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

Support from DOE and NSF

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 → a

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

Vector **r** → –**r**

Axial Vector **C** → **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

$$P\,\vec{F} = -\vec{F} = P\,(M\,\vec{a}) = -M\,\vec{a}$$

Maxwell's Equations: Unchanged

Vectors: E, J

Axial Vector: B

Scalar: ρ_t

$$\nabla \cdot \mathbf{E} = \frac{\rho_t}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

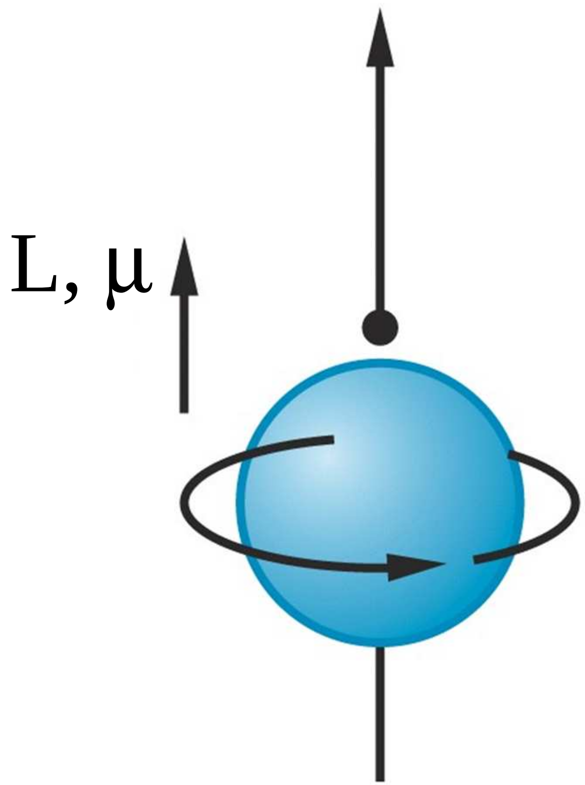
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

P Violation

Lee and Yang gave arguments for possibility of parity violation in weak decays

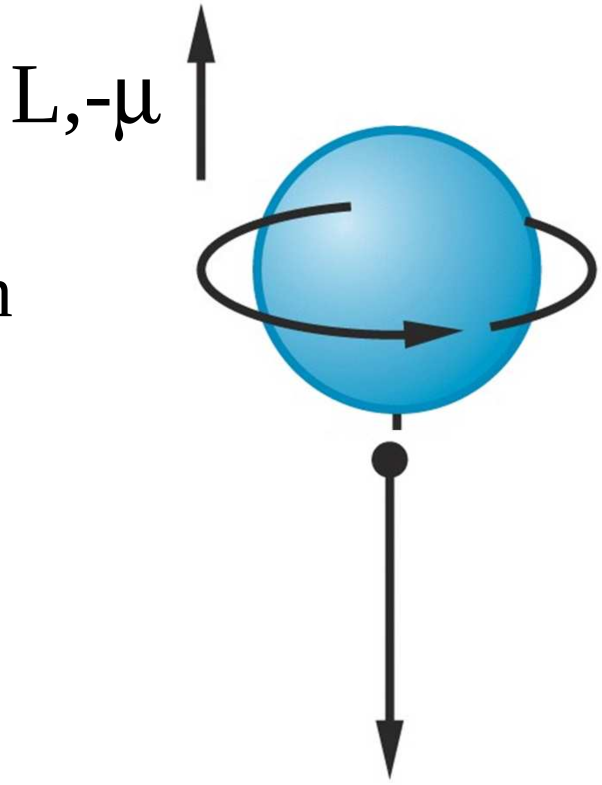
C.S. Wu found signal in β decay of ^{60}Co by orienting magnetic moment in large magnetic field and low temperature.



CP OK!

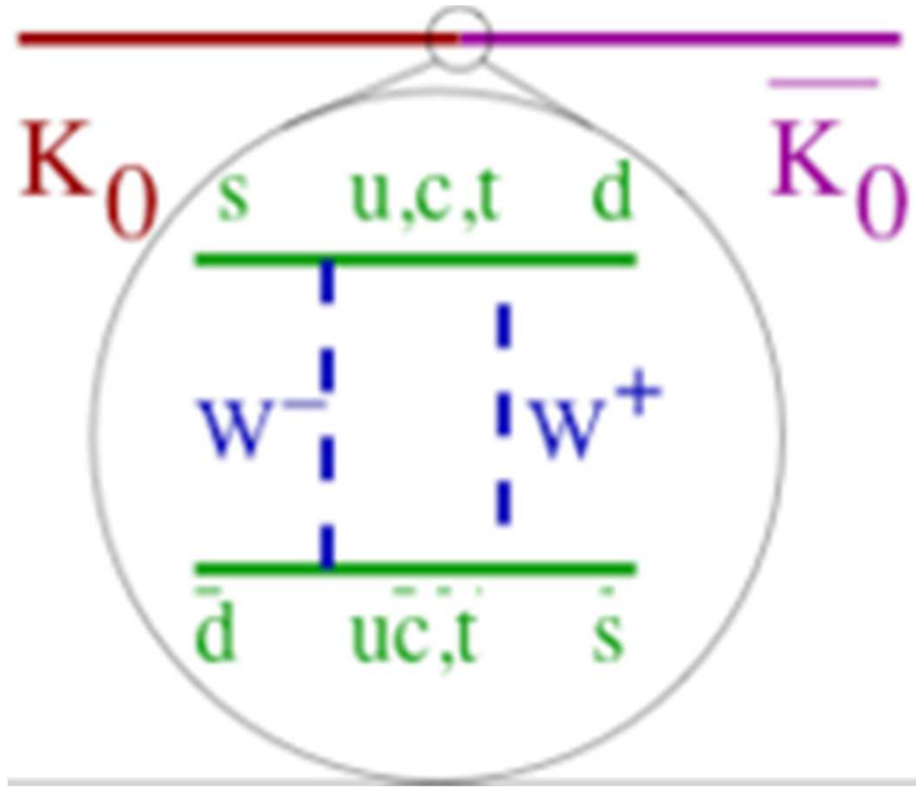
C = Charge conjugation transformation (Q → –Q)

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



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 π
CP = -1
K_S always decays into 2 π
CP = +1

K_L sometimes decays into 2 π. This is different CP symmetry. One phase in Standard Model. (2008 Nobel)

CPT OK?

✶ Any local quantum field theory, obeying Lorentz invariance and usual spin-statistics connection → CPT Invariance

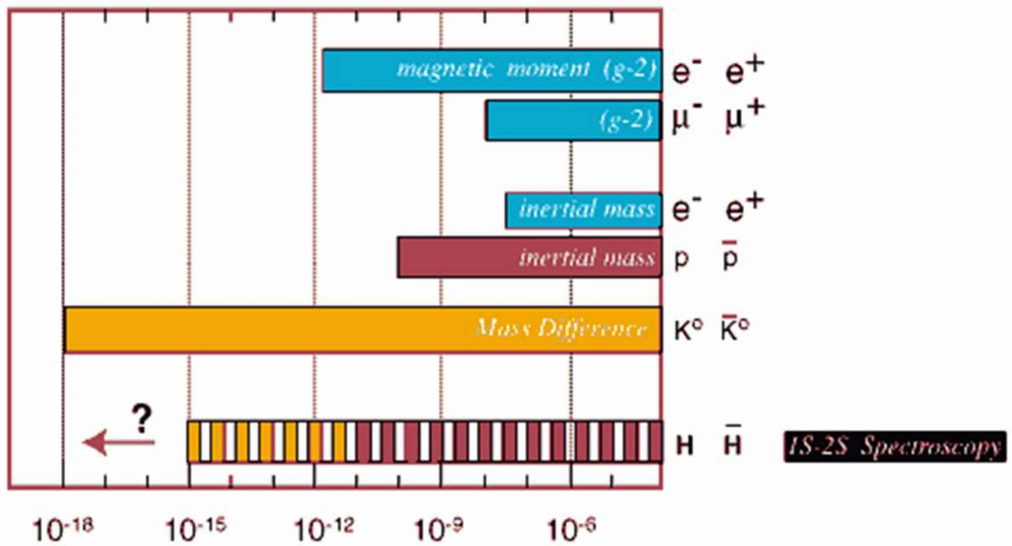
G. Lüders, Ann. Phys. 2, 1-15 (1957)
(also: W. Pauli, J. Schwinger)

MATTER = ANTIMATTER at any level of precision

T is the time reversal operation.

The most precise CPT Tests

(note the logarithmic scale)



Anti-hydrogen

Hydrogen atom = 1 proton & 1 electron

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

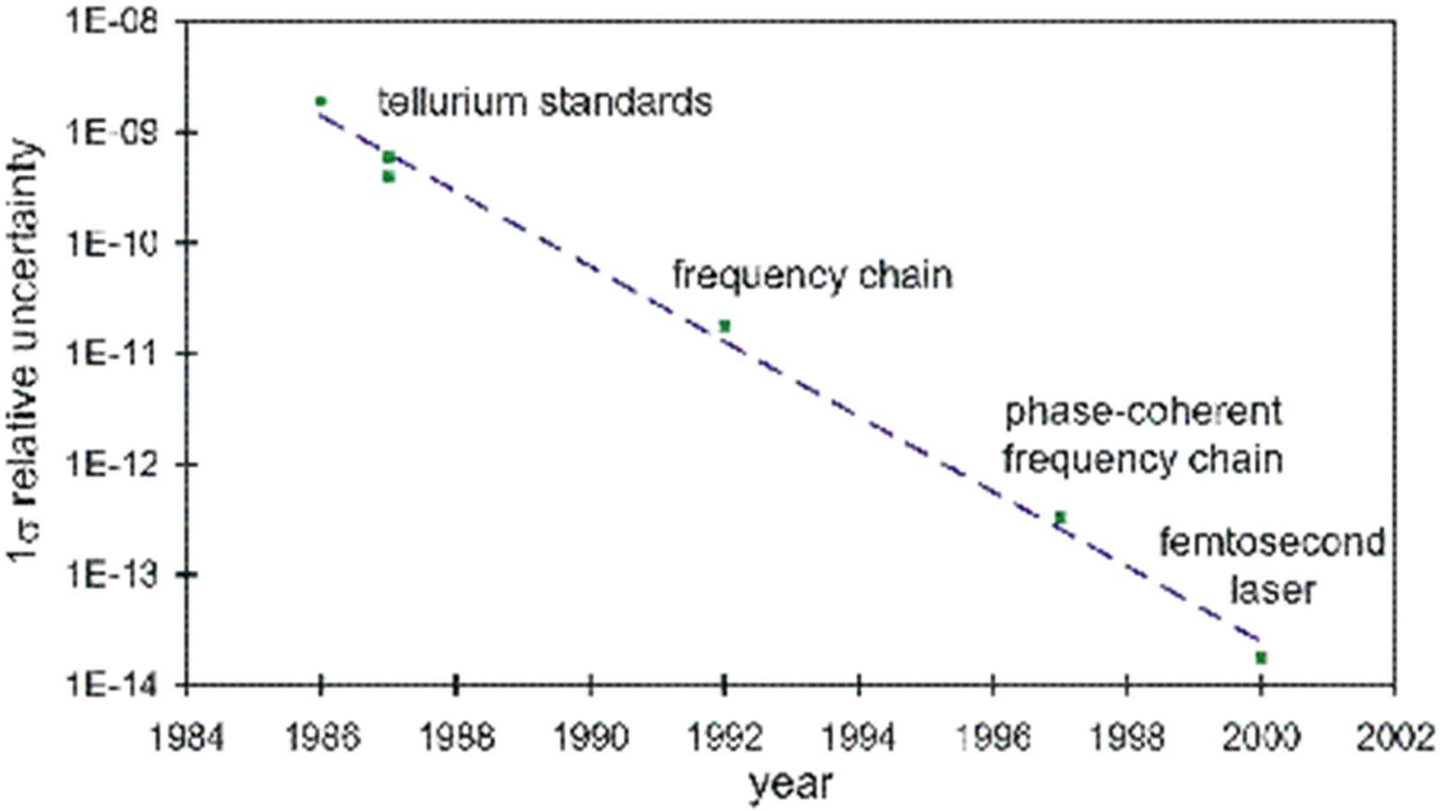
Don't let the anti-matter touch matter.
Positron finds an electron, they disappear and gamma rays come out.
Antiproton finds a nucleus, antiproton "disappears" and a bunch of stuff comes out.

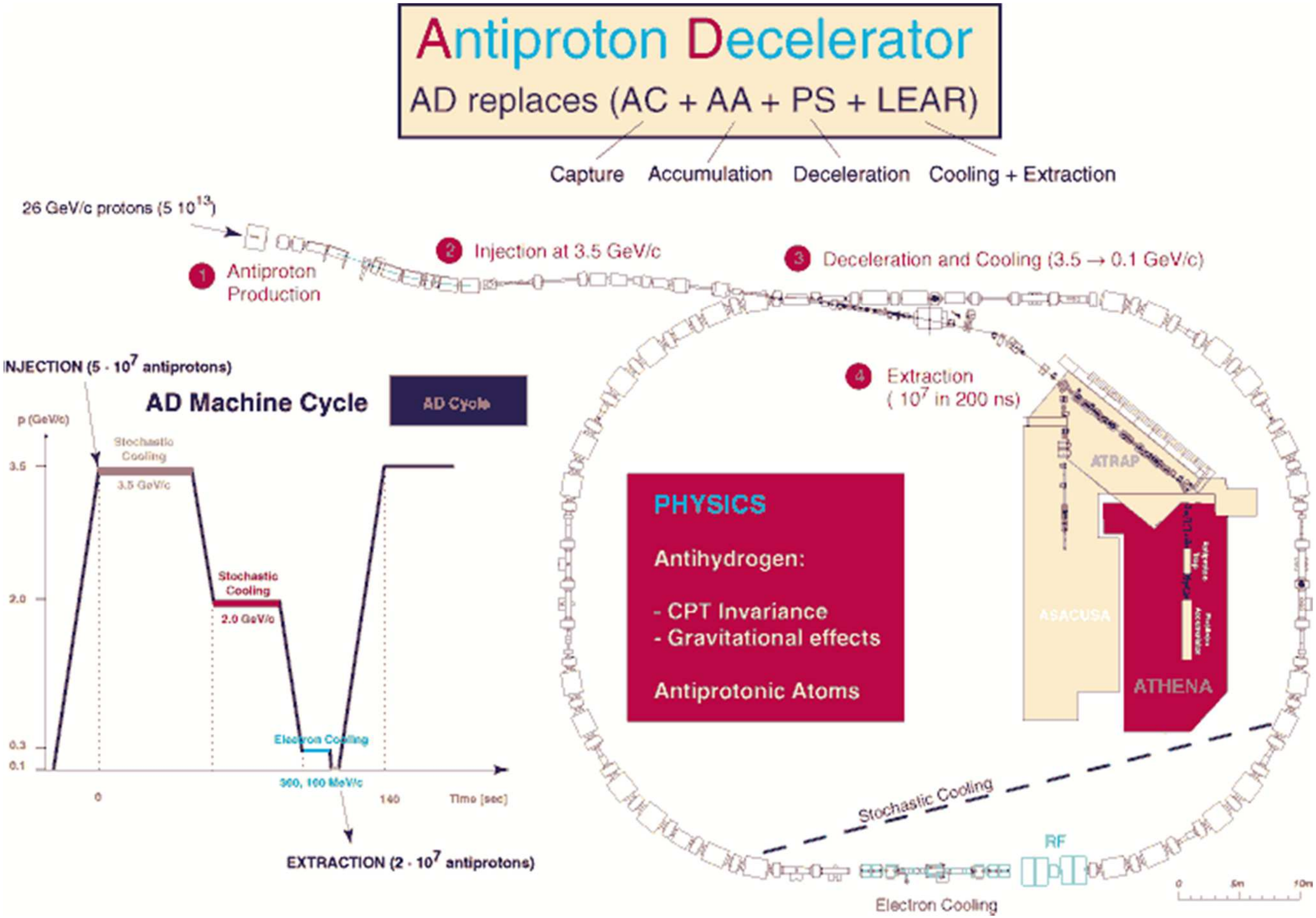
If you have a good vacuum, you could hold antihydrogen for a looooooooooooong time.

