15 January 2013

Antihydrogen and Antiproton Magnetic Moment

2012 Progress Report by the
Antihydrogen TRAP Collaboration (ATRAP)

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From the Beginning ATRAP was Built to do Two Types of Experiments Simultaneously

Antihydrogen
Experiments

Precision Measurements
with Antiprotons

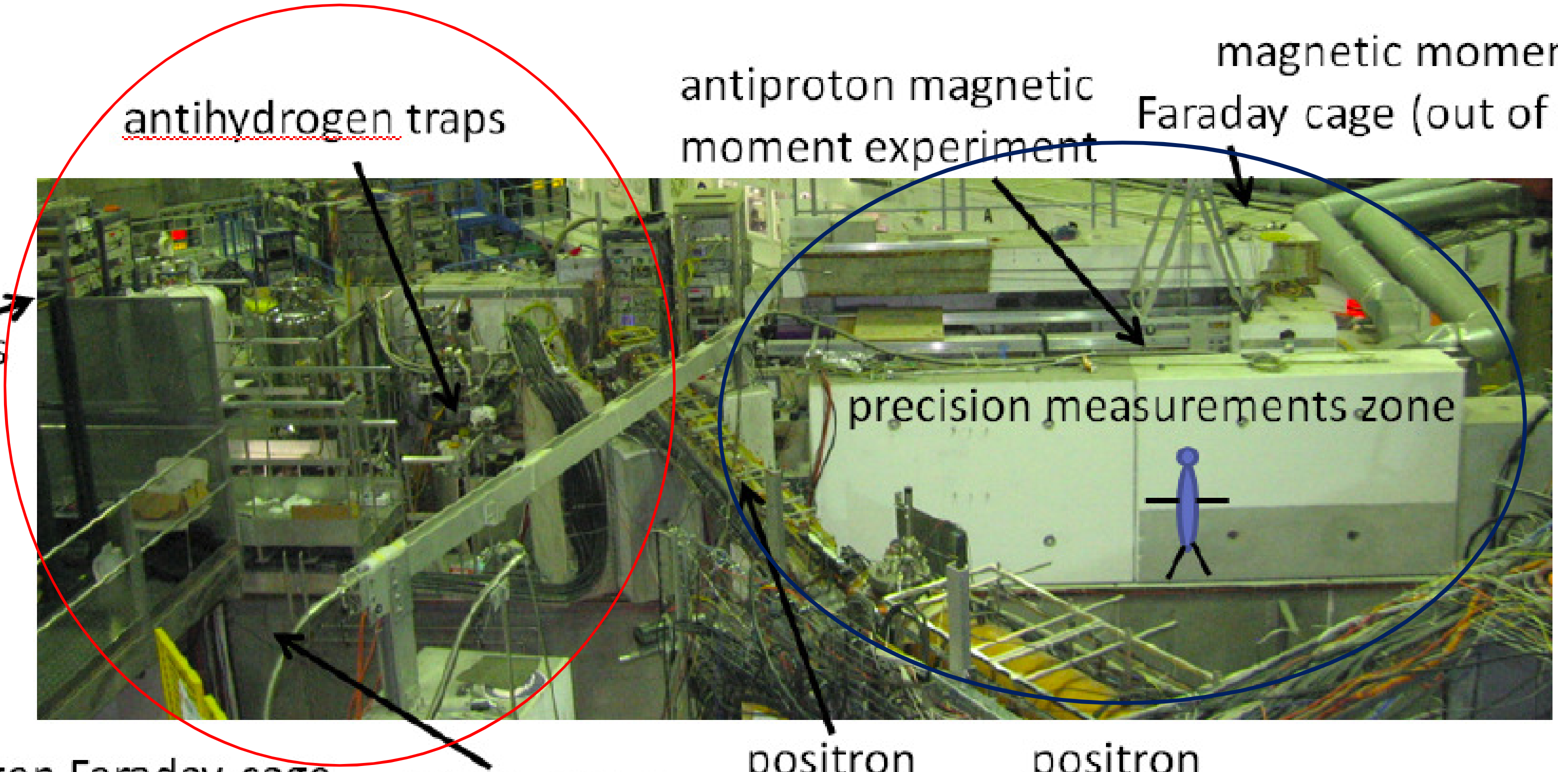
Antiprotons
from AD

SPSC has heard a lot from us about antihydrogen

SPSC has heard less from us about the precision measurements

- Preparations taking place off site
- Brief report each annual report

Simultaneous Antihydrogen Experiments and Precision Measurements


antihydrogen traps

antiproton magnetic
moment experiment

magnetic moment
Faraday cage (out of view)

Ioffe trap
electronics
platform

precision measurements zone

antihydrogen Faraday cage
(out of view)

shielded laser
cabin (below)

positron
guide

positron
accumulator

ATRAP Experimental Area

2012 Summary:

Good news: Measured the antiproton magnetic moment
to 4.4 ppm (parts per million)

Bad news: Despite a very intense effort that continues,
no progress in the antihydrogen experiments

Antiproton Magnetic Moment

$$\boldsymbol{\mu}_{\overline{\mathrm{p}}} = \mu_{\overline{\mathrm{p}}} \boldsymbol{S}/(\hbar/2)$$

Precise Proton Magnetic Moment Measurement Method Cannot be Used with Antiprotons

$$\frac{\mu_p}{\mu_N} \equiv \frac{g_p}{2} = \frac{\mu_e}{\mu_B}\frac{m_p}{m_e}\frac{\mu_p(H)}{\mu_e(H)}\frac{\mu_e(H)}{\mu_e}\frac{\mu_p}{\mu_p(H)}$$

theory corrections
1 ppb

free electron
magnetic
moment

0.0003 ppb

10 ppb

hydrogen
maser

2 ppb or 0.7 ppb

bound electron
magnetic
moment

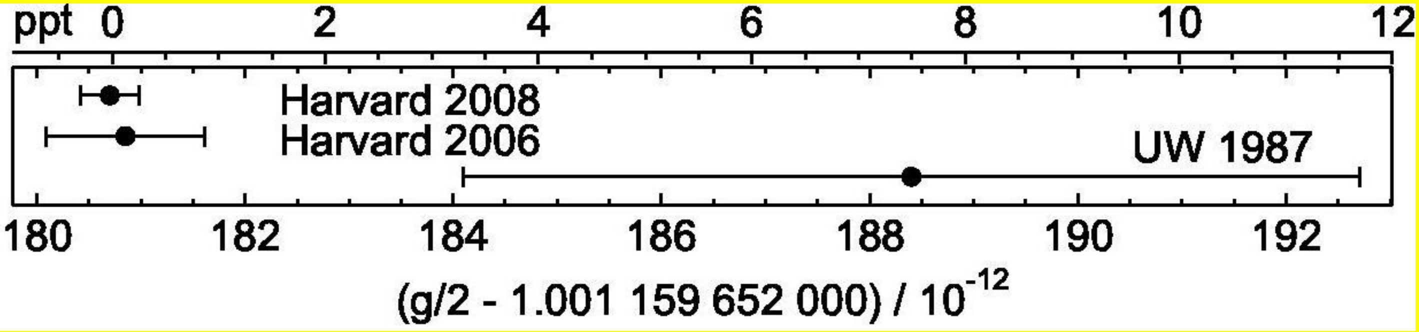
ppb = 10^{-9}

Exotic Atom Measurements

Works with antiprotons
but get only 3000 ppm precision
and does not work with proton.

Electron (Positron) Magnetic Moment Measurements to 3 x 10^{-13}

2.8×10^{-13}



(improved measurement is currently underway)

electron magnetic moment in Bohr magnetons

Can do as well with positron as with electron to compare

Can We Do A Similar Measurement with Antiprotons?

Harder: nuclear magneton rather than Bohr magneton

$$\mu_N/\mu_B = m_e/m_p \sim 1/2000$$

Single Particle Measurements
Have Three Big Advantages

Can be done with antiparticles

Can Reach a Much Higher Precision

Direct measurement → same measurement and apparatus
is used with a particle and antiparticle

Antiproton Magnetic Moment

$$\boldsymbol{\mu}_{\overline{\mathrm{p}}} = \mu_{\overline{\mathrm{p}}} \boldsymbol{S}/(\hbar/2)$$

Single particle method: Measure two frequencies

current challenge

$$\frac{\mu_{\overline{\mathrm{p}}}}{\mu_N} \equiv \frac{g_{\overline{\mathrm{p}}}}{2} \frac{q_{\overline{\mathrm{p}}}/m_{\overline{\mathrm{p}}}}{q_p/m_p} \approx -\frac{g_{\overline{\mathrm{p}}}}{2} = -\frac{f_s}{f_c}$$

