \frac{e^2}{2} r B$
$= |PE|/2 B$

$v_{\text{drift}} = E/B << v_{cyc}$
$= k \frac{e}{r^2} B$

$|PE| < KE_{cyc}$ means GCA low field seeker
High/Low Field Seekers

B does not strongly affect $\mu$ for more deeply bound states ($n < 30$).

**High Field Seeker**

$$|v| \sim v_0 - e B r/2 m_e$$

$v_0 = 73 \text{ km/s}$

$e B r/2 m_e = 4 \text{ km/s}$

for $n = 30$, $B = 1 \text{ T}$

**Low Field Seeker**

$$|v| \sim v_0 + e B r/2 m_e$$

$v_0 = (k e^2/r m_e)^{1/2}$

$$|\mu| \sim e^2 (k r/m_e)^{1/2}/2$$

$= e |L| /2 m_e$
How many antiprotons?

Should you want to have as many antiprotons as possible?

Argument for: More antiprotons means you will have more antiH and, thus, more trappable antiH.

Argument against: More antiprotons leads to more scattering between antiprotons (heating) and you could get charge exchange (trapped antiH converts to untrapped!)
Charge Transfer Always to Untrapped

The potential wells for antiprotons mean that the antiprotons are mostly high KE >> well depth.
Estimate

Energy ~ couple eV gives \( v \sim 2 \times 10^4 \text{ m/s} \)

Geometric size atom ~ \( 2 n^2 a_0 \sim 3 \times 10^{-7} \text{ m} \) for \( n \sim 50 \)

Time to decay ~ \( 0.1 \text{ s} \) for \( n \sim 50 \)

Transfer probability ~ density \( X \) \( 10 \) \((3 \times 10^{-7} \text{ m})^2 \) \( 2 \times 10^4 \text{ m/s} \times 0.1 \text{ s} \) ~ density \( X \) \( 2 \times 10^{-9} \text{ m}^3 \)

ALPHA density ~ \( 10^4 / (\pi [0.02 \text{ m}]^2 0.2 \text{ m}) \sim 4 \times 10^7 \text{ m}^{-3} \)

ATRAP density ~ \( 0.5 \times 10^6 / (\pi [0.02 \text{ m}]^2 0.1 \text{ m}) \sim 4 \times 10^9 \text{ m}^{-3} \) (from recent PRL, I probably overestimate)