H Spectroscopy

H is excited from 1s to 2s by 2 photons with λ ~ 243 nm

f(1S-2S) = 2 466 061 413 187 074(34) Hz




Antiproton Decelerator
AD replaces (AC + AA + PS + LEAR)
Capture
Accumulation
Deceleration
Cooling + Extraction
26 GeV/c protons (5 10^13)
1 Antiproton Production
2 Injection at 3.5 GeV/c
3 Deceleration and Cooling (3.5 → 0.1 GeV/c)
4 Extraction (10^7 in 200 ns)
INJECTION (5 · 10^7 antiprotons)
AD Machine Cycle
AD Cycle
p (GeV/c)
Stochastic Cooling
3.5 GeV/c
Stochastic Cooling
2.0 GeV/c
Electron Cooling
300, 100 MeV/c
Time [sec]
EXTRACTION (2 · 10^7 antiprotons)
PHYSICS
Antihydrogen:
- CPT Invariance
- Gravitational effects
Antiprotonic Atoms
ATRAP
ASACUSA
ATHENA
Stochastic Cooling
RF
Electron Cooling

ALPHA Collaboration

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

ALPHA

TRIUMF

RIKEN

UNIVERSITY OF CALGARY

THE UNIVERSITY of LIVERPOOL

UNIVERSITY OF MANITOBA

1856 2006 AUBURN UNIVERSITY Sesquicentennial

Making Antihydrogen

Movie

letters to nature

Sept 18, 2002

Production and detection of cold antihydrogen atoms

M. Amoretti*, C. Amsler†, G. Bonomi‡§, A. Bouchta‡, P. Bowe‖, C. Carraro*, C. L. Cesar¶, M. Charlton#, M. J. T. Collier#, M. Doser‡, V. Filippini☆, K. S. Fine‡, A. Fontana☆, M. C. Fujiwara††, R. Funakoshi††, P. Genova☆**, J. S. Hangst‖, R. S. Hayano†† M. H. Holzscheiter‡, L. V. Jørgensen#, V. Lagomarsino*‡‡, R. Landua‡, D. Lindelöf†, E. Lodi Rizzini§☆, M. Macrì*, N. Madsen†, G. Manuzio*‡‡, M. Marchesotti☆, P. Montagna☆**, H. Pruys†, C. Regenfus†, P. Riedler‡, J. Rochet†#, A. Rotondi☆**, G. Rouleau‡#, G. Testera*, A. Variola*, T. L. Watson# & D. P. van der Werf#**

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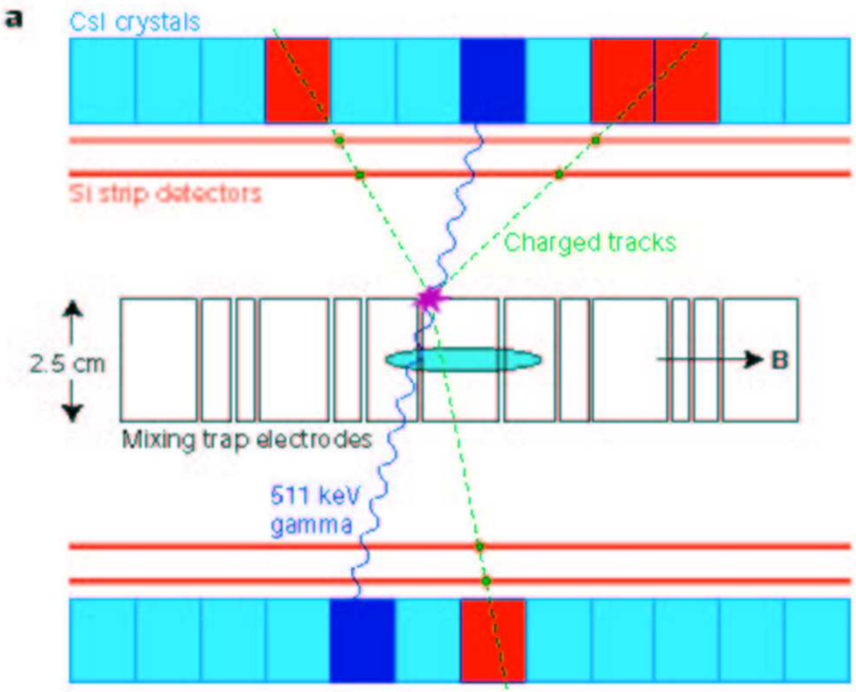
a



Signal

Cold Mixing
Hits on walls

Hot Mixing
Hits on gas impurities

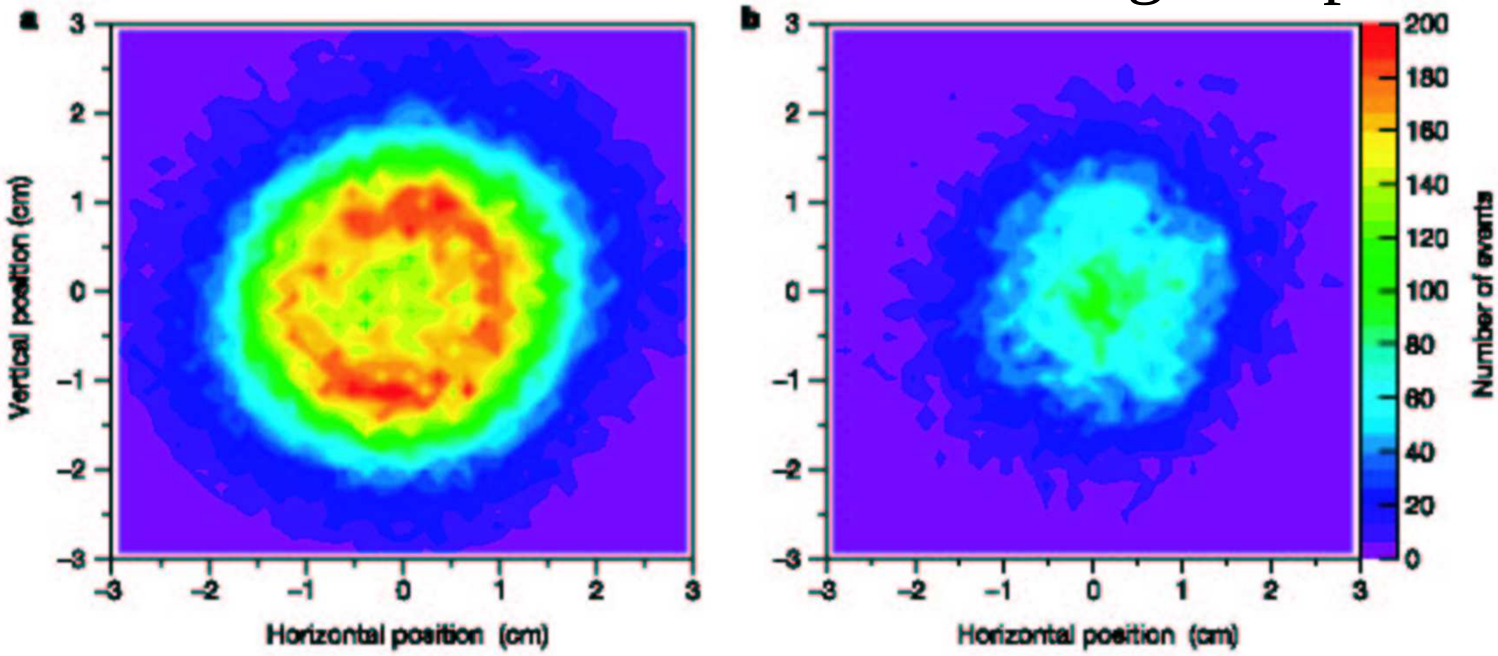
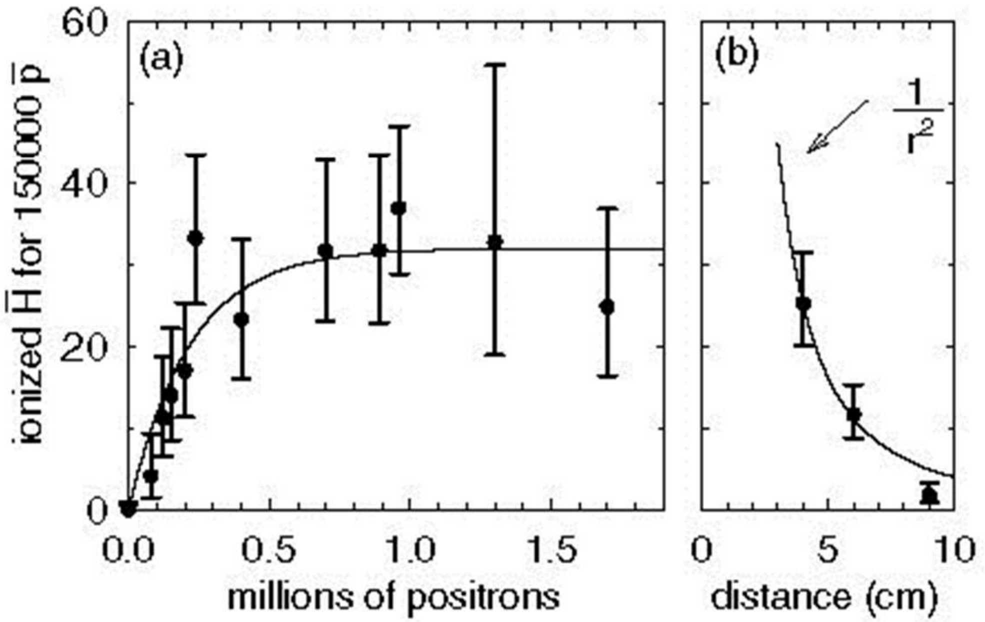


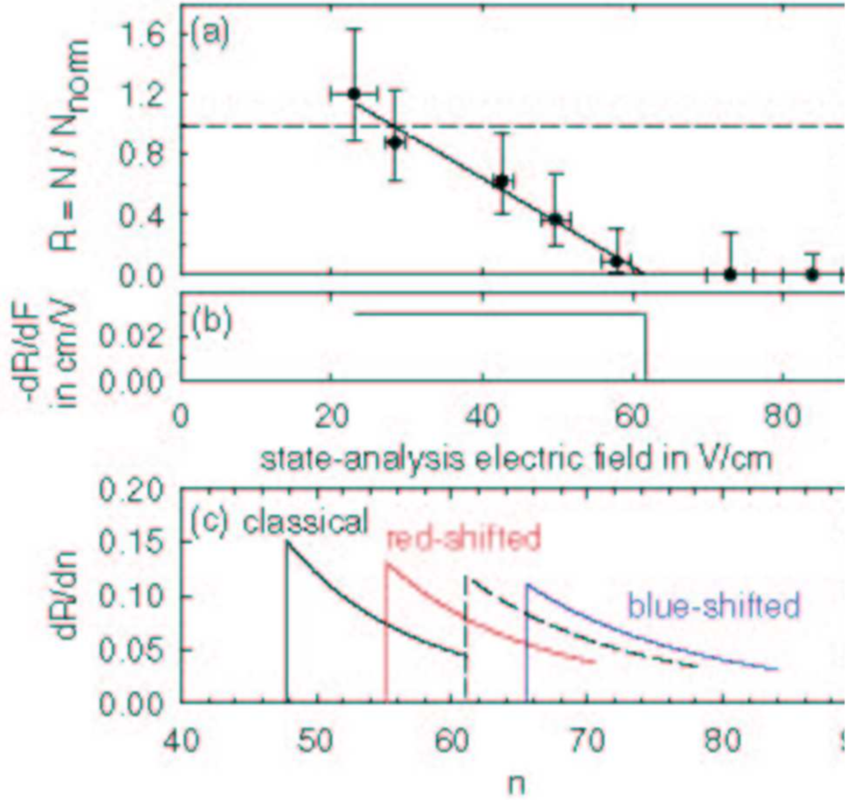
Figure 3 Colour contour plots of the distribution (obtained by projecting into the plane perpendicular to the magnetic field) of the vertex positions of reconstructed events. **a**, Cold mixing. All reconstructed antiproton annihilation vertices from the mixing region are plotted—no crystal cuts are 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. Hessels[6]

(ATRAP Collaboration)





PHYSICAL REVIEW A **69**, 010701(R) (2004)

Three-body recombination for protons moving in a strong magnetic field

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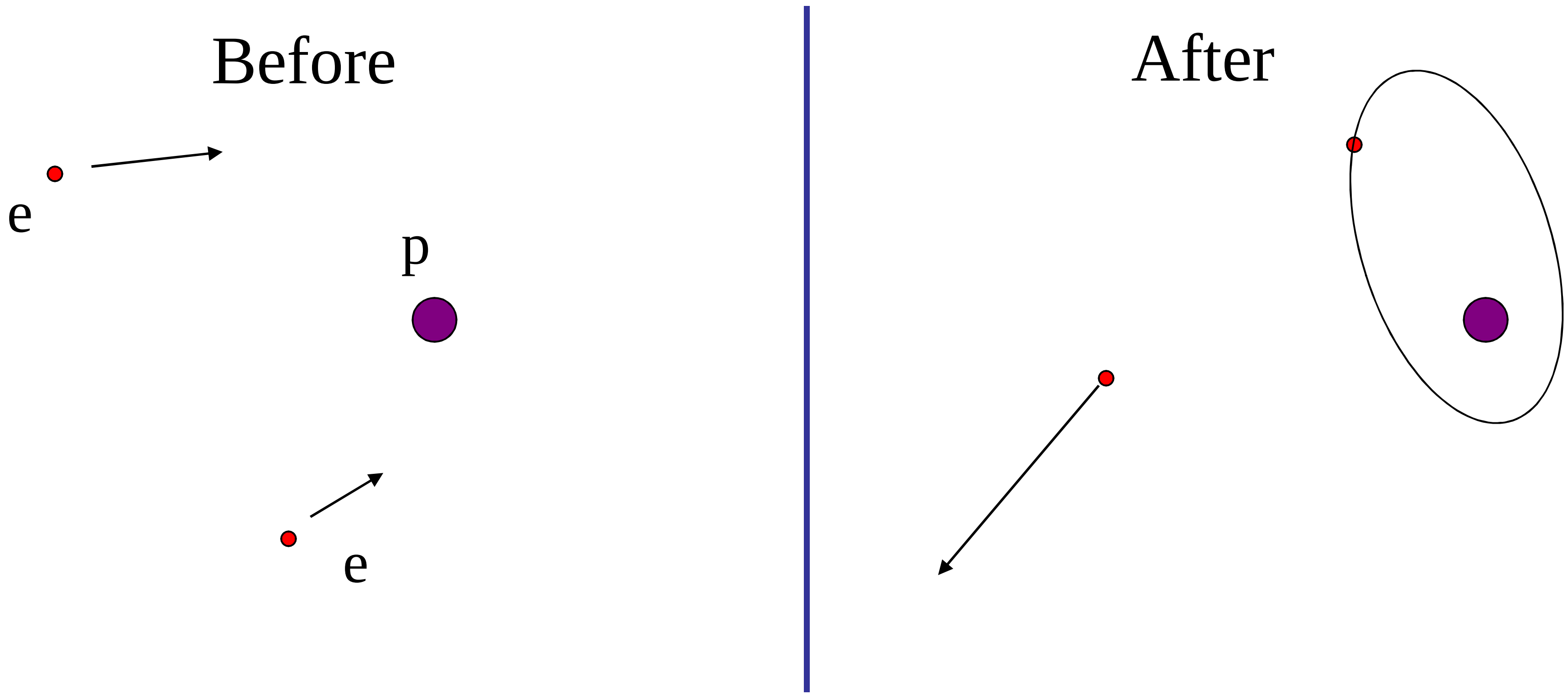
(Received 23 July 2003; published 27 January 2004)

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: $e+e+p\rightarrow \mathrm{H}+e$) 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-



Results: Fast H?

$$\text{Rate} = C\, n^2\, v\, b^5$$

n = density

$v = (k_B\, T/m_e)^{1/2}$

$b = k\, e^2/k_B\, T$

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 $V_0 = \sqrt{2k_BT_e/m_e} = 1.1\times10^4$ m/s. The energy of a proton with speed V_z is also given.