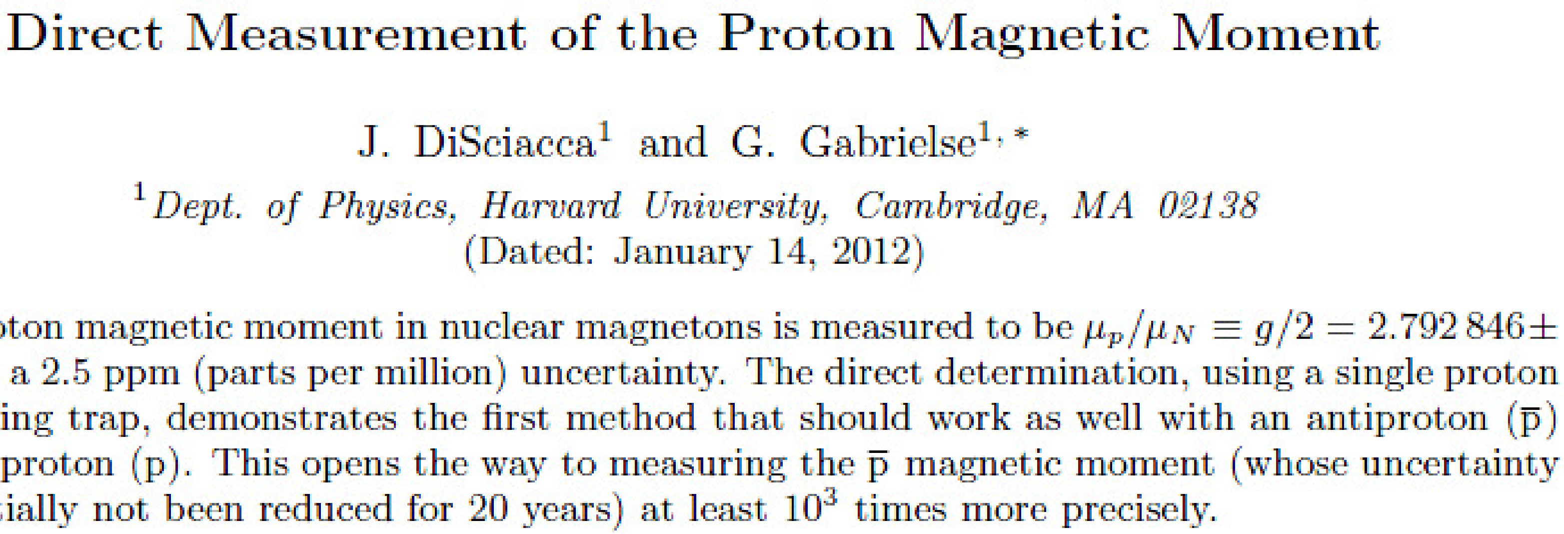
nuclear magneton

we measured to < 9 x10^{-11}

-1
we measured to be
to 9 parts in 10^{11}

Where ATRAP Was Last Year

Phys. Rev. Lett. 180, 153001 (2012)



Direct Measurement of the Proton Magnetic Moment

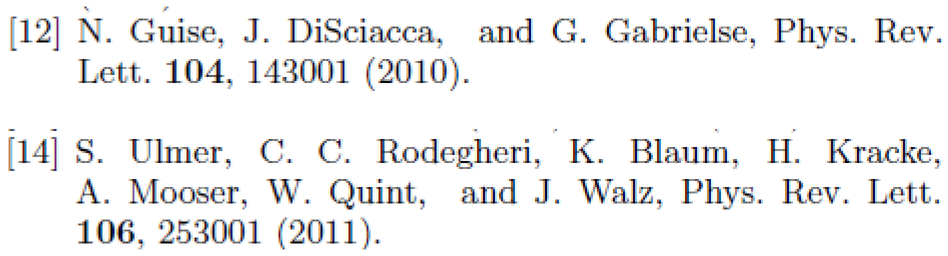
J. DiSciacca[1] and G. Gabrielse[1,*]

[1]*Dept. of Physics, Harvard University, Cambridge, MA 02138*

(Dated: January 14, 2012)

The proton magnetic moment in nuclear magnetons is measured to be $\mu_p/\mu_N \equiv g/2 = 2.792\,846 \pm 0.000\,007$, a 2.5 ppm (parts per million) uncertainty. The direct determination, using a single proton in a Penning trap, demonstrates the first method that should work as well with an antiproton ($\bar{\mathrm{p}}$) as with a proton (p). This opens the way to measuring the $\bar{\mathrm{p}}$ magnetic moment (whose uncertainty has essentially not been reduced for 20 years) at least 10^3 times more precisely.

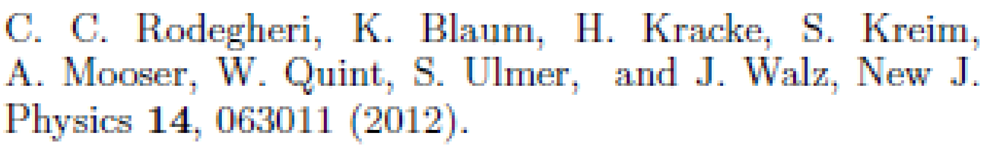
Earlier contributions



[12] N. Guise, J. DiSciacca, and G. Gabrielse, Phys. Rev. Lett. **104**, 143001 (2010).

[14] S. Ulmer, C. C. Rodegheri, K. Blaum, H. Kracke, A. Mooser, W. Quint, and J. Walz, Phys. Rev. Lett. **106**, 253001 (2011).

Later measurement with similar methods



C. C. Rodegheri, K. Blaum, H. Kracke, S. Kreim, A. Mooser, W. Quint, S. Ulmer, and J. Walz, New J. Physics **14**, 063011 (2012).

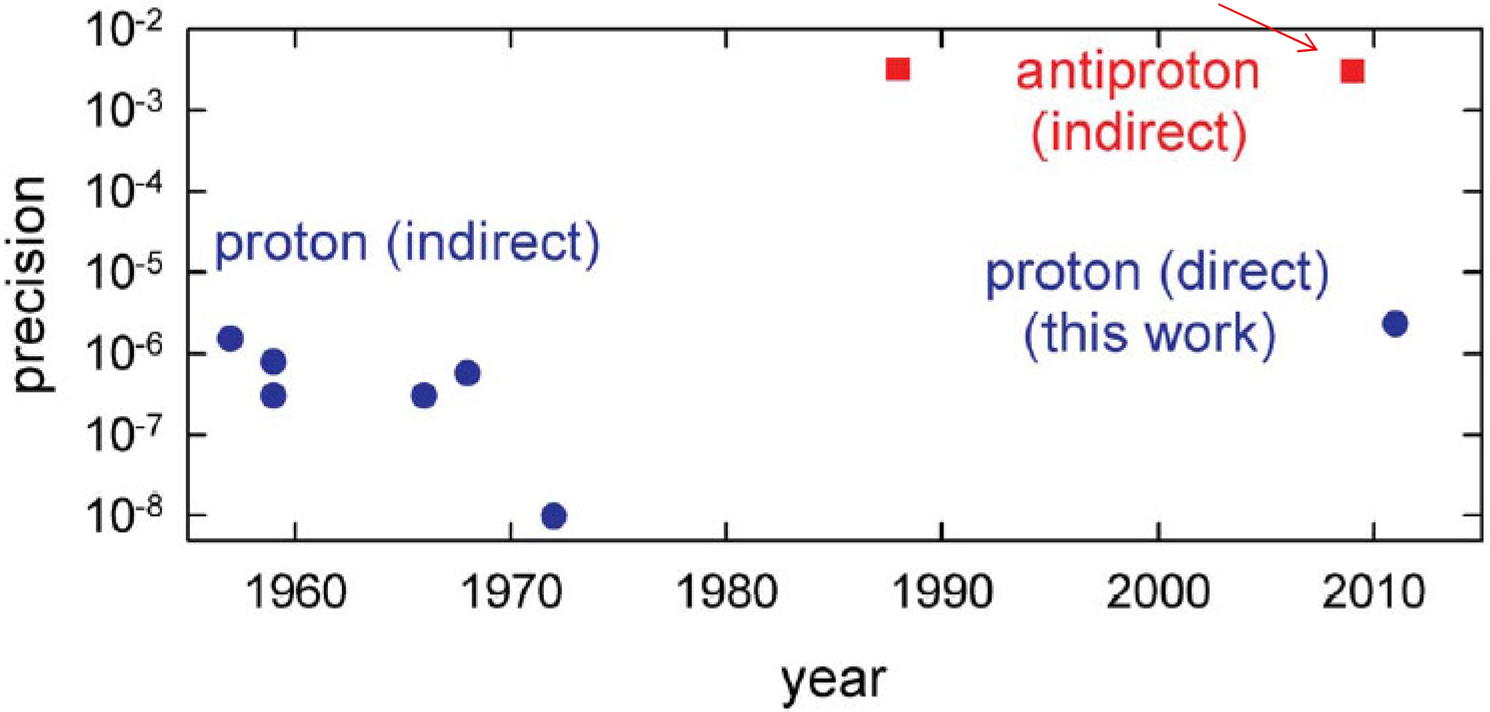
→

Competing letter of intent

Slide from one year ago

Could Now Realize a Thousand-fold Improved Measurement of the Antiproton Moment

ASACUSA



ATRAP

2012
??

Later

If everything went exactly right it would be possible to do this with antiprotons in 2012 → currently under consideration

Expect to eventually be more precise than all proton measurements

Could ATRAP Adapt the Apparatus, Move to CERN, and Make the Measurement in 2012?