V_z/V_0	C	E (eV)
0.000	0.100	0.00
0.167	0.081	0.04
0.333	0.051	0.14
0.500	0.031	0.32
0.667	0.018	0.56
0.833	0.011	0.88
1.000	0.008	1.27

PHYSICAL REVIEW A **70**, 022510 (2004)

Simulations of antihydrogen formation

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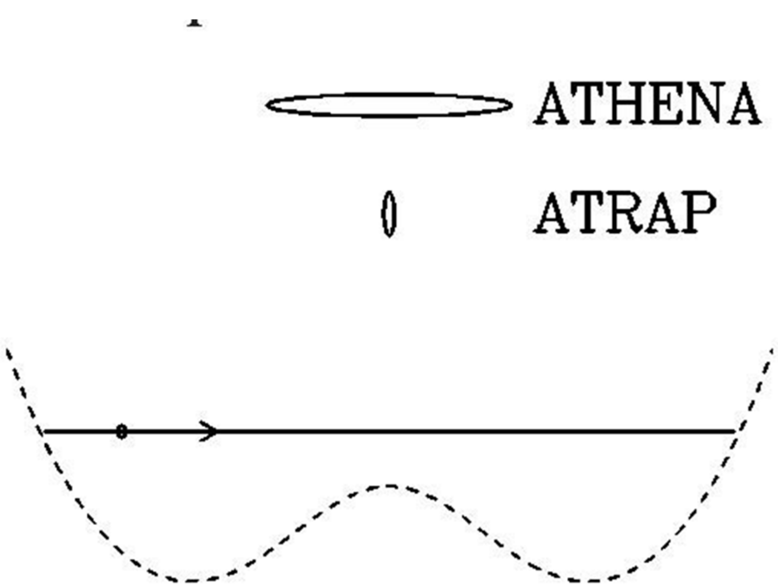
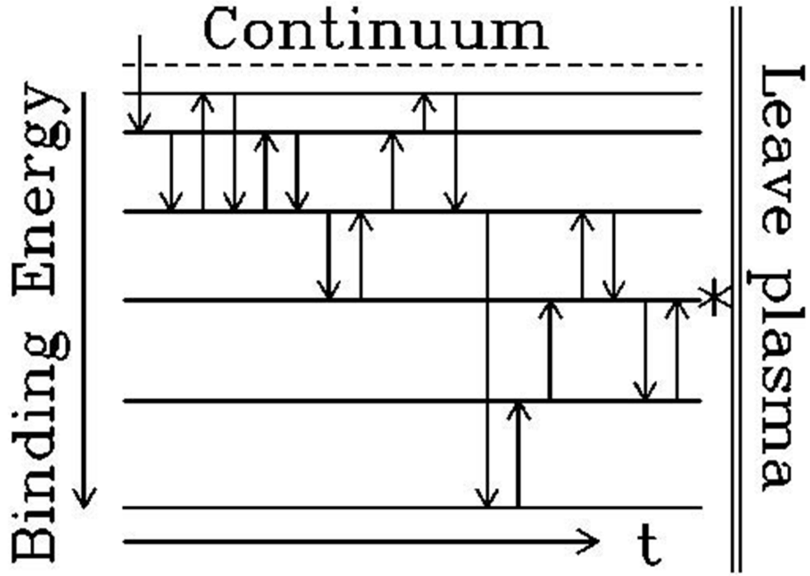
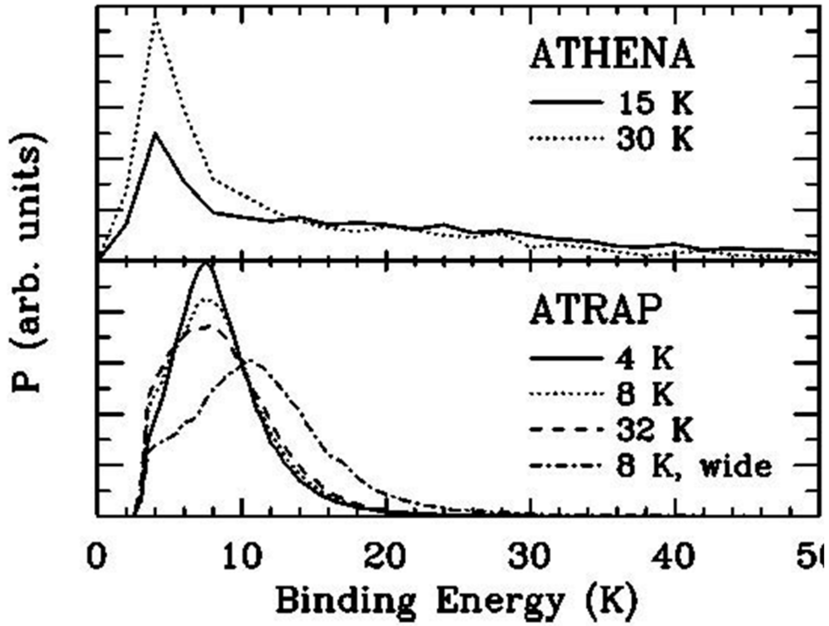
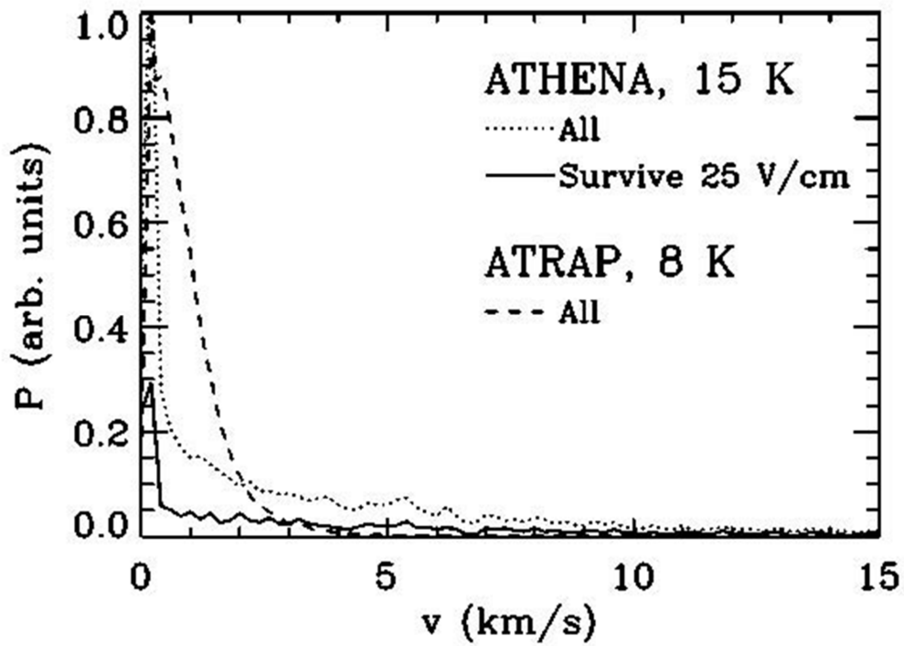
(Received 31 October 2003; published 20 August 2004)





Results: Small BE & Fast!





Binding energy much less than expected

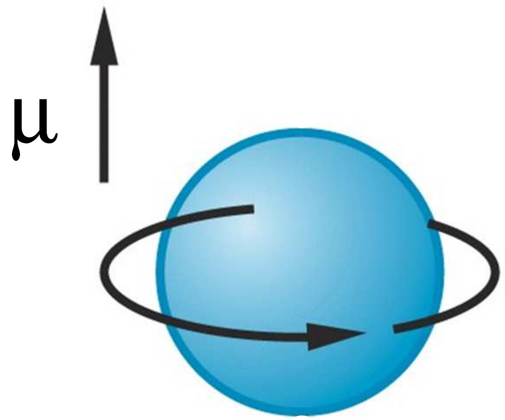
Speed of Hbar much larger than thermal (250 m/s) or trap depth (110 m/s).

Trapping Neutral Particles

$$PE = -\vec{\mu} \bullet \vec{B}$$

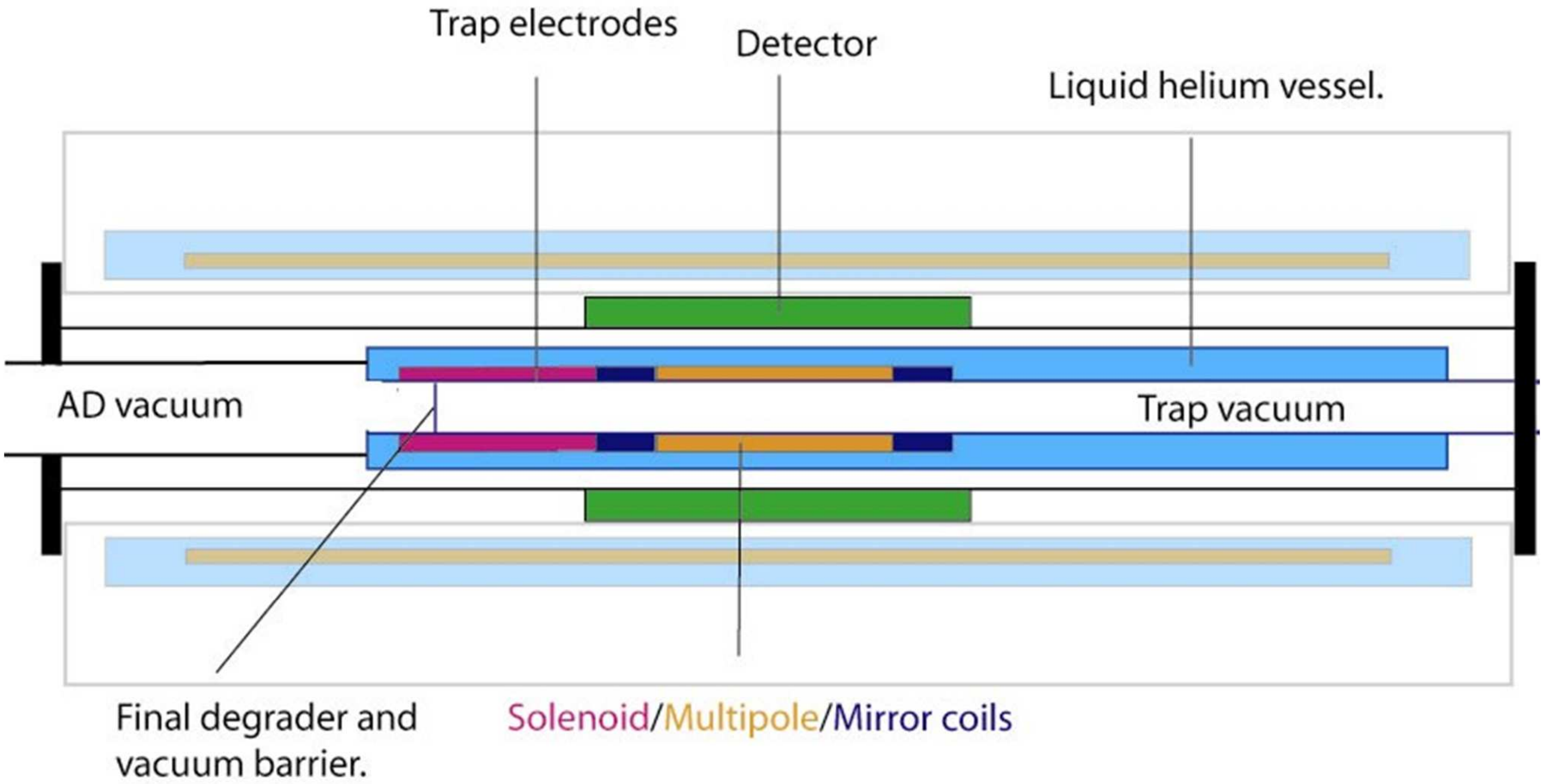
$$\vec{\mu} \bullet \hat{B} \cong \text{constant}$$

$$PE = -\left(\vec{\mu} \bullet \hat{B}\right) B(x, y, z)$$



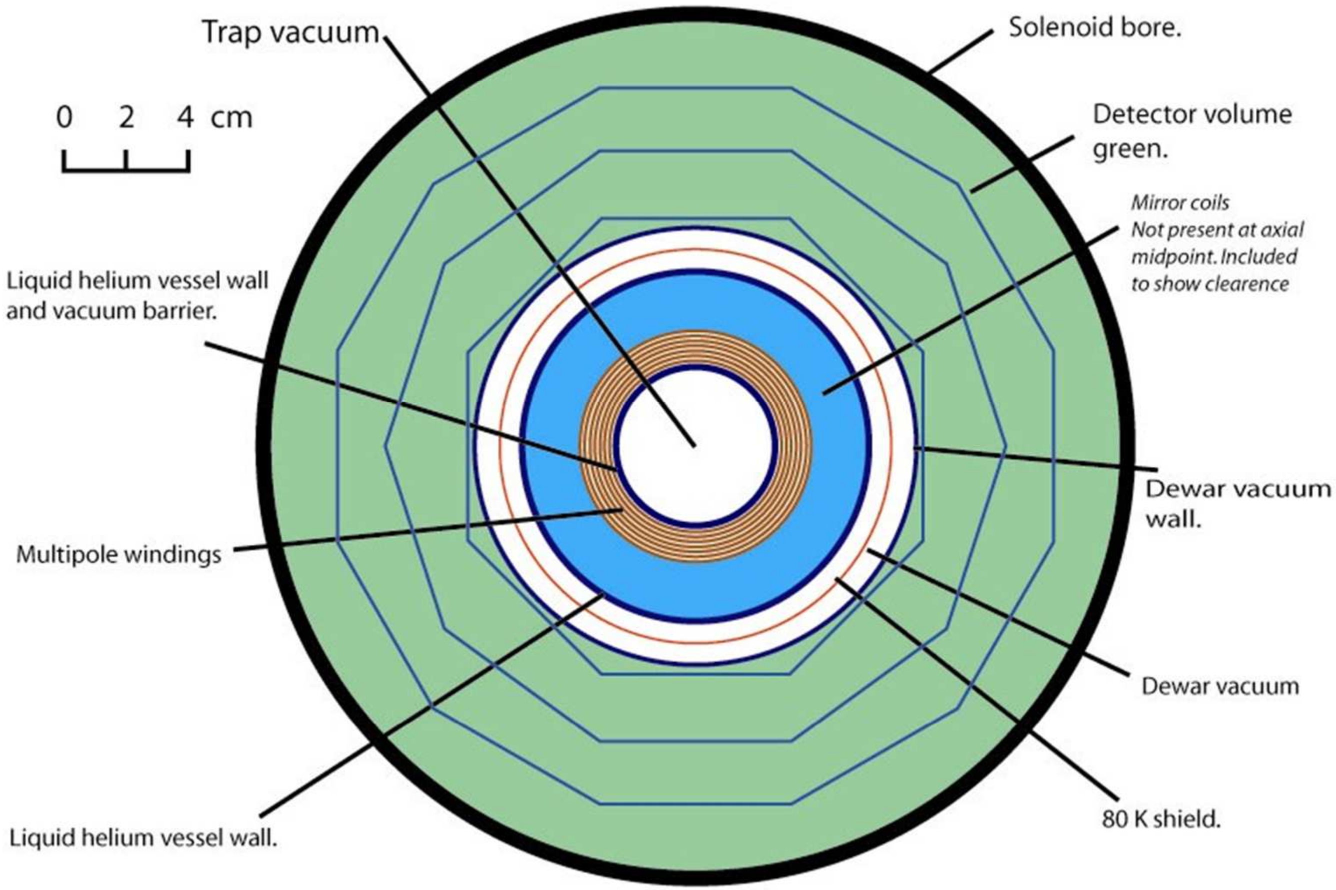
μ for ground state ~2/3 K/T

Antiparticle Trap

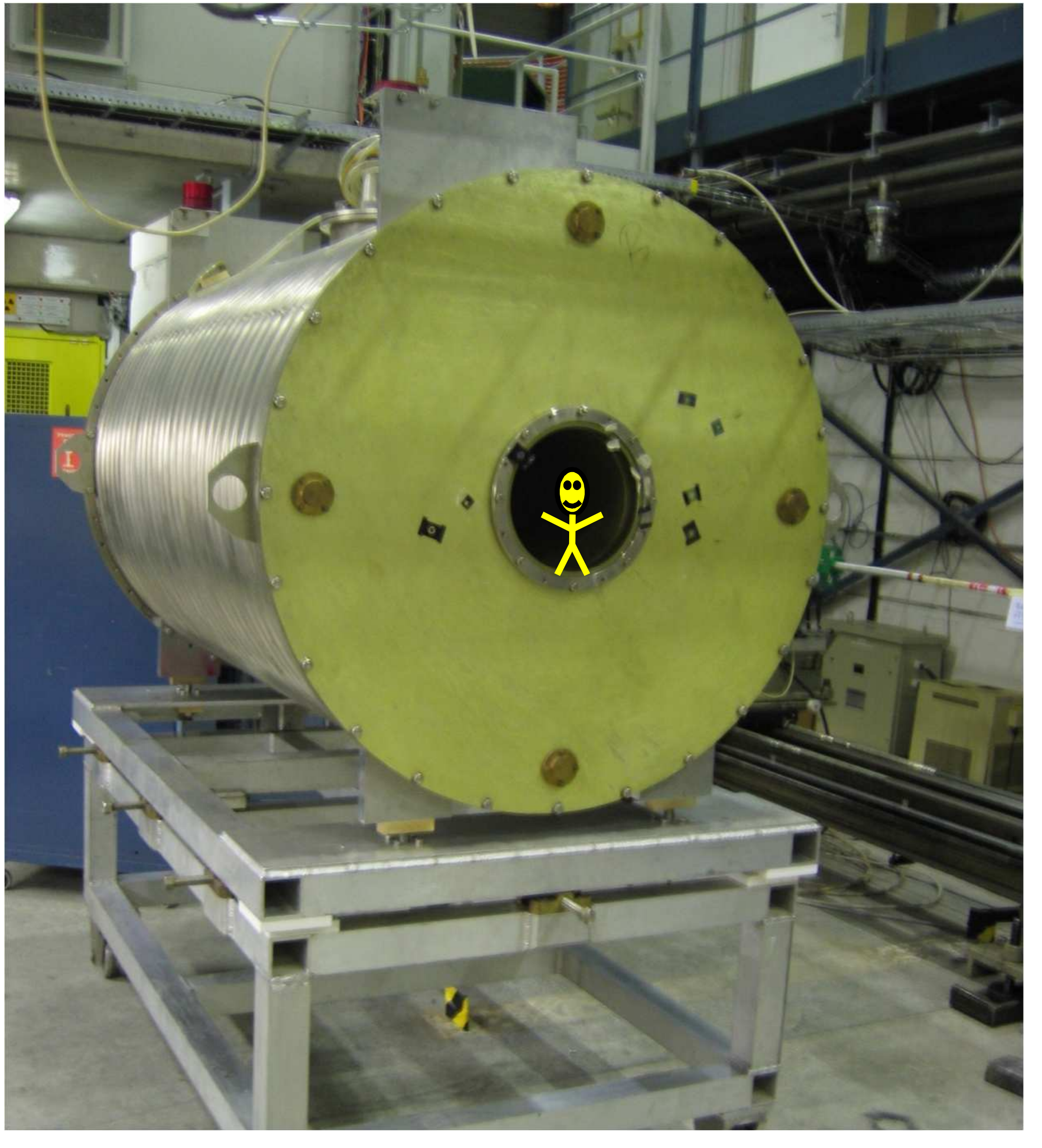


Horizontal to Vertical scale 1 : 2

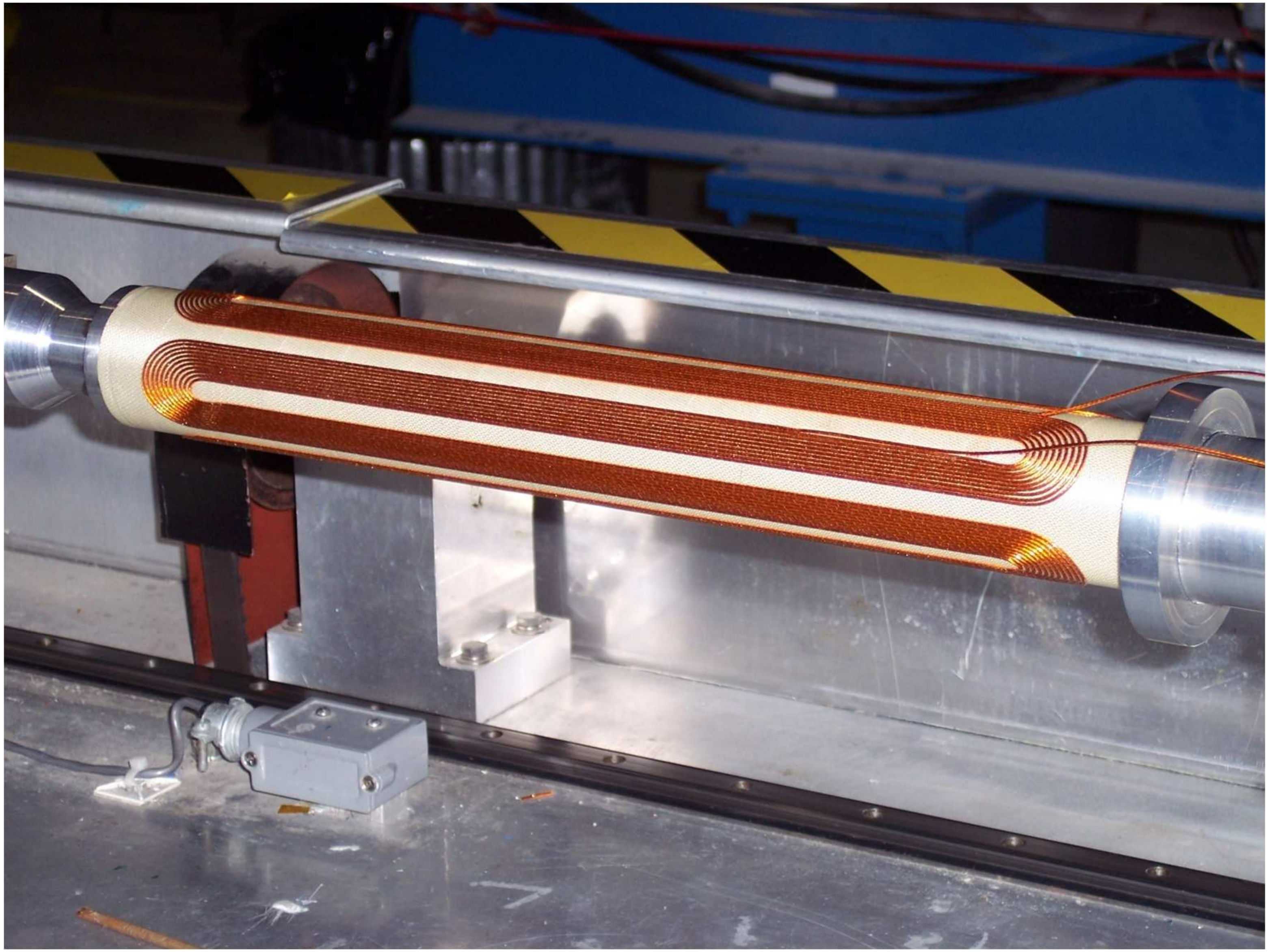
Antiparticle Trap



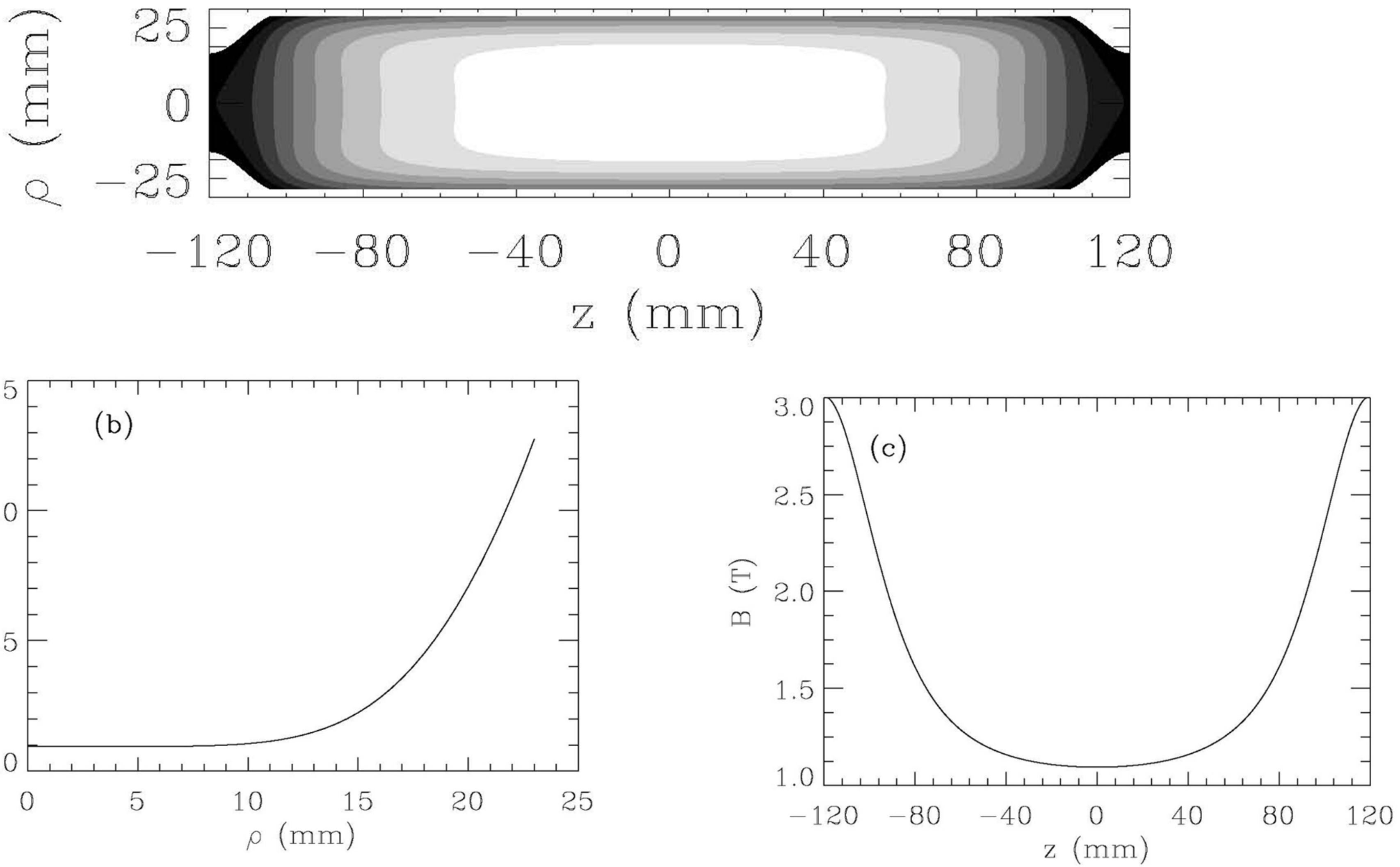
Actual Magnets: Uniform B



Actual Magnets: Octupole



Antiparticle Trap



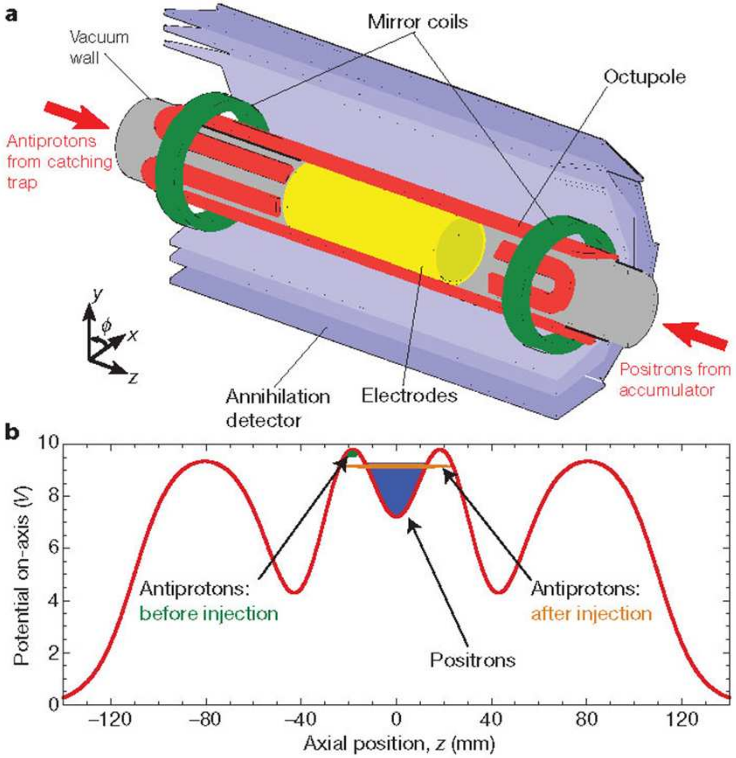
LETTER

Dec 2, 2010

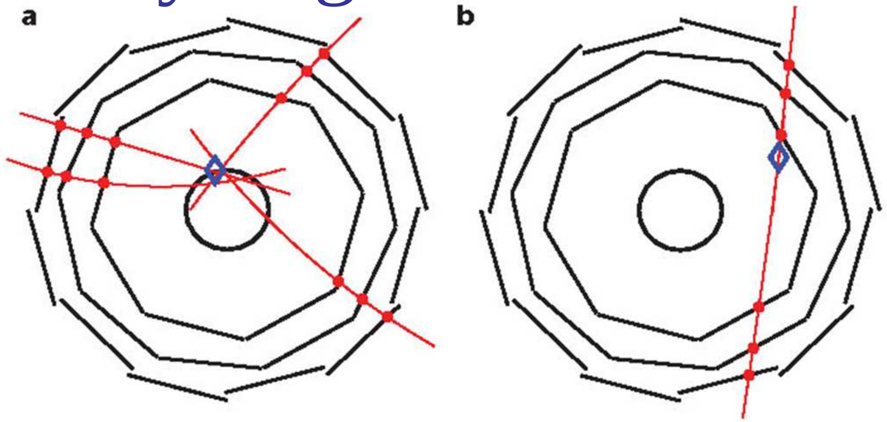
doi:10.1038/nature09610

Trapped antihydrogen

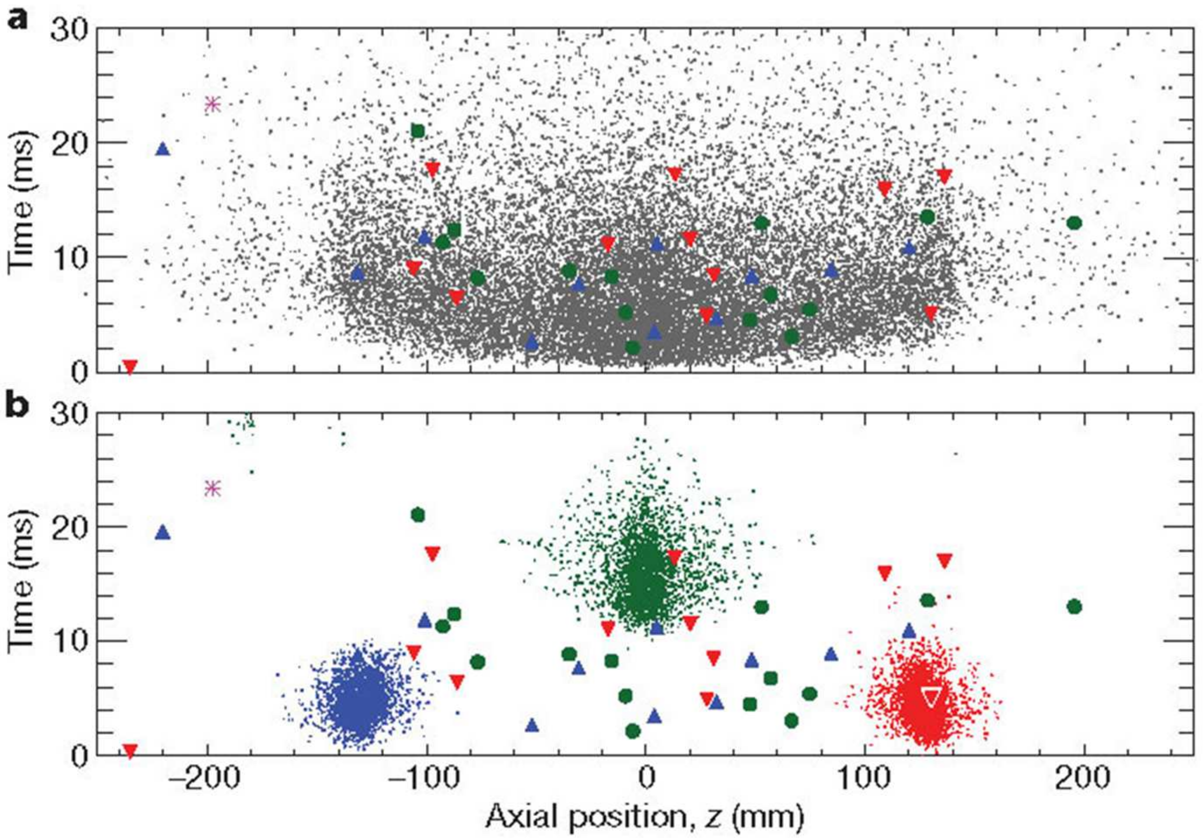
G. B. Andresen[1], M. D. Ashkezari[2], M. Baquero-Ruiz[3], W. Bertsche[4], P. D. Bowe[1], E. Butler[4], C. L. Cesar[5], S. Chapman[3], M. Charlton[4], A. Deller[4], S. Eriksson[4], J. Fajans[3,6], T. Friesen[7], M. C. Fujiwara[8,7], D. R. Gill[8], A. Gutierrez[9], J. S. Hangst[1], W. N. Hardy[9], M. E. Hayden[2], A. J. Humphries[4], R. Hydomako[7], M. J. Jenkins[4], S. Jonsell[10], L. V. Jørgensen[4], L. Kurchaninov[8], N. Madsen[4], S. Menary[11], P. Nolan[12], K. Olchanski[8], A. Olin[8], A. Povilus[3], P. Pusa[12], F. Robicheaux[13], E. Sarid[14], S. Seif el Nasr[9], D. M. Silveira[15], C. So[3], J. W. Storey[8]†, R. I. Thompson[7], D. P. van der Werf[4], J. S. Wurtele[3,6] & Y. Yamazaki[15,16]



antihydrogen cosmic



1st Trapped antiHydrogen

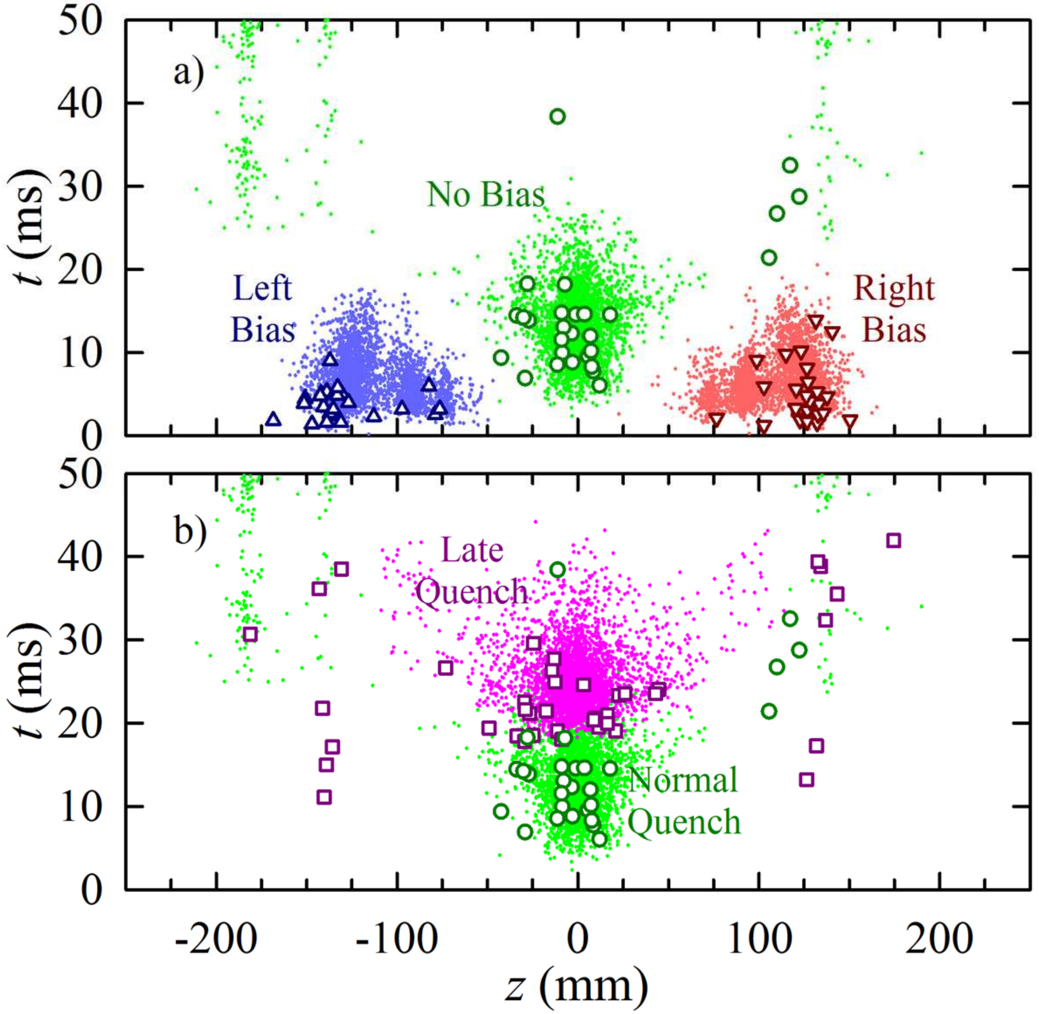


simulation of antihydrogen hits

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!"

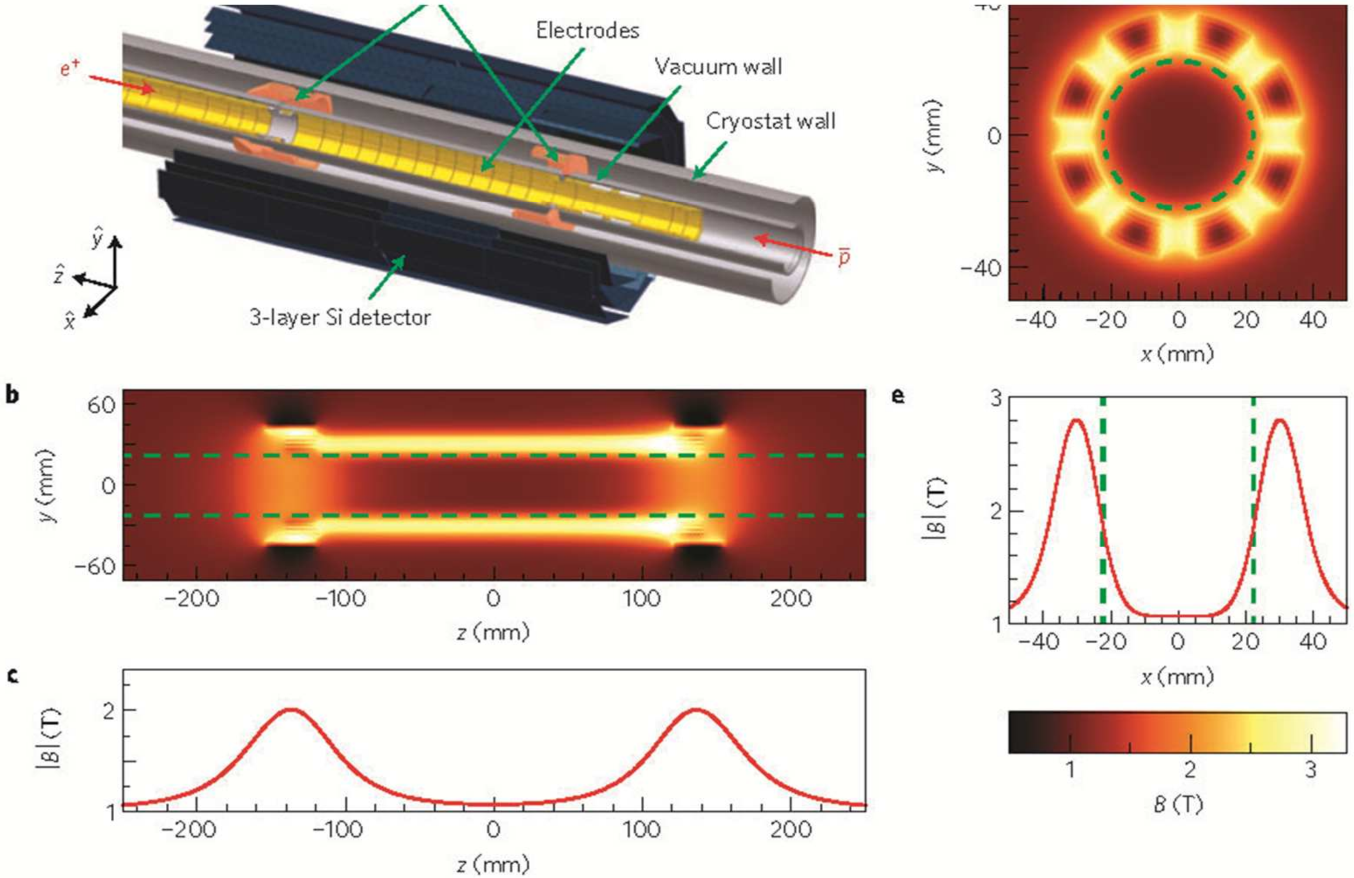
nature physics

ARTICLES

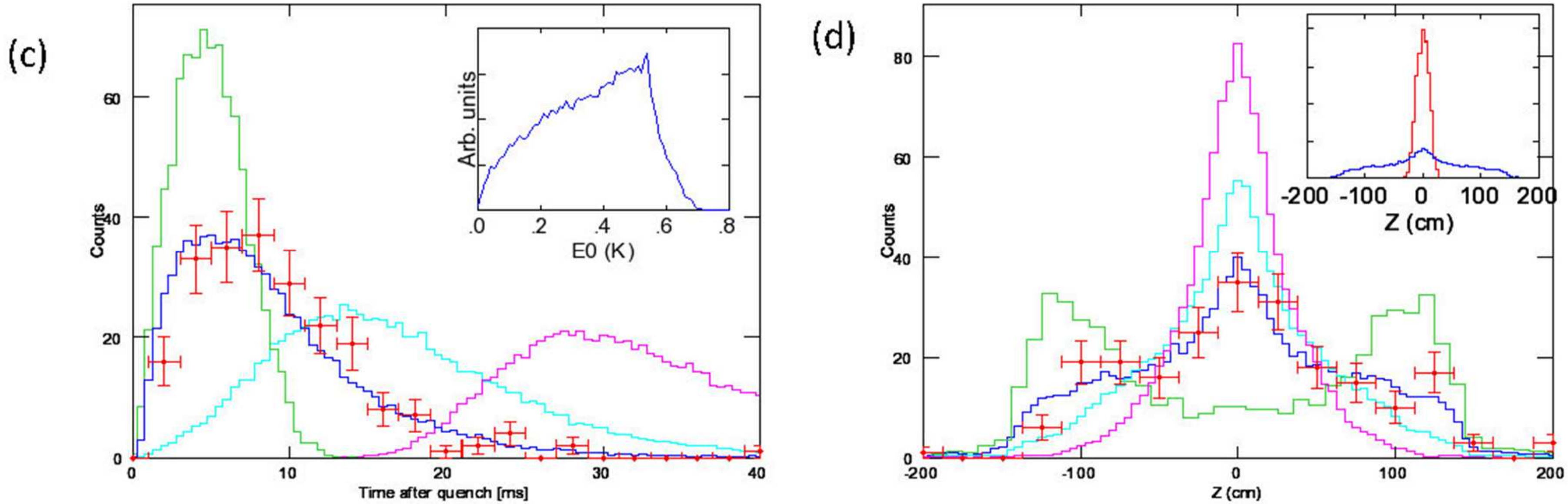
PUBLISHED ONLINE: 5 JUNE 2011 | DOI: 10.1038/NPHYS2025

Confinement of antihydrogen for 1,000 seconds

The ALPHA Collaboration*



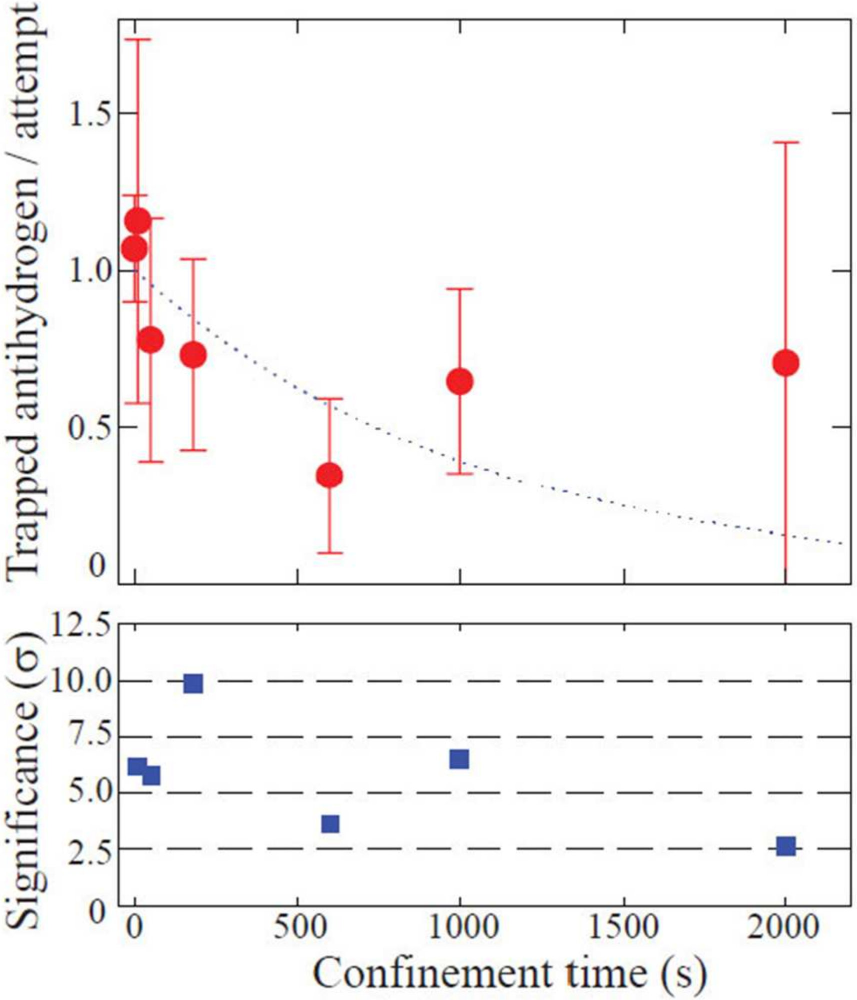
t and z hit distributions



time after quench distrib. z-hit distrib.