Told the SPSC that we were considering this

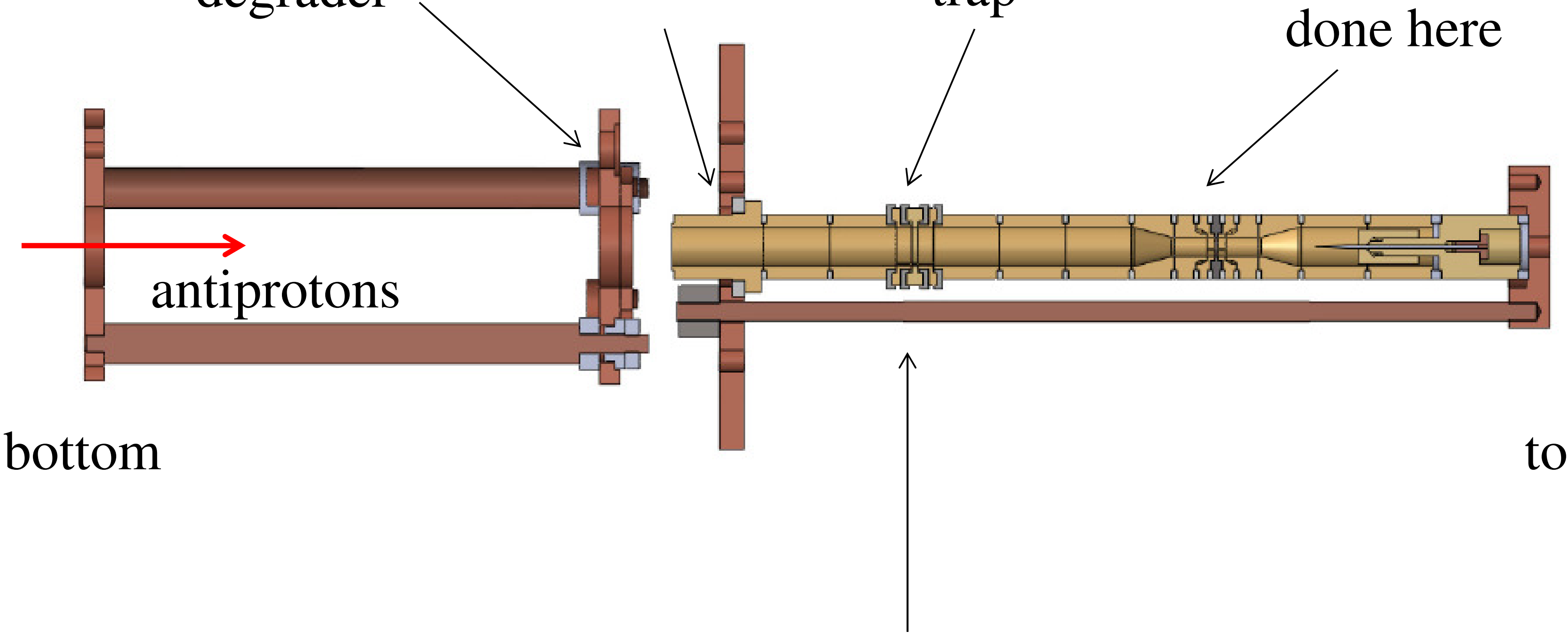
Decided soon after to take the risk:

- -- even if we failed, we would learn what to work on over the long shutdown

- -- we were not anticipating any major scientific accomplishments at the ATRAP or the AD in 2012

- -- perhaps we could succeed

Three Antiproton Traps



degrader

catch and cool
antiprotons

cyclotron
cooling
trap

proton and antiproton
measurements
done here

antiprotons

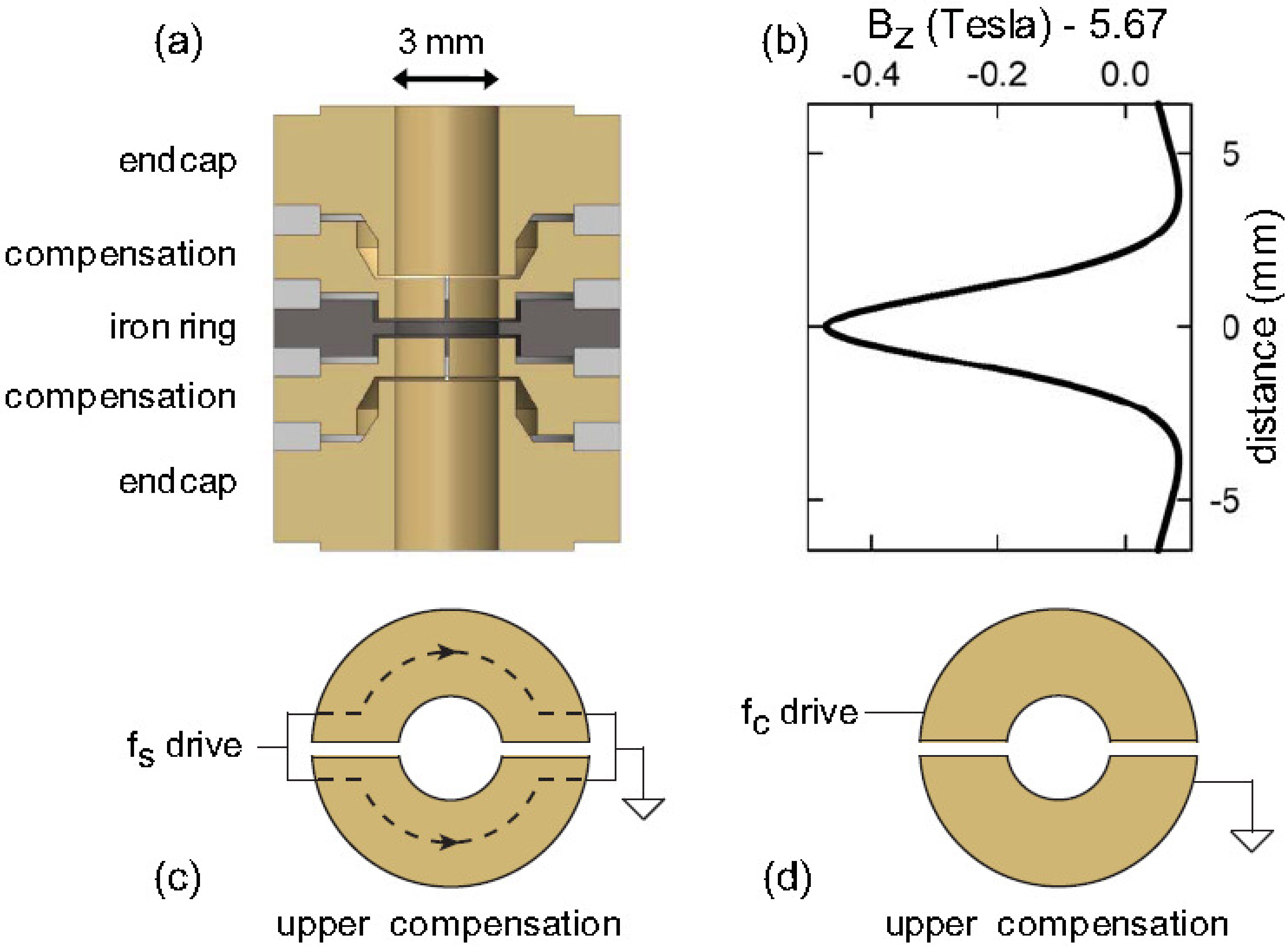
bottom

top

more precise measurements
will take place here

Huge Magnetic Bottle Gradient

190 times larger than used for electron



One-Particle Method

With one proton or antiproton suspended in a trap, measure spin and cyclotron frequencies

$$\frac{\mu_p}{\mu_N} \equiv \frac{g_p}{2} = \frac{f_s}{f_c}$$

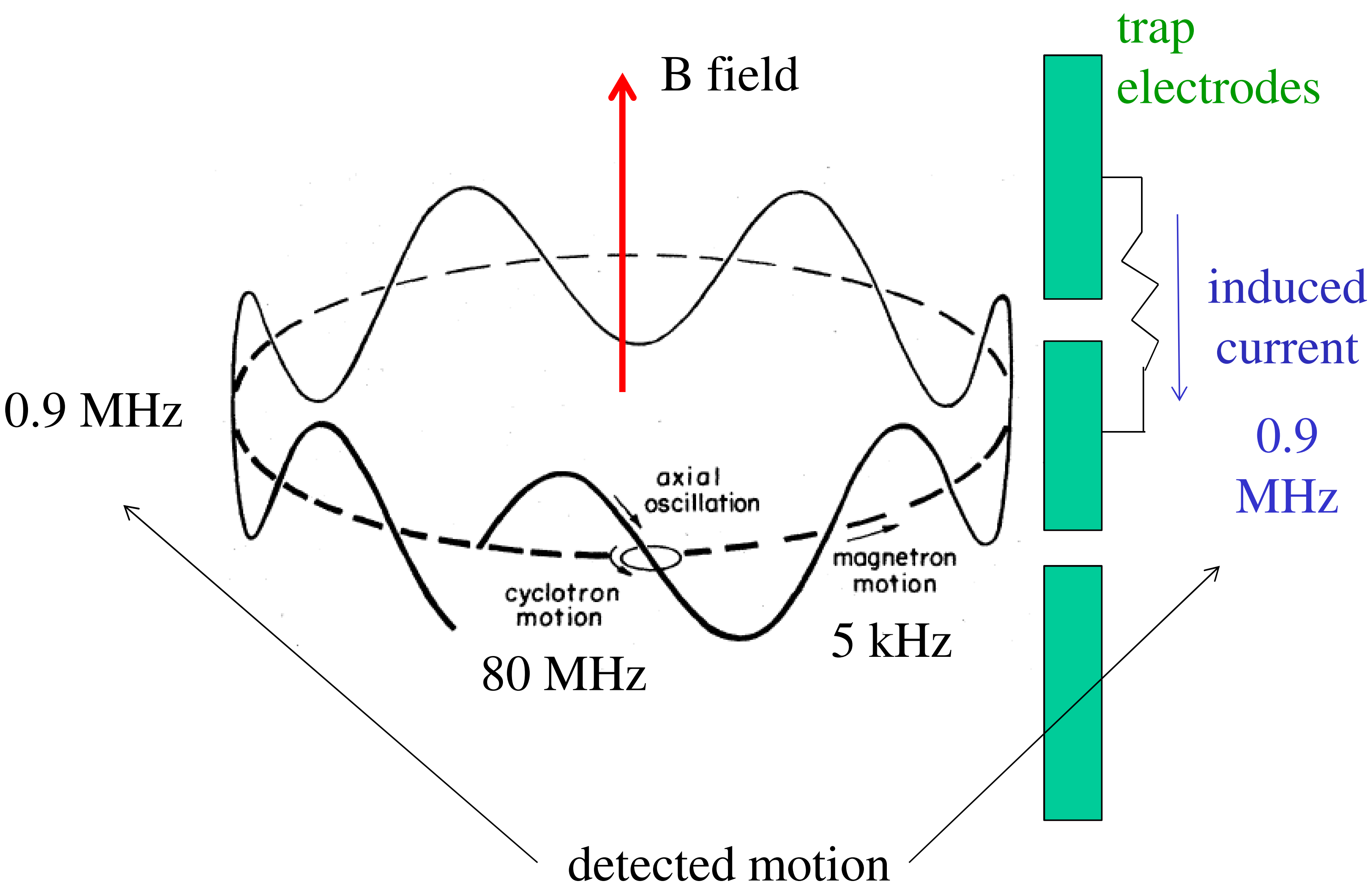
current challenge

we measured to
$< 9 \times 10^{-11}$
back at LEAR

no previous method has been devised to measure antiproton and proton moments in the same way

Gabrielse

Antiproton Orbits in a Penning Trap



B field

trap electrodes

induced current

0.9 MHz

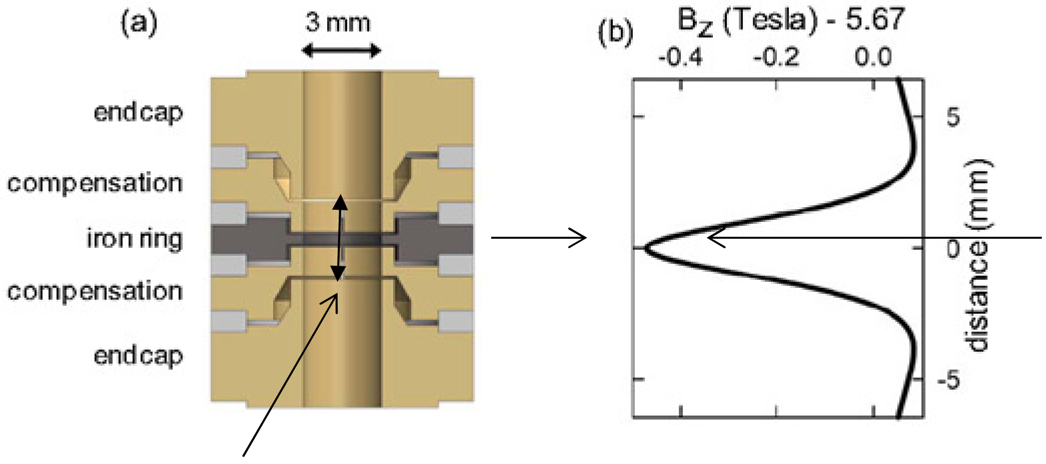
0.9 MHz

80 MHz

5 kHz

detected motion

Detecting the Antiproton Magnetic Moment



$$\Delta \mathbf{B} = \beta_2[(z^2 - \rho^2/2)\hat{\mathbf{z}} - z\rho\hat{\boldsymbol{\rho}}]$$