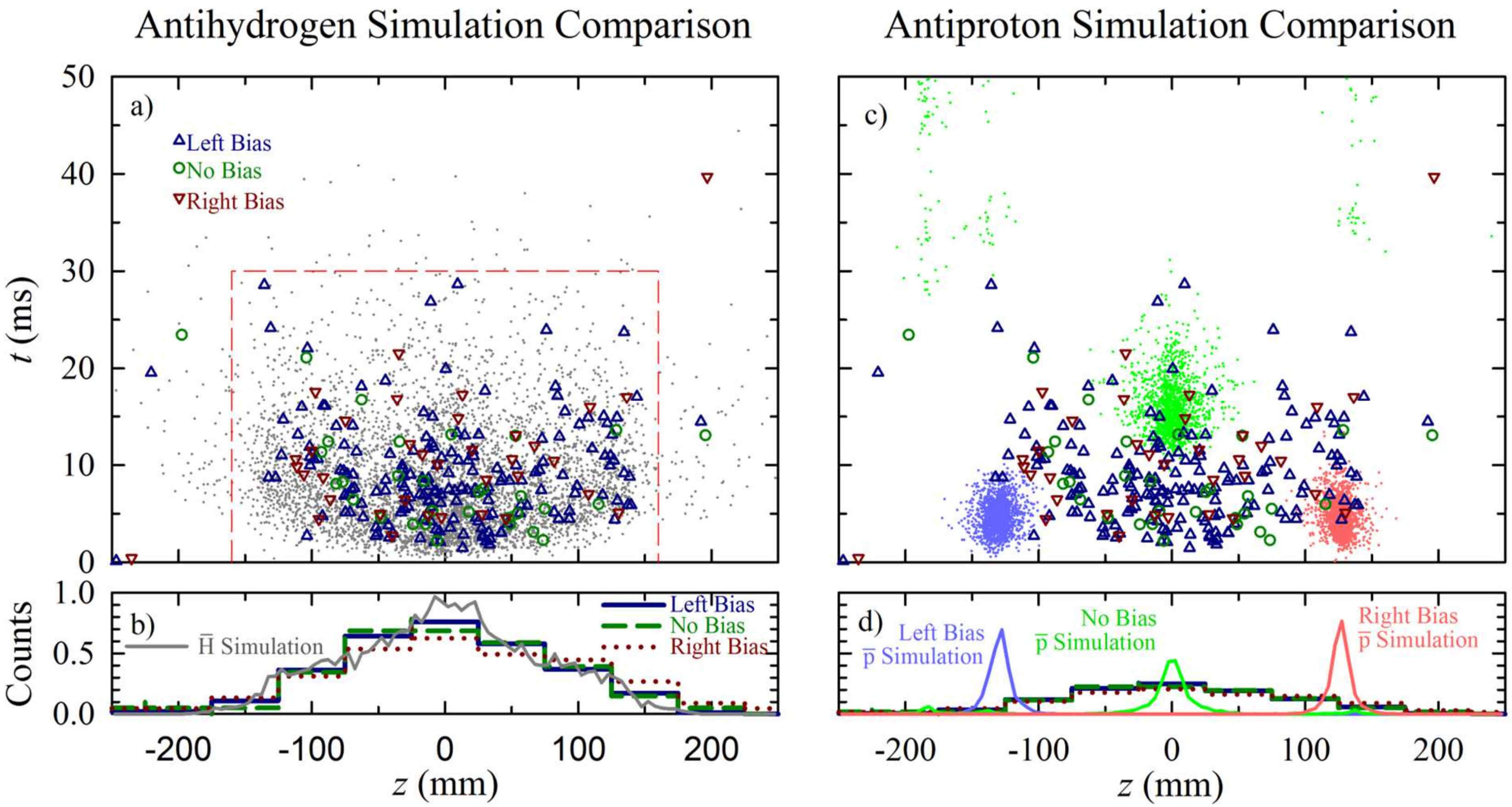
lines are simulations of Hbar hits
purple 10 mK, light blue 100 mK, blue 50 K
(any T >> well depth), green quasi-bound

Number trapped vs delay



number of hits vs delay between mixing and magnet quench

Full z-t data/simulation compare



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 ~0 inside positron plasma

$V \sim e\,\rho\, r^2/(4\,\varepsilon_0)$

E X B drift speed $\sim e\,\rho\, r/(2\,B\,\varepsilon_0)$

$\omega = v/r \sim e\,\rho/(2\,B\,\varepsilon_0)$

The antiproton rotates with the positron plasma (same EXB drift). The antiH will have an initial KE from thermal distribution plus the plasma rotation.

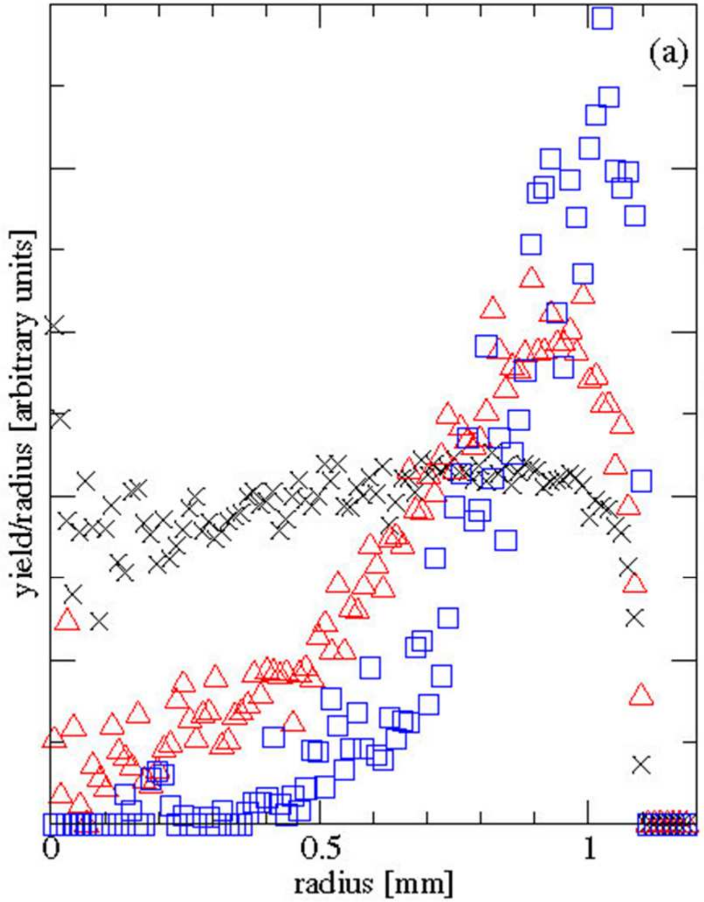
IOP PUBLISHING
JOURNAL OF PHYSICS B: ATOMIC, MOLECULAR AND OPTICAL PHYSICS
J. Phys. B: At. Mol. Opt. Phys. **42** (2009) 215002 (14pp)
doi:10.1088/0953-4075/42/21/215002

Simulation of the formation of antihydrogen in a nested Penning trap: effect of positron density

S Jonsell[1], D P van der Werf[1], M Charlton[1] and F Robicheaux[2]

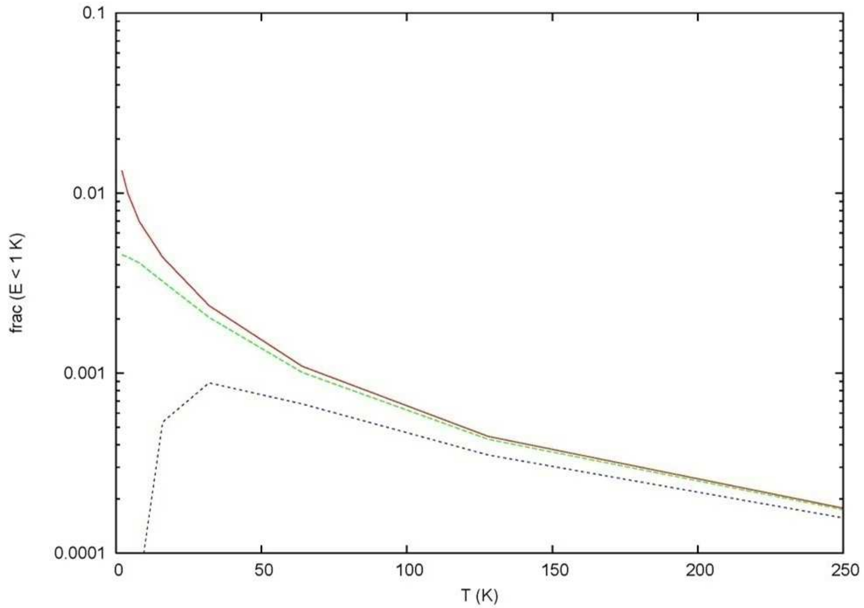
Radial position of where antiH formed during 0-0.1 ms, 0.4-0.5 ms, and > 1 ms

Radial drift to edge of positron plasma due to multiple formation and stripping of antiH

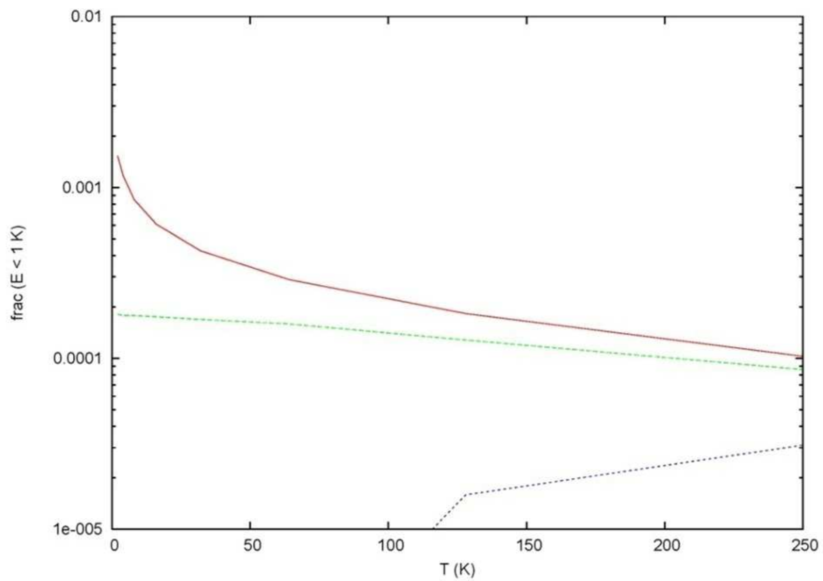


Fraction of antiH formed < 1 K

Positron plasma 1 mm radius



3 mm radius



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

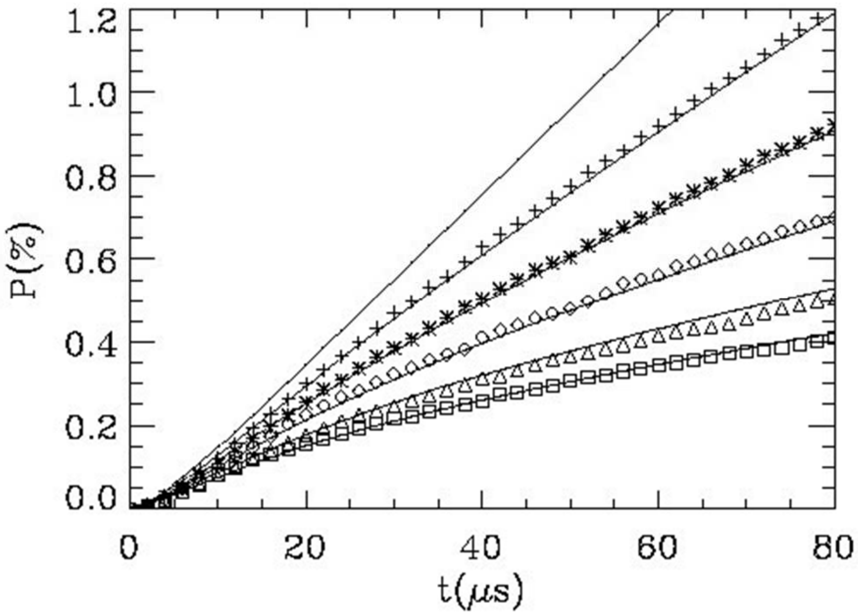
Also, if you try a dynamic mixing, average charge/mass will fluctuate.

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS B: ATOMIC, MOLECULAR AND OPTICAL PHYSICS

J. Phys. B: At. Mol. Opt. Phys. **40** (2007) 271–280 doi:10.1088/0953-4075/40/2/003

Three-body recombination with mixed sign light particles

F Robicheaux



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.

PRL 105, 013003 (2010) PHYSICAL REVIEW LETTERS week ending 2 JULY 2010

Evaporative Cooling of Antiprotons to Cryogenic Temperatures

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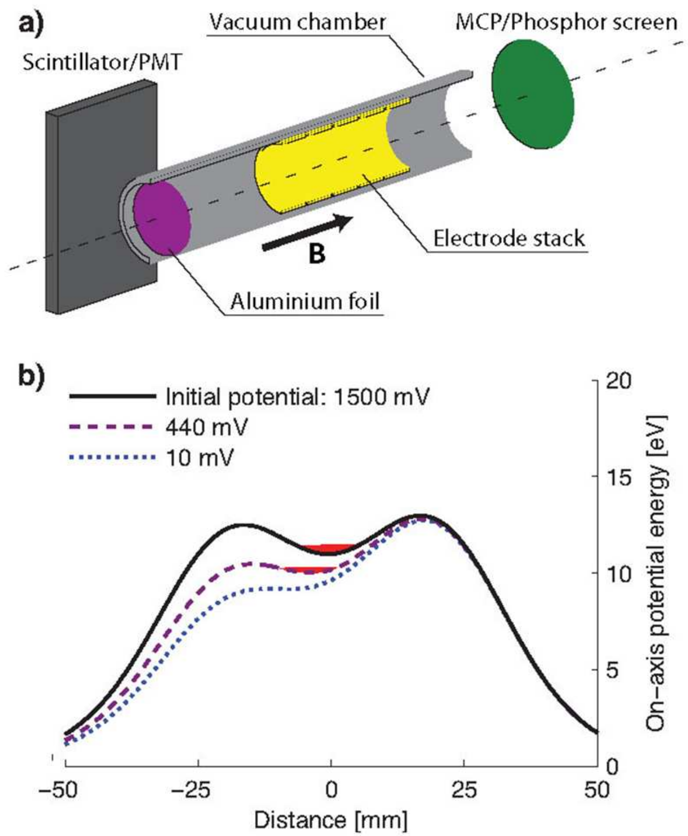
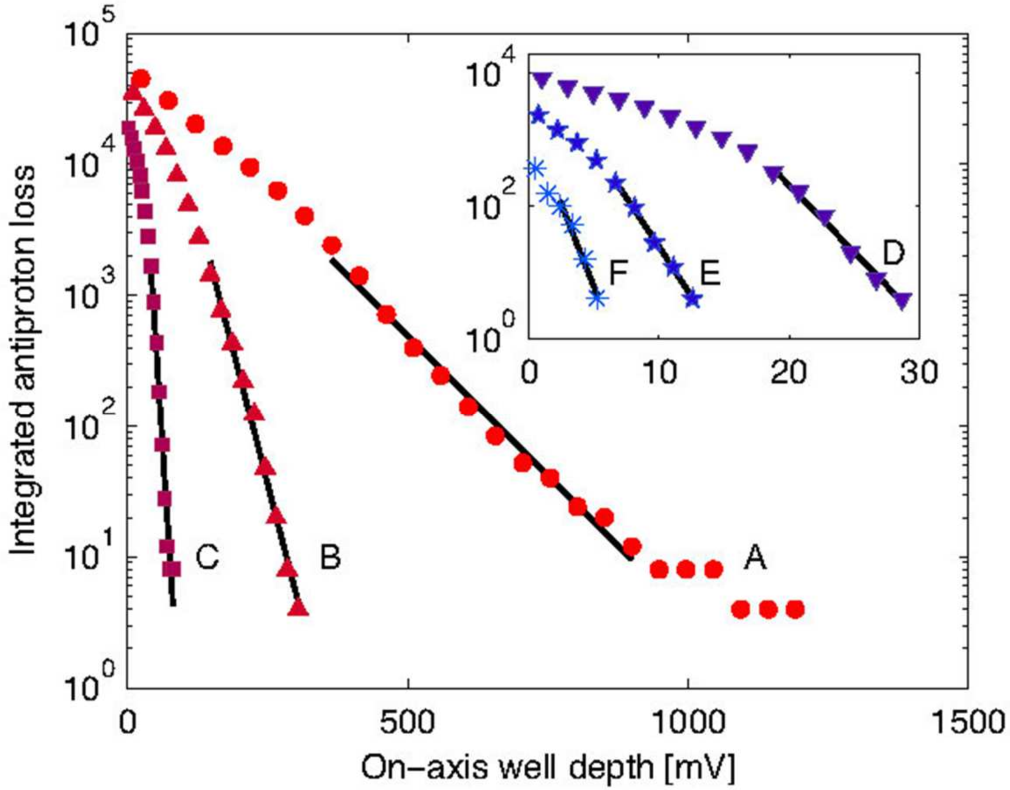
(ALPHA Collaboration)