Harmonic oscillator

$$H \sim f^2 z^2$$

oscillation frequency

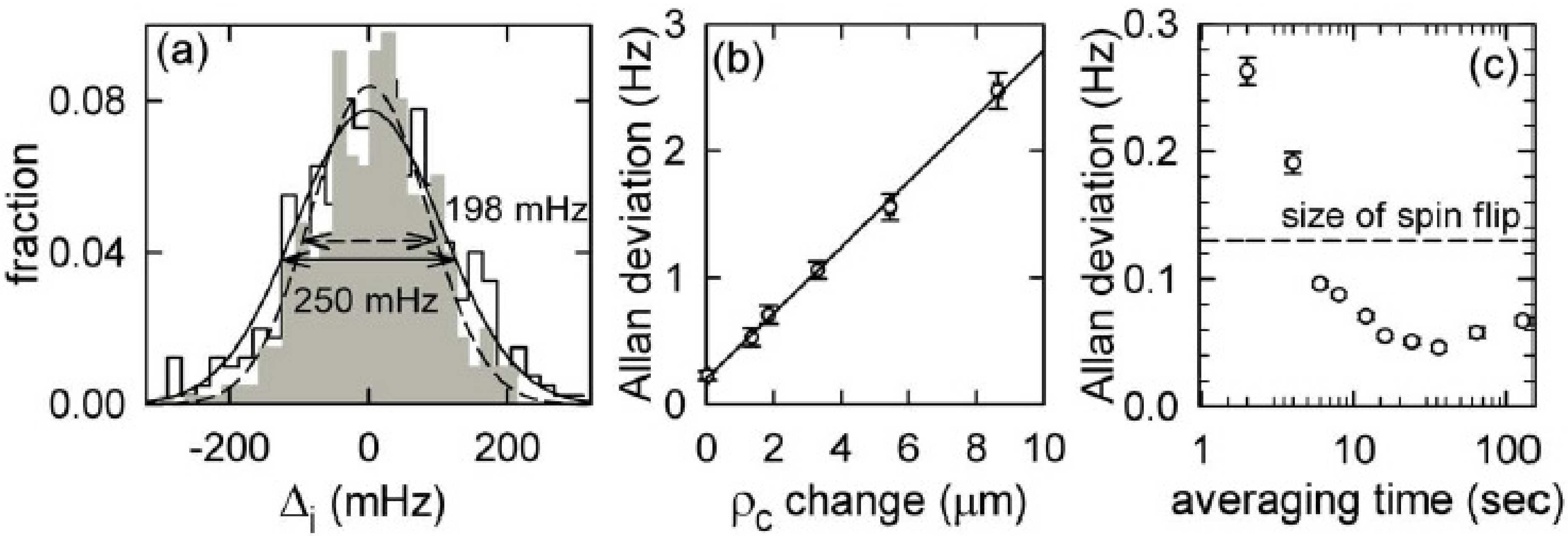
magnetic moment

$$\Delta H \sim -\mu\, \Delta B \sim \mu\, z^2$$

$$\Delta f \sim \mu$$

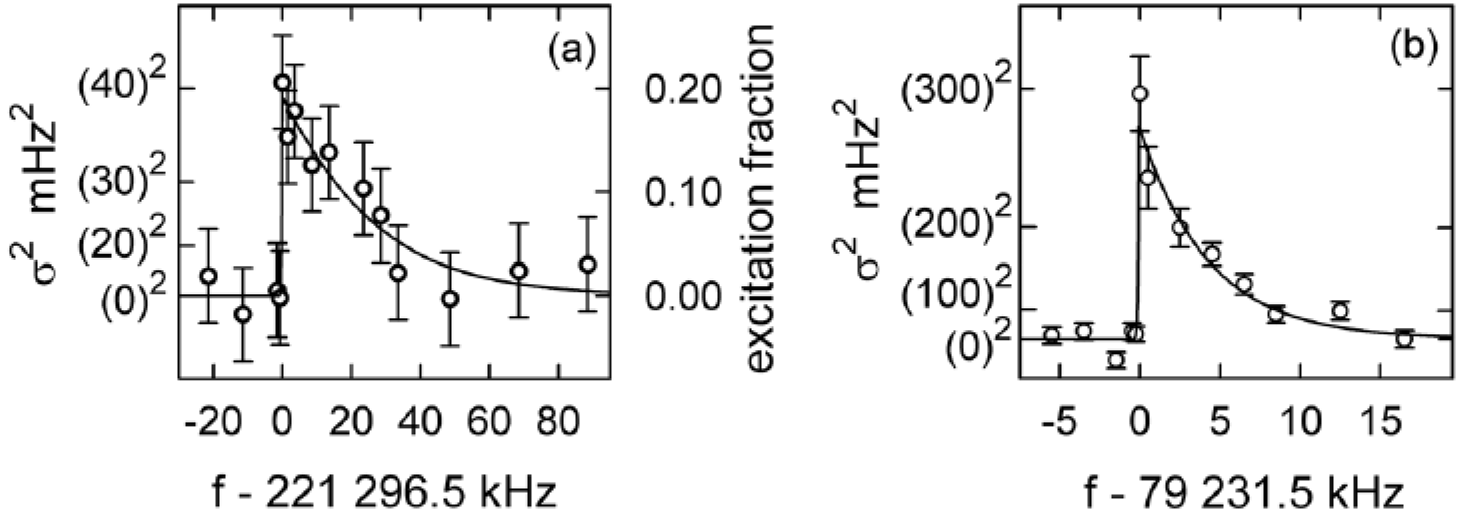
shift in oscillation frequency

Spin-Flips Increase Allan Deviation

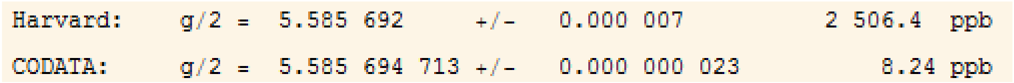


Direct Measurement of the Proton Mag. Moment

$$\frac{\mu_p}{\mu_N} \equiv \frac{g_p}{2} = \frac{f_s}{f_c}$$

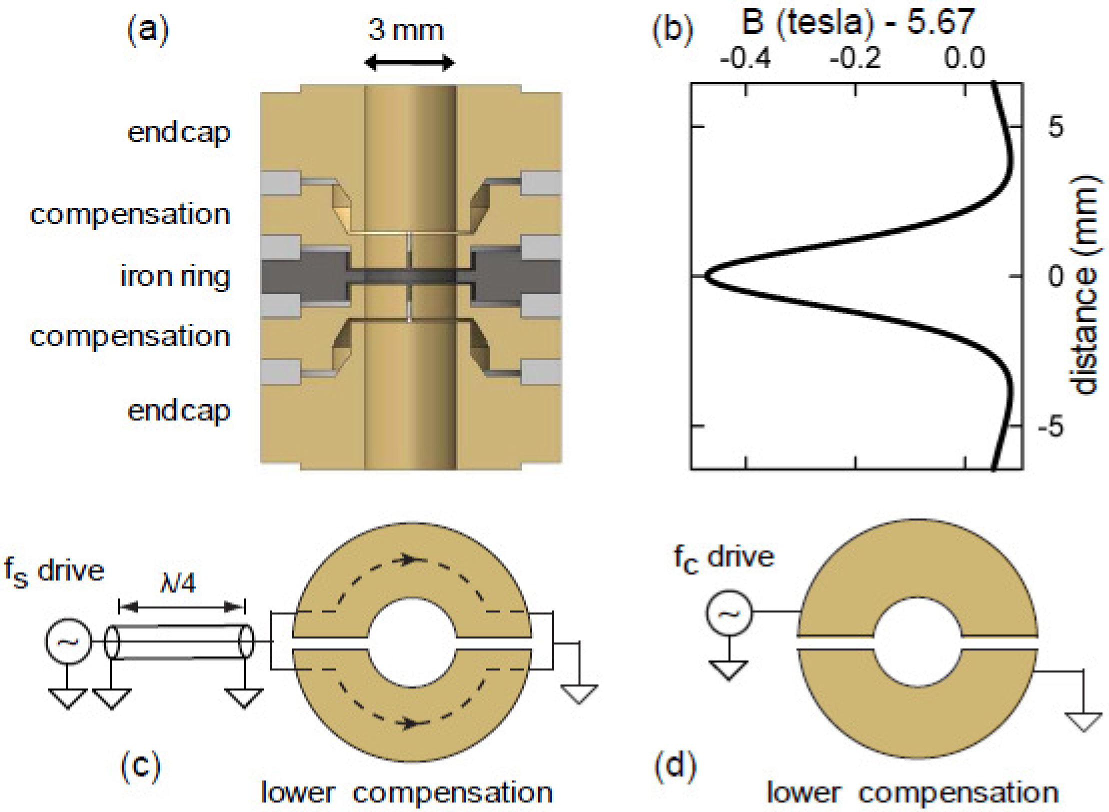


$$\frac{\mu_p}{\mu_N} = \frac{g}{2} = 2.792\,846 \pm 0.000\,007 \qquad [2.5\ \text{ppm}]$$

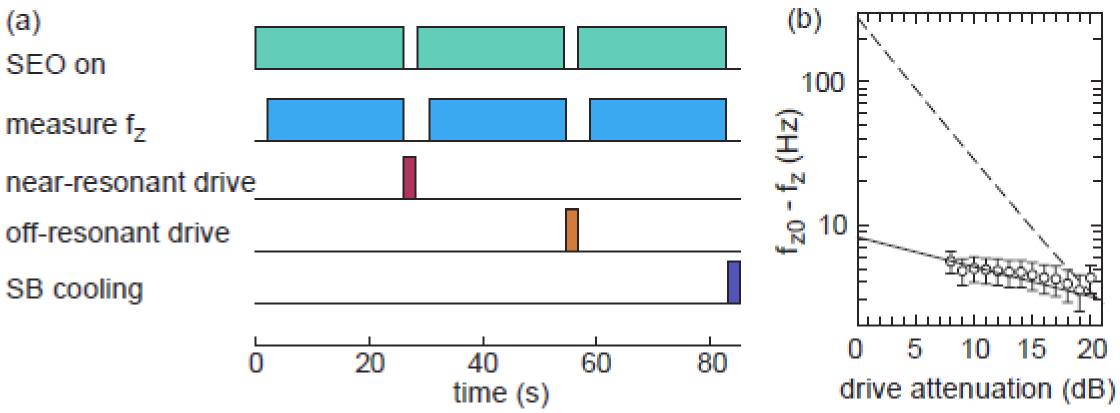


```
Harvard:     g/2 =   5.585 692      +/-    0.000 007            2 506.4  ppb
CODATA:      g/2 =   5.585 694 713 +/-    0.000 000 023            8.24 ppb
```

Slightly Improved Apparatus



Measurement Sequence – for Spin Measurement



Resonance Lines to Determine the “Two” Frequencies

square
of extra
width

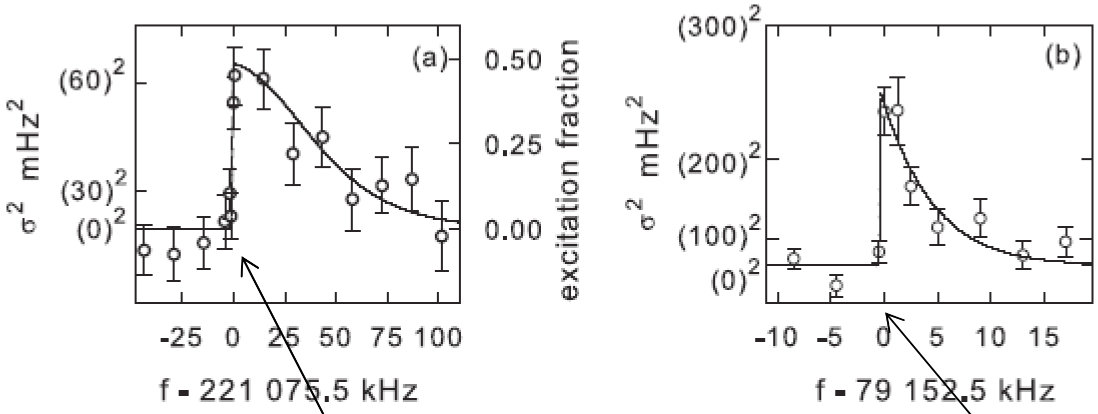


FIG. 4. (a) The spin line. (b)The cyclotron line.

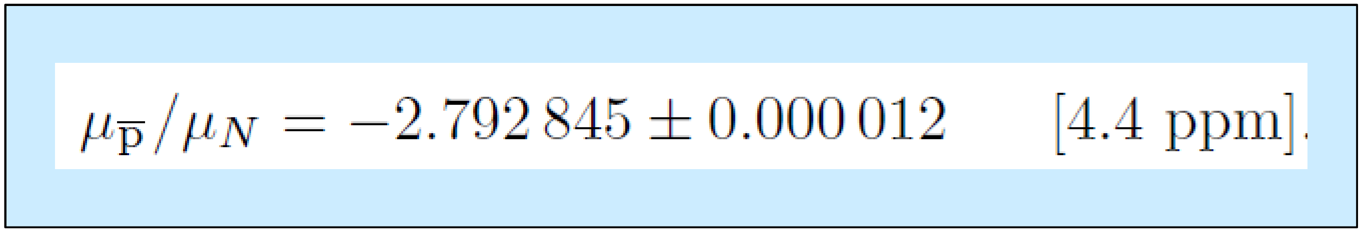
$$\frac{\mu_p}{\mu_N} \equiv \frac{g_p}{2} = \frac{f_s}{f_c}$$

$$f_c^2 = f_+^2 + f_z^2 + f_-^2$$

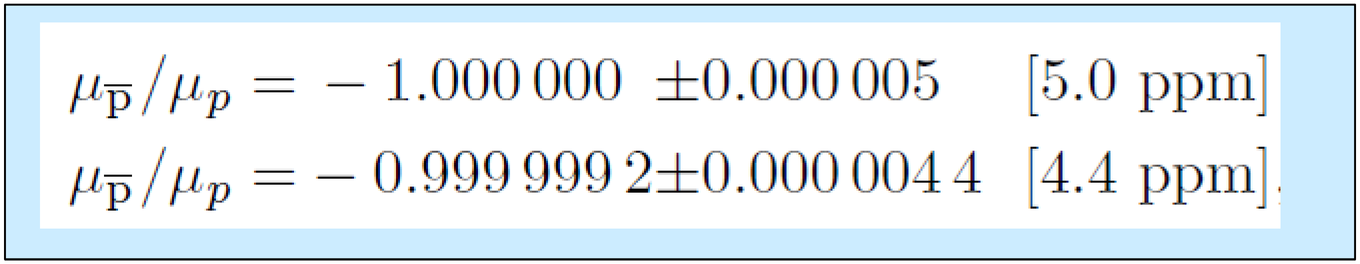
Brown-Gabrielse
Invariance Theorem

Gabrielse

First One-Particle Measurement of the Antiproton Magnetic moment



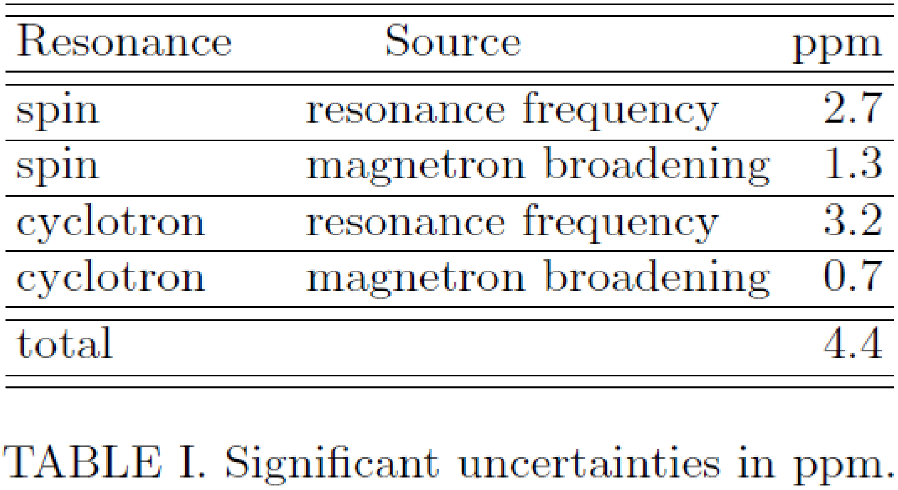
$$\mu_{\overline{\mathrm{p}}}/\mu_N = -2.792\,845 \pm 0.000\,012 \qquad [4.4\ \mathrm{ppm}]$$



$$\mu_{\overline{\mathrm{p}}}/\mu_p = -\,1.000\,000\ \pm 0.000\,005 \qquad [5.0\ \mathrm{ppm}]$$

$$\mu_{\overline{\mathrm{p}}}/\mu_p = -\,0.999\,999\,2 \pm 0.000\,004\,4 \qquad [4.4\ \mathrm{ppm}]$$

680 times lower than previous



Resonance	Source	ppm
spin	resonance frequency	2.7
spin	magnetron broadening	1.3
cyclotron	resonance frequency	3.2
cyclotron	magnetron broadening	0.7
total		4.4

TABLE I. Significant uncertainties in ppm.

680 – Fold Improved Precision

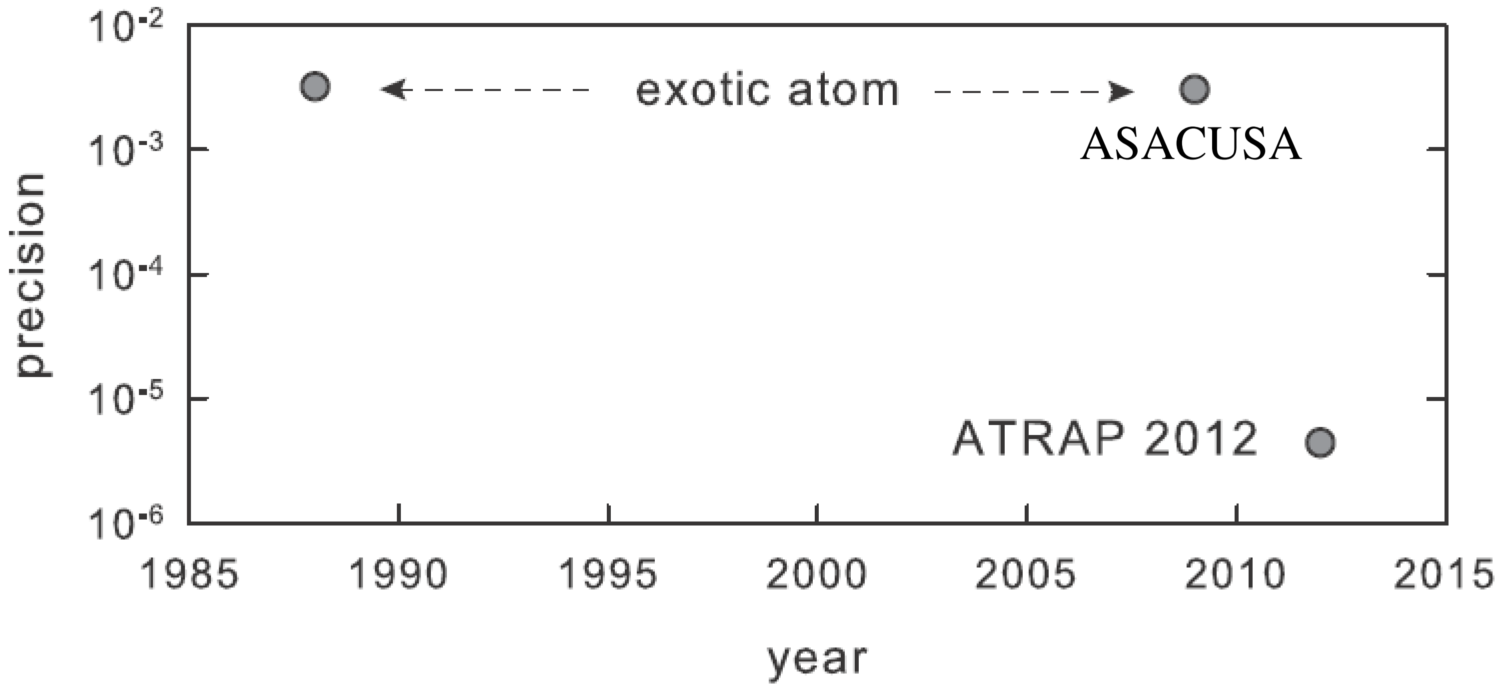


FIG. 1. Uncertainties in measurements of the $\overline{\mathrm{p}}$ magnetic moment measured in nuclear magnetons, $\mu_{\overline{\mathrm{p}}}/\mu_N$.

Antihydrogen

Proposal to Trap Cold Antihydrogen – 1986

- **Produce cold antihydrogen from cold antiprotons**

“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. ..."

- **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.”

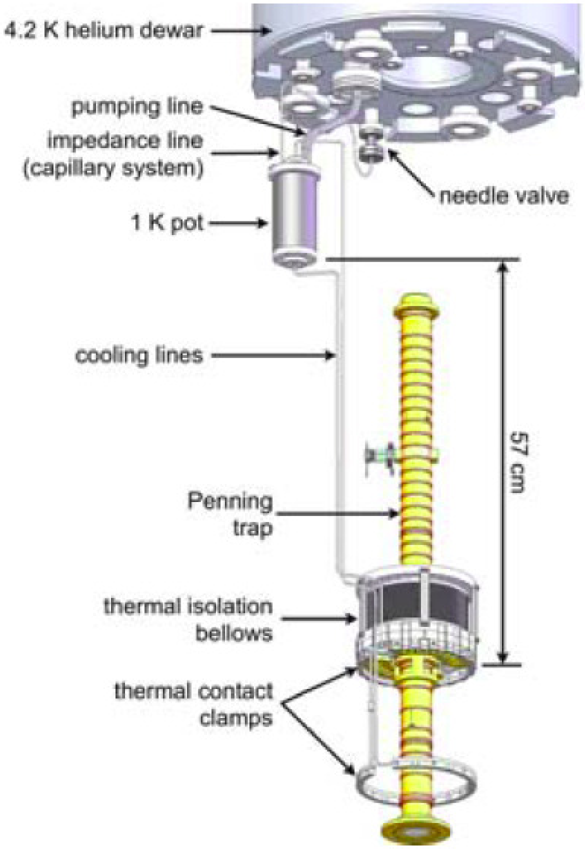
Gerald Gabrielse, 1986 Erice Lecture (shortly after first pbar trapping)
In **Fundamental Symmetries**, (P.Bloch, P. Paulopoulos, and R. Klapisch, Eds.) p. 59, Plenum, New York (1987).

Use trapped antihydrogen
to measure antimatter gravity

G. Gabrielse, Hyperfine Interact. 44, 349 (1988)

Gabrielse

1.2 K Electrodes and Millions of Antiprotons



1.2 K Using
Pumped Helium

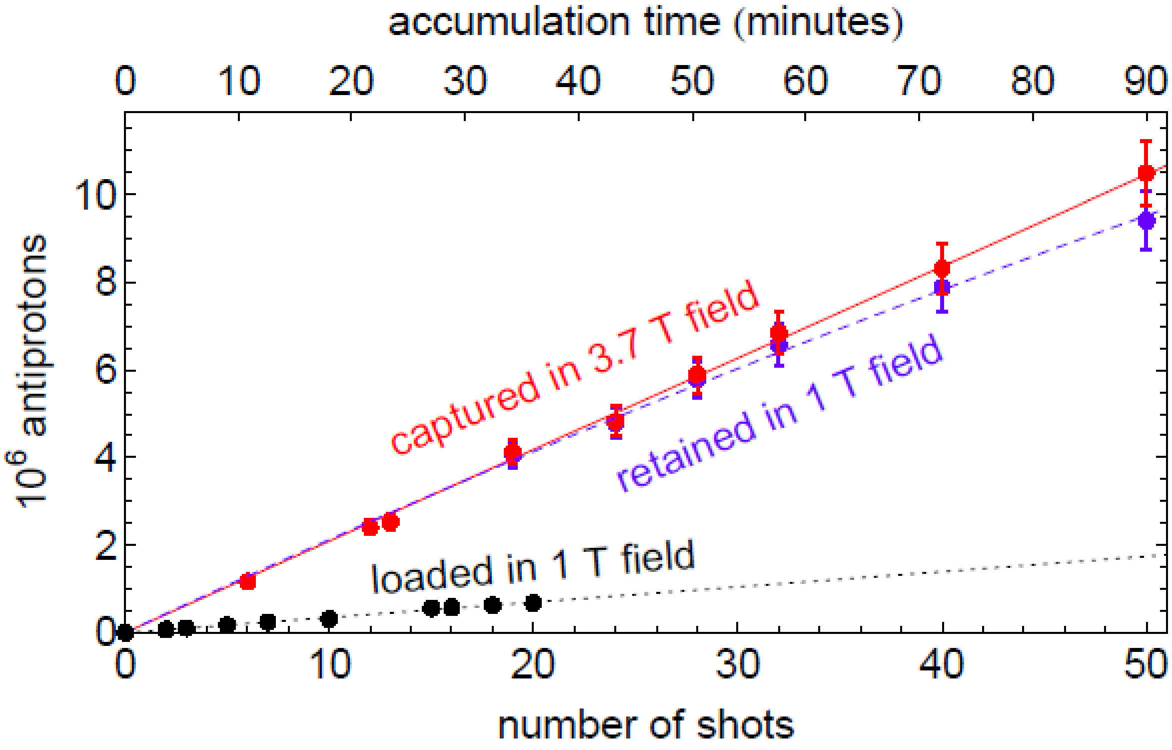
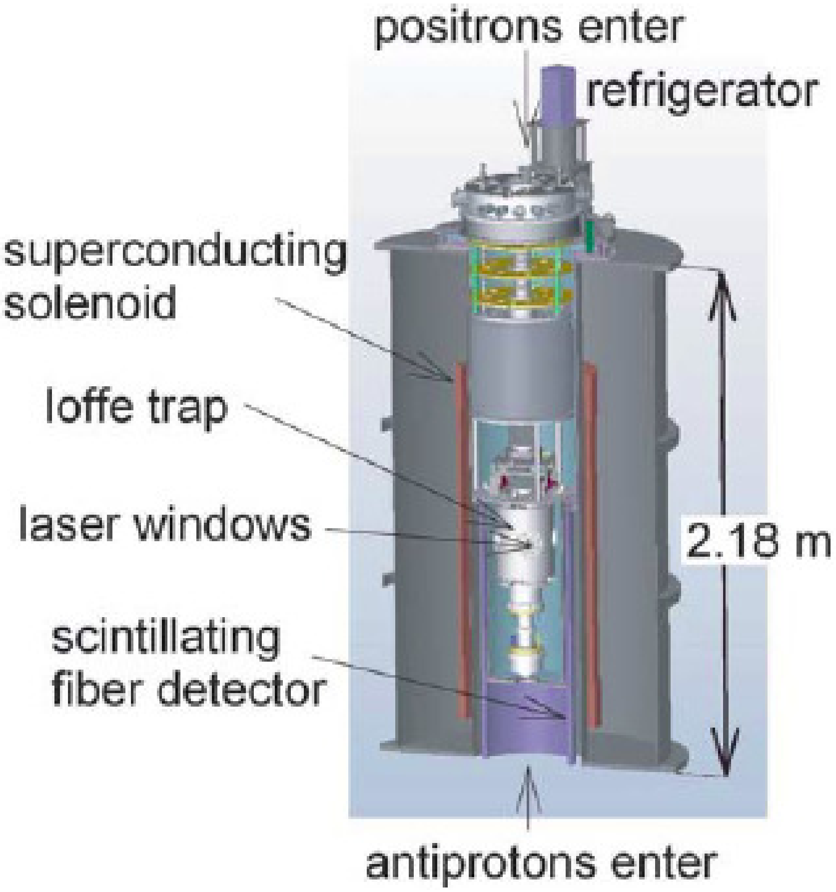
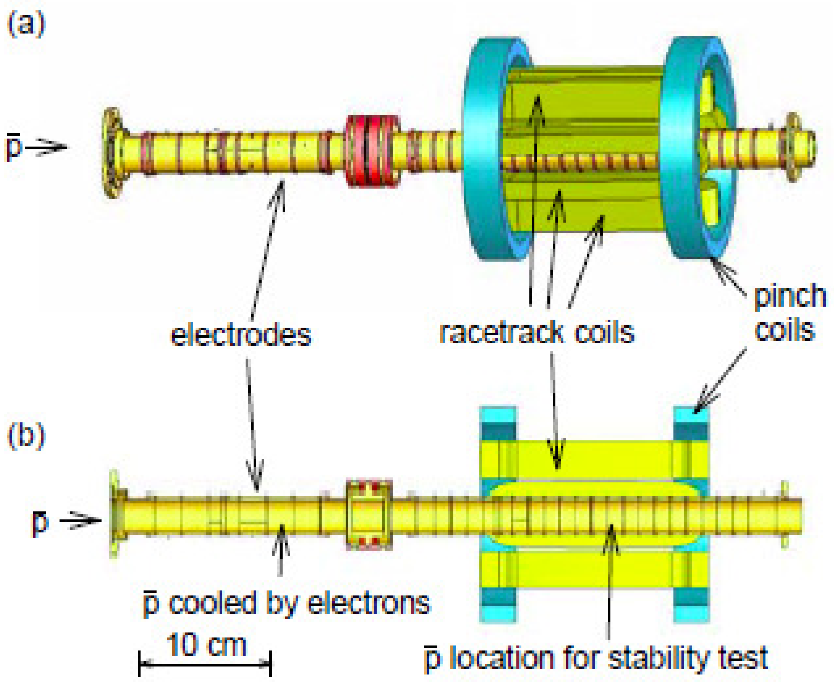