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

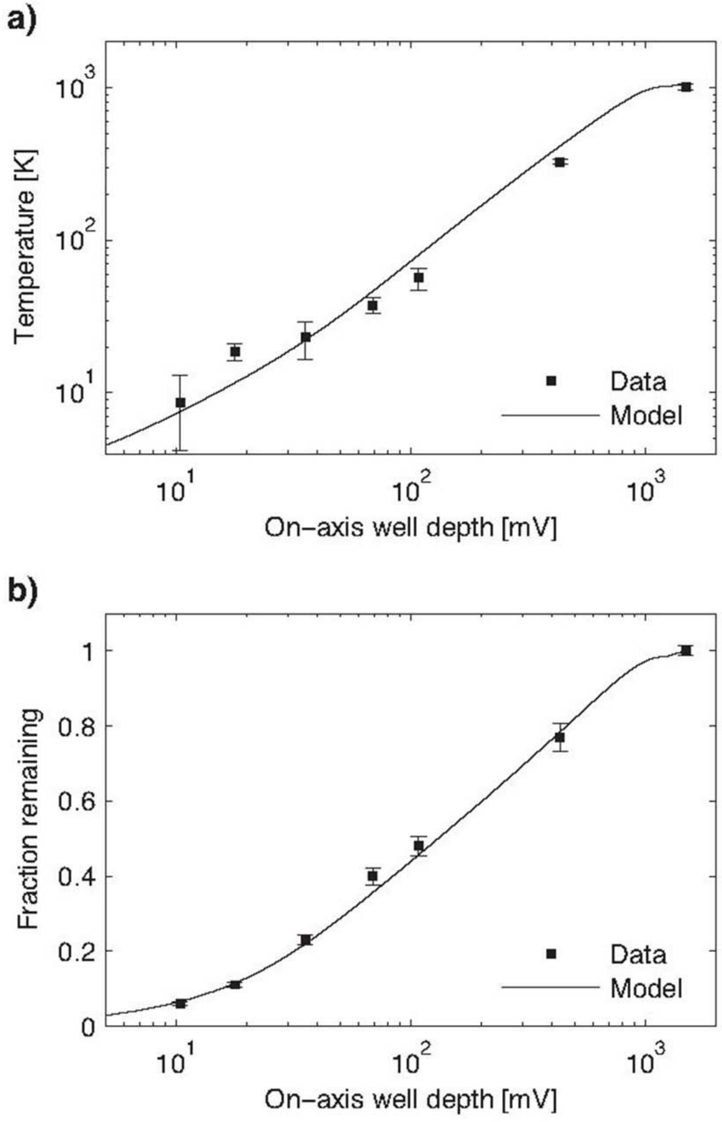
A=1040 K, B=325 K, C=57 K, D=23 K, E=19 K, F=9 K

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?

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Cooling of Rydberg $\bar{\mathrm{H}}$ during radiative cascade

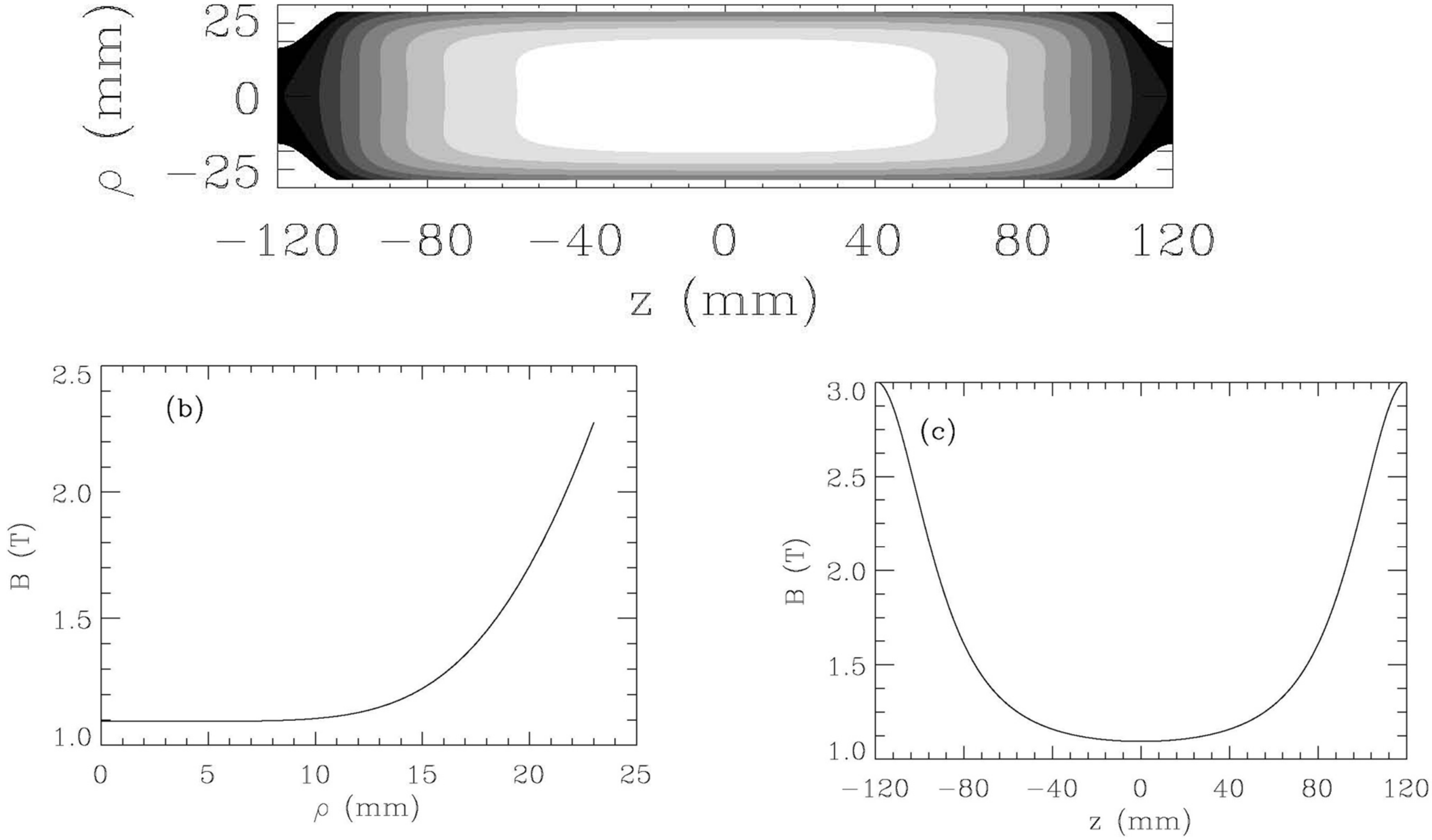
C L Taylor, Jingjing Zhang and F Robicheaux

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

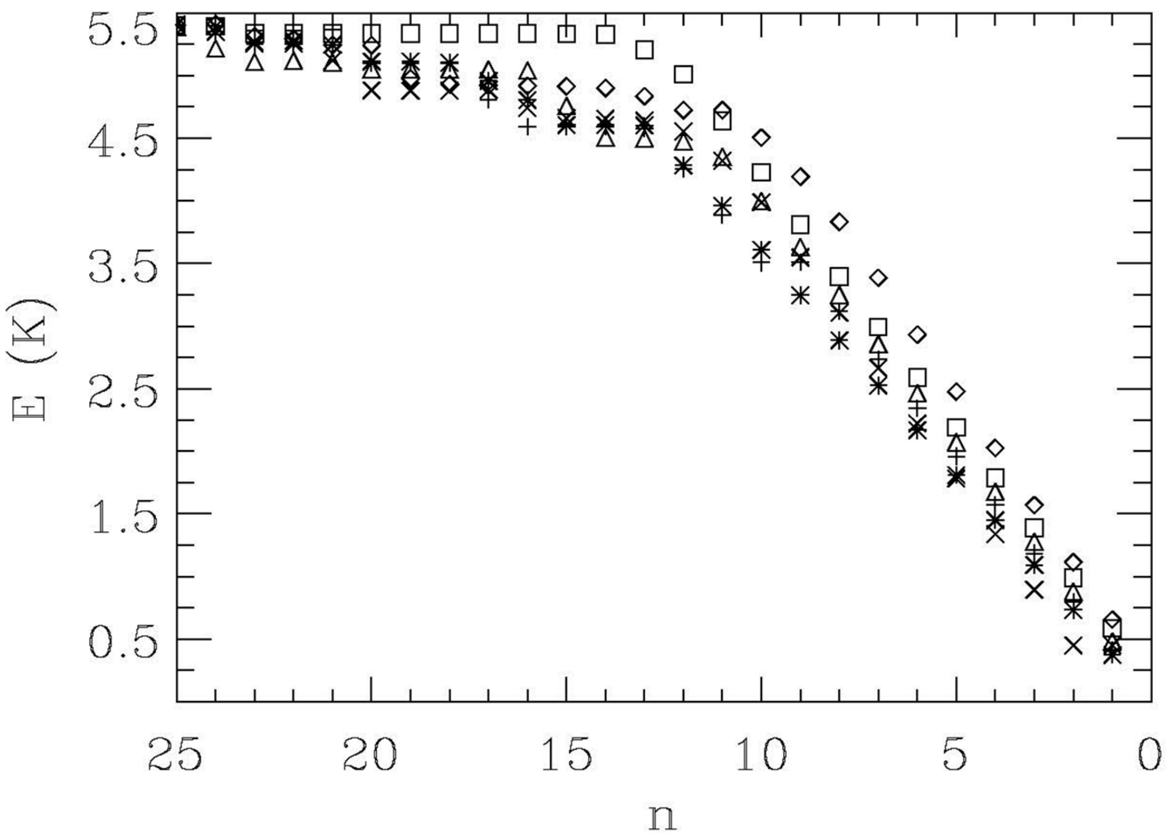
Atoms start out in perfect circular state: n,n-1,n-1
Approximate non-circular states (quasi-classical rates)

Solve Newton’s equation for C.O.M. motion with random emission of photon

Antiparticle Trap



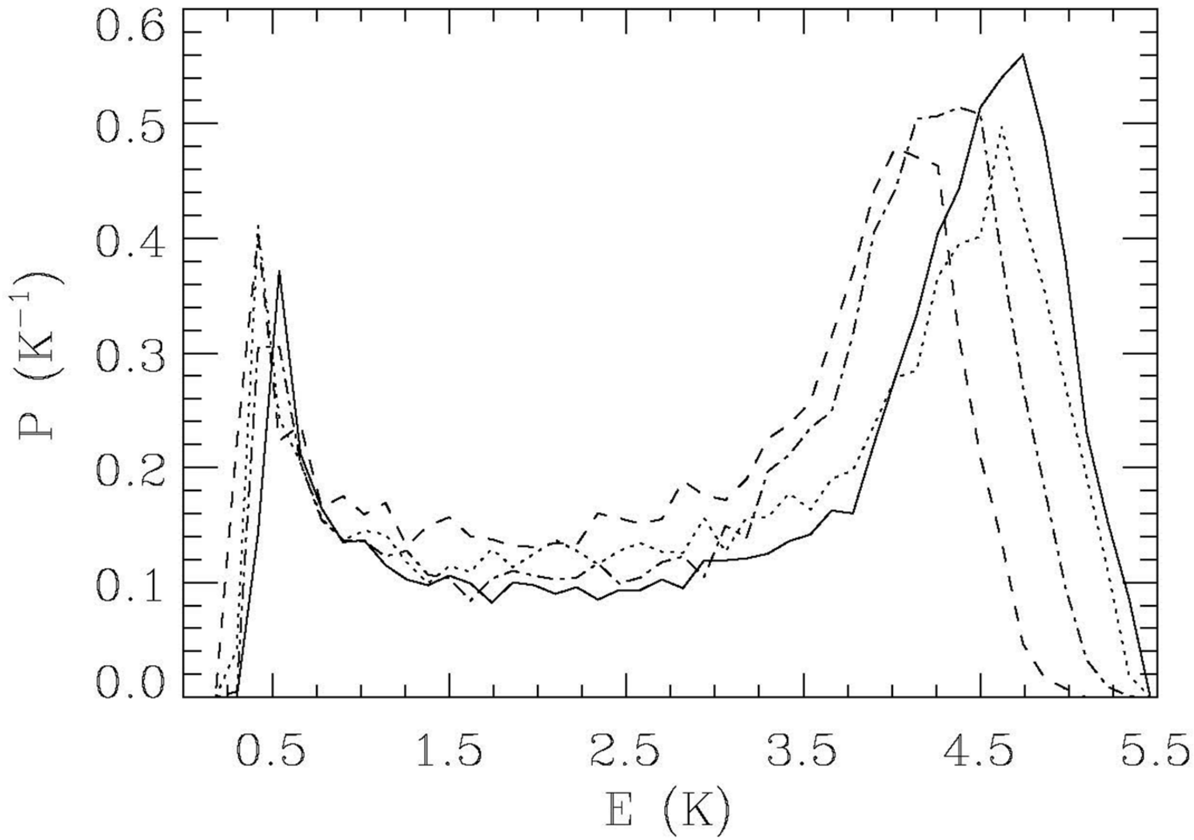
Adiabatic vs. Sudden Cooling



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

Only look at atoms with final E_{com} < 0.79 K

Final E_{com} Distribution



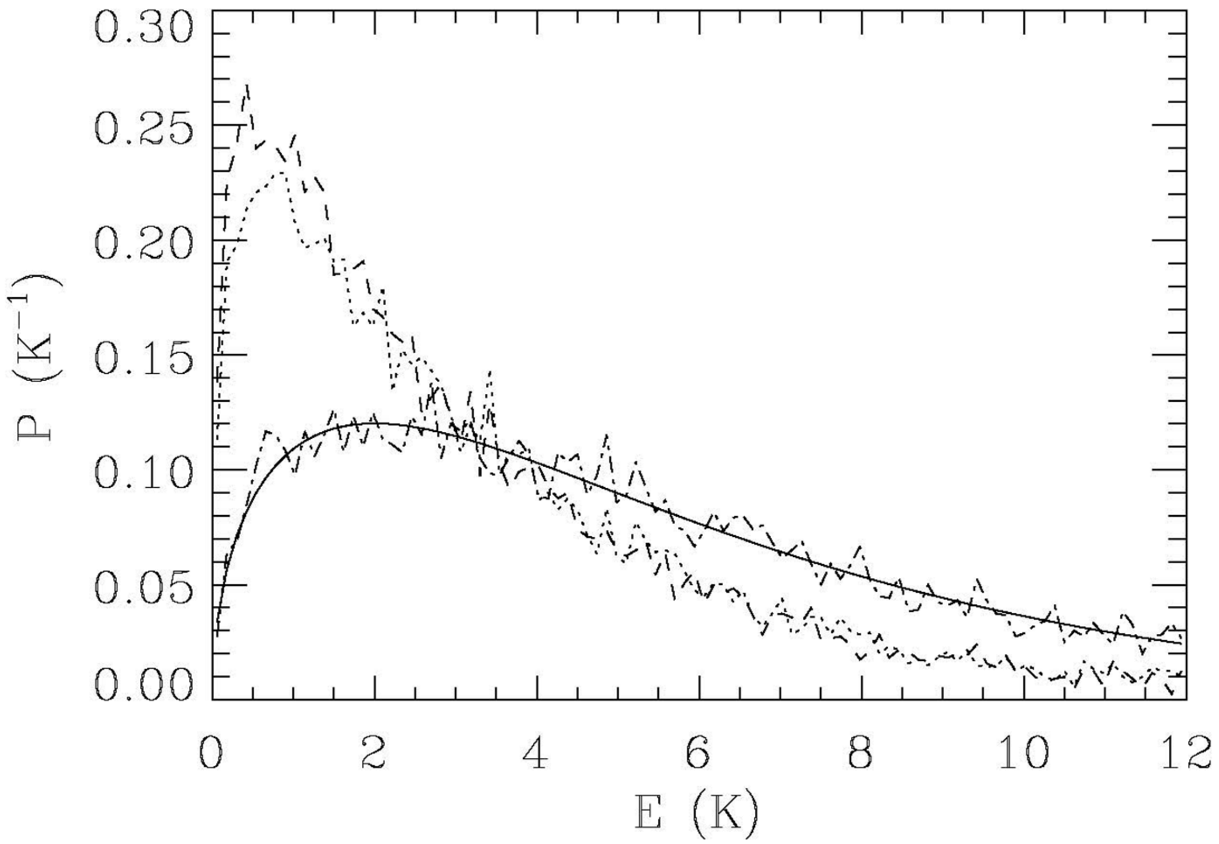
Shape and # predicted from simple theory

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

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

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

Final E_{com} Distribution



Fraction Trapped:
18%
16%
6%
Nice increase

Cushion

Thermal KE = 4 K, n = 25, spheroid (2mm,15mm radii)

dash = circ;   dotted = random m>15

dash-dot = initial distribution, solid = Maxwell

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Possible mechanism for enhancing the trapping and cooling of antihydrogen

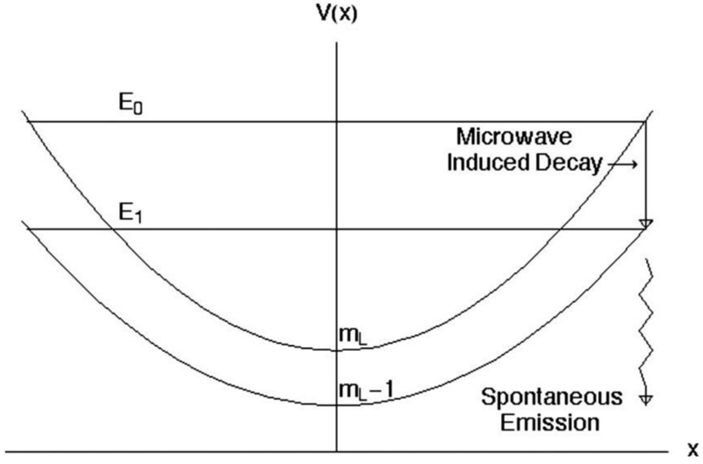
C. L. Cesar,[1] F. Robicheaux,[2] and N. Zagury[1]

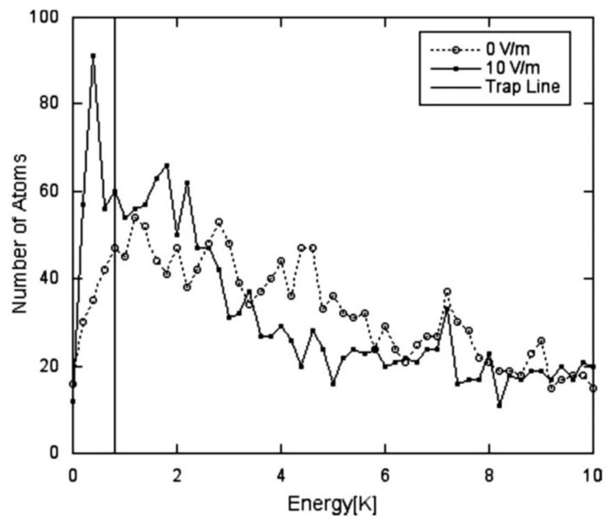
Microwave cause l,m transition at large B

Weak microwave because electric dip.

Lower l,m radiates faster

Leads to extra cooling (factor of 1.5 started at 16 K)



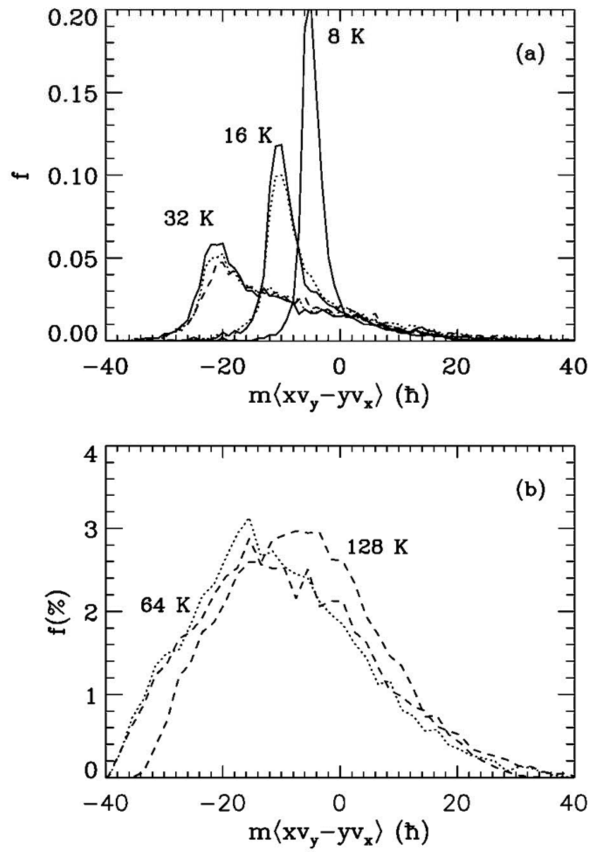


TBR Temperature Surprise?

PHYSICAL REVIEW A **73**, 033401 (2006)

Three-body recombination for electrons in a strong magnetic field: Magnetic moment

F. Robicheaux



Atoms bound by more than 32 K

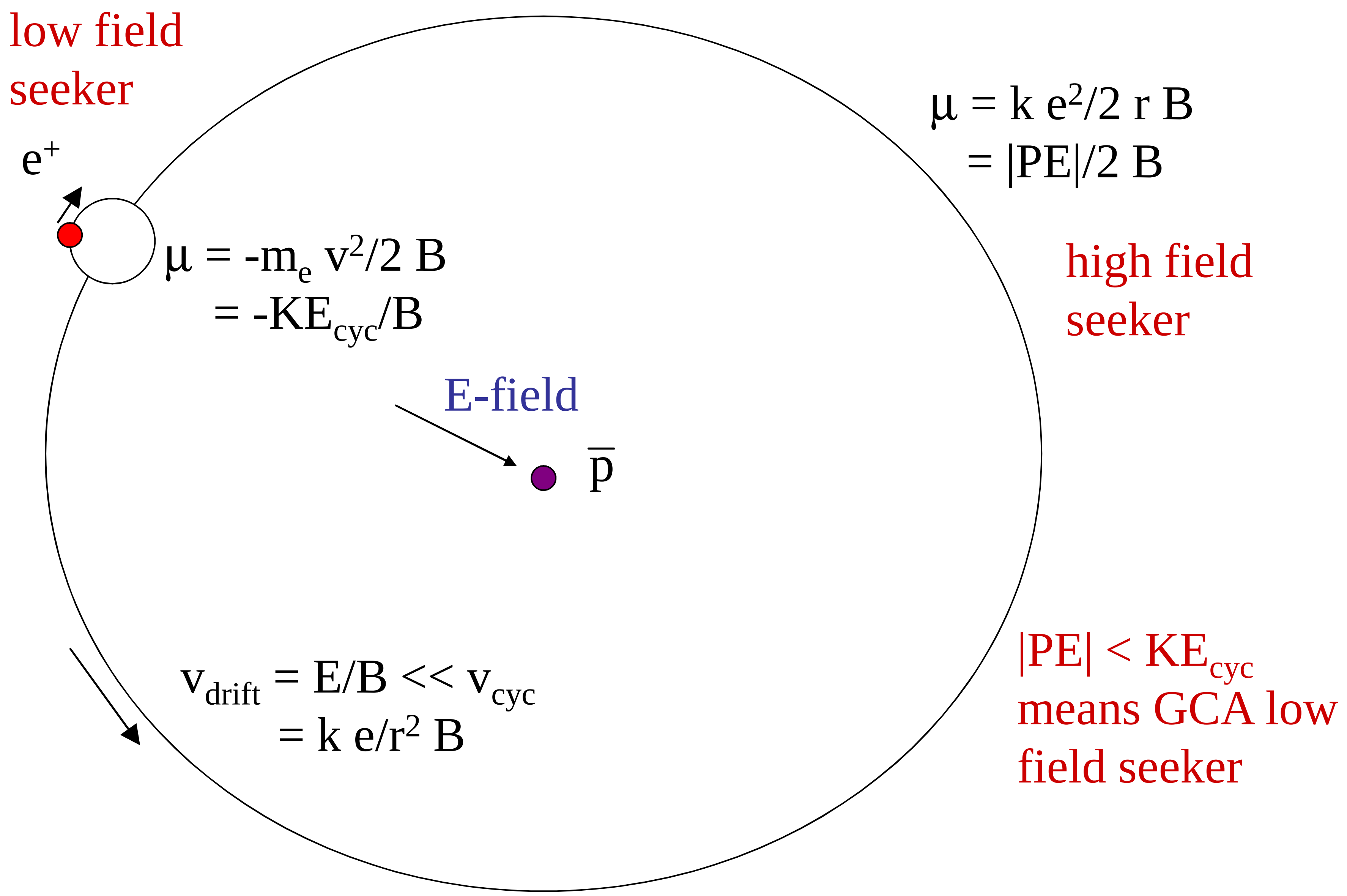
Fraction with dE/dB > 0 and dE/dB > 10 K/T increases with increasing positron temperature!

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

Magnetic moment vs T and BE

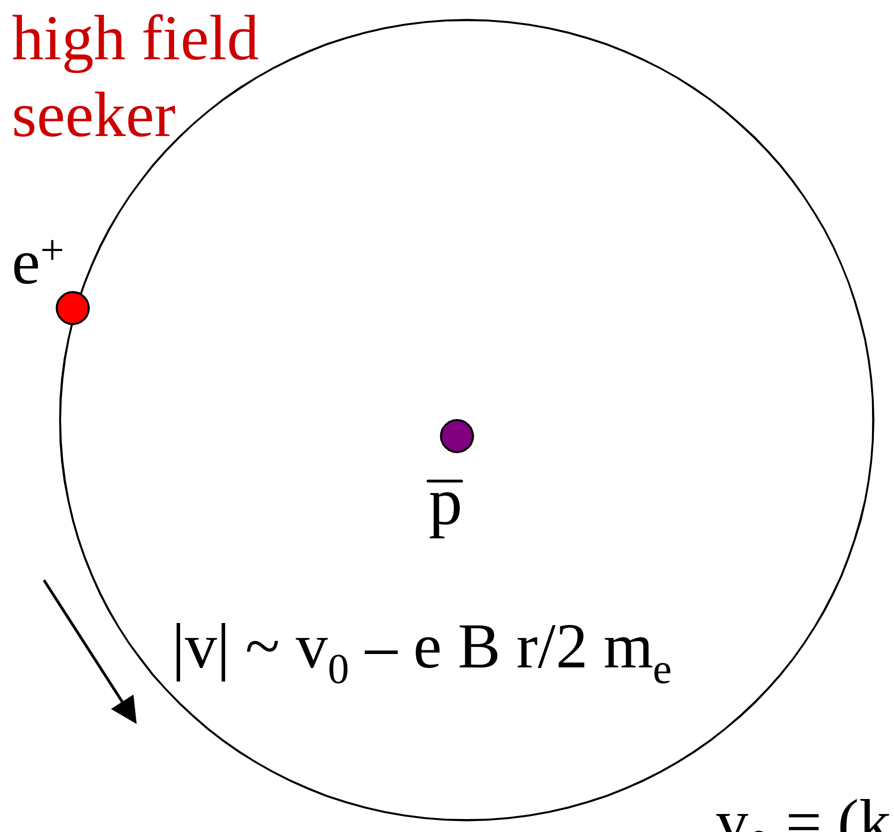
μ proportional to $m<xv_y - yv_x>$

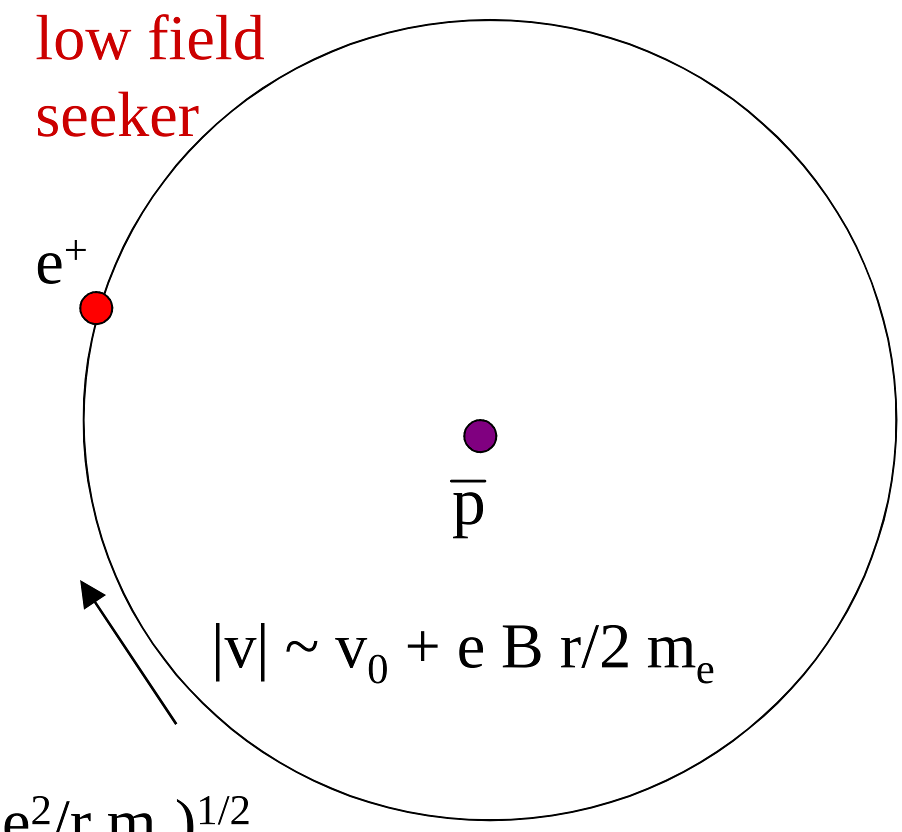
Guiding Center Atom: μ



High/Low Field Seekers

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





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

$v_0 = 73$ km/s
$e\,B\,r/2\,m_e = 4$ km/s
for n = 30, B = 1 T

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

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.

Before After

Estimate

Energy ~ couple eV gives v ~ 2 X 10^4 m/s

Geometric size atom ~ 2 n^2 a_0 ~ 3 X 10^{-7} m for n~50

Time to decay ~ 0.1 s for n~50

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

ALPHA density ~ $10^4/(\pi\,[0.02\ \mathrm{m}]^2\ 0.2\ \mathrm{m})$ ~ 4 X 10^7 m^{-3}

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