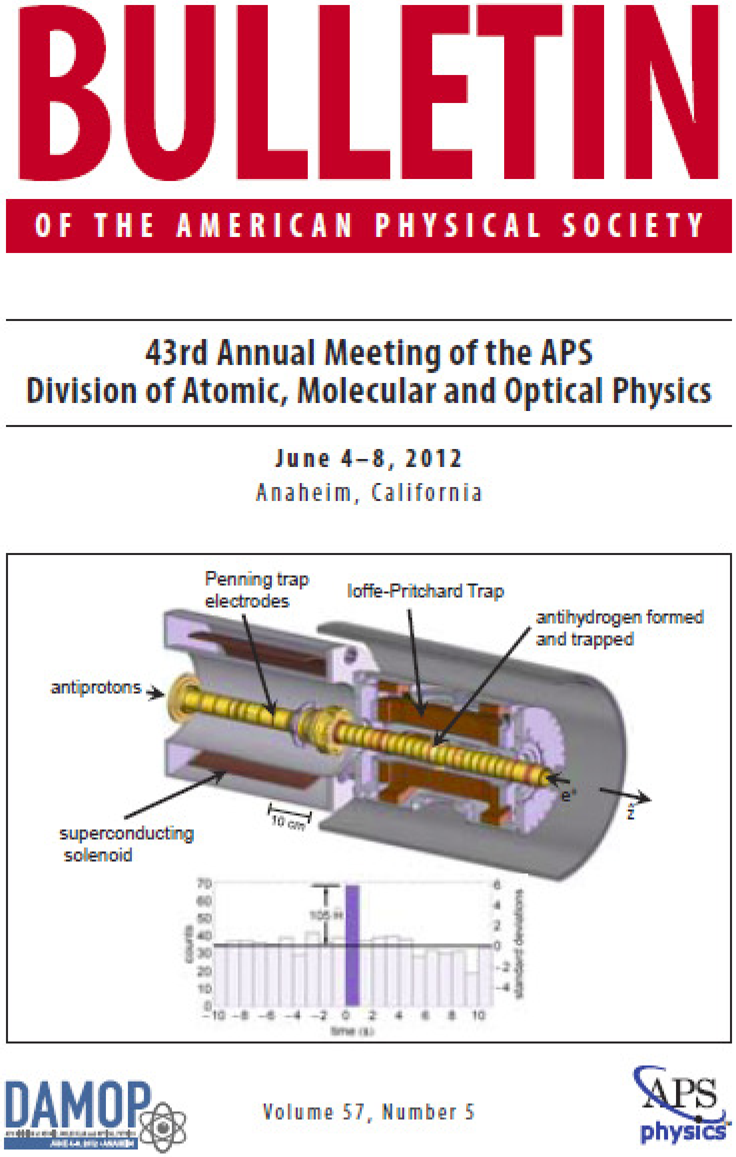
Figure 4: Accumulation of ten million $\overline{\mathrm{p}}$.

First Generation Penning-Ioffe Apparatus





What ATRAP Did in 2011



BULLETIN

OF THE AMERICAN PHYSICAL SOCIETY

43rd Annual Meeting of the APS
Division of Atomic, Molecular and Optical Physics

June 4–8, 2012
Anaheim, California

Volume 57, Number 5

5 +/- 1 ground state atoms
simultaneously trapped

ATRAP, “Trapped Antihydrogen in Its Ground State”, Phys. Rev. Lett. **108**, 113002 (2012)

Lack of

Antihydrogen Progress

Needed a Second Generation Penning Ioffe Trap

We needed a trap with side windows to allow Lyman alpha to enter to do laser cooling

- First generation trap had such windows
- But, we could only use it make one or two antihydrogen trials per 8 hour shifts

Slide from last year SPSC report

Second Generation Ioffe Trap

~~Fully assembled, vacuum tested cold~~

~~Wiring finished this week~~

~~Cold testing at high current → soon~~

~~Intend to use from the beginning of the 2012 run~~

second generation Ioffe trap

ports for laser and microwaves

Two Problems

1. Silver-titanium welds failure
    - Had worked this out for other experiments
    - Small shop had a new welder do the job
    - After the old guy got out of the hospital → did it right
    - → fixed

2. Epoxy, G10, aluminum vacuum system failure
    - 3 full scale prototypes were successfully cold tested
    - real system failed
    - tried a patch – long shot, only way to possible get success still in 2012
    - → could not control thermal gradients that stressed the epoxy joints

Vacuum enclosure has been machined off. New enclosure is designed. Test pieces being prepared.

Plan: Use the Shutdown to Produce and Tests a Vacuum Enclosure For the Ioffe Trap

→ Have it ready to go after when antiprotons are next available

Why Compare Matter and Antimatter

Start general

Embarrassing, Unsolved Mystery: How did our Matter Universe Survive Cooling After the Big Bang?

Big bang → equal amounts of matter and antimatter created during hot time

As universe cools → antimatter and matter annihilate

Big Questions:

- How did any matter survive?
- How is it that we exist?

Our experiments are looking for evidence of any way that antiparticles and particles may differ

Our “Explanations” are Not so Satisfactory

Baryon-Antibaryon Asymmetry in Universe is Not Understood

Standard “Explanation”

- CP violation
- Violation of baryon number
- Thermodynamic non-equilibrium

Alternate

- CPT violation
- Violation of baryon number
- Thermo. equilib.

Bertolami, Colladay, Kostelecky, Potting
Phys. Lett. B 395, 178 (1997)

Why did a universe made of matter survive the big bang?
Makes sense look for answers to such fundamental questions in the few places that we can hope to do so very precisely.

Bigger problem: don’t understand dark energy within 120 orders of magnitude

Why Compare H and $\bar{\text{H}}$ (or P and $\bar{\text{P}}$)?

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

Comparing the CPT Tests

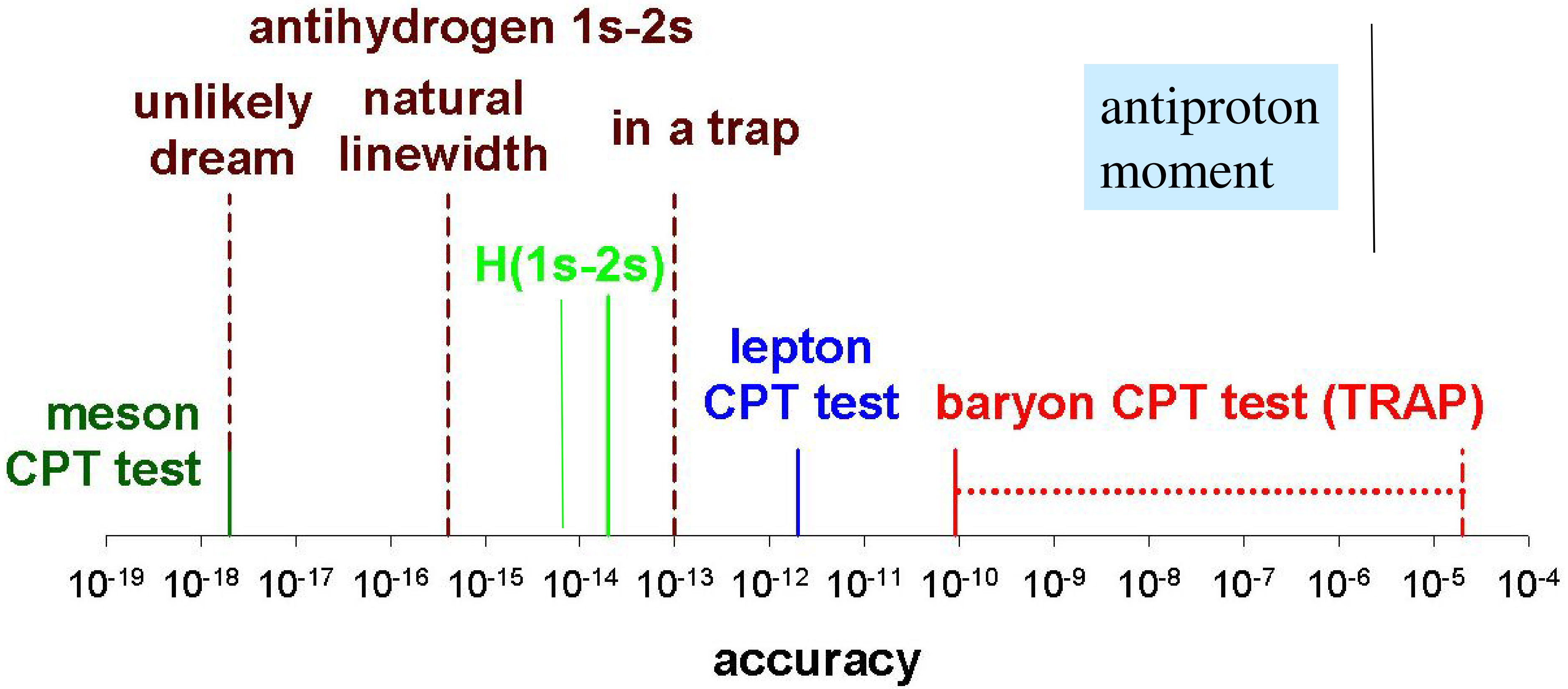
Warning – without CPT violation models it is hard to compare

3 fundamentally different types of particles

	CPT Test Accuracy	Measurement Accuracy	Free Gift
$K_0 \overline{K}_0$ Mesons	2×10^{-18}	2×10^{-3}	10^{15}
$e^+ e^-$ Leptons	2×10^{-12}	2×10^{-9}	10^{3}
$P \overline{P}$ baryons	9×10^{-11}	9×10^{-11}	1

improve with antihydrogen

Seek to Improve Lepton and Baryon CPT Tests



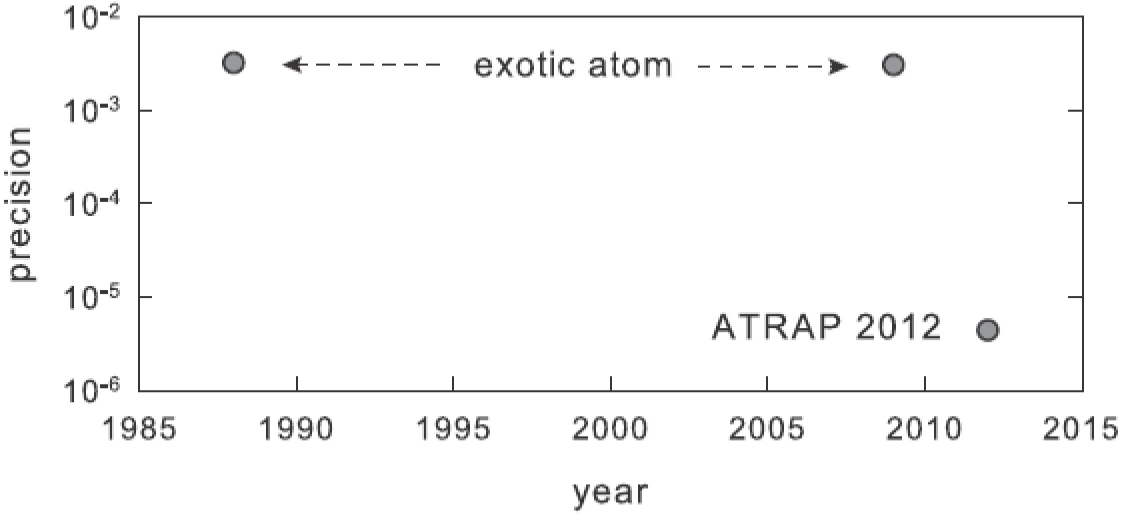
$$\frac{R_\infty[\overline{\mathrm{H}}]}{R_\infty[\mathrm{H}]} = \frac{m[e^+]}{m[e^-]}\left(\frac{q[e^+]}{q[e^-]}\right)^2\left(\frac{q[\overline{p}]}{q[p]}\right)^2 \frac{1+m[e^-]/M[p]}{1+m[e^+]/M[\overline{p}]}$$

CPT for Antiprotons and Antihydrogen

Antihydrogen and Hydrogen structure

Compare Antiproton and Proton

q/m	TRAP (direct)
q and m separately	TRAP + ASACUSA (partly indirect)
μ	ATRAP



10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
precision
exotic atom
ATRAP 2012
1985
1990
1995
2000
2005
2010
2015
year

High Precision Tests of CPT Invariance

The Most Precise CPT Test with Baryons → by TRAP at CERN

G. Gabrielse, A. Khabbaz, D. S. Hall, C. Heimann, H. Kalinowsky, and W. Jhe, Phys. Rev. Lett. **82**, 3198 (1999).

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

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

(most precise result of CERN's antiproton program)

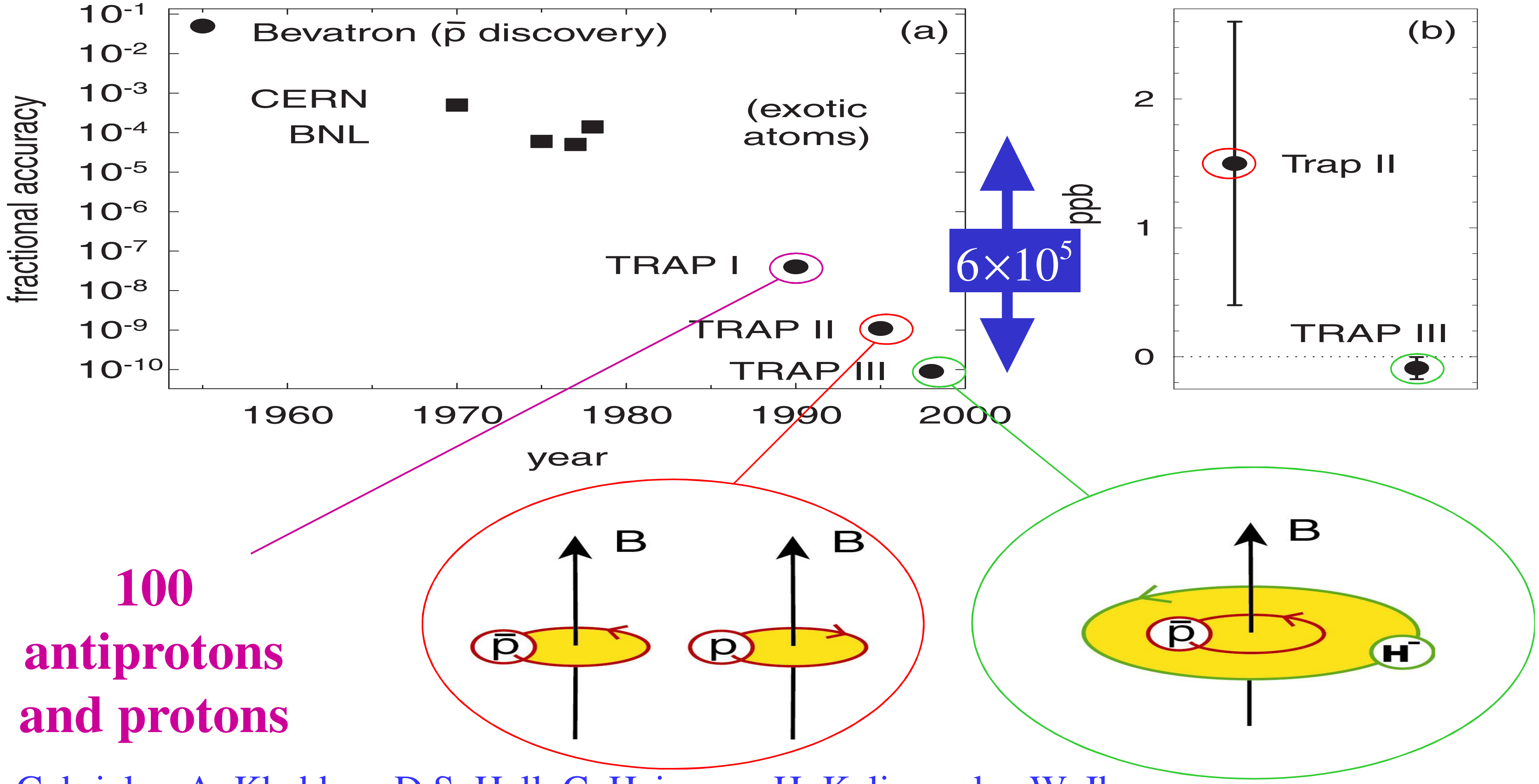
Goal at the AD: Make CPT test that approach
exceed this precision

TRAP Improved the Comparison of Antiproton and Proton by ~10^6

$$\frac{q/m\ \text{(antiproton)}}{q/m\ \text{(proton)}} = -0.999\,999\,999\,91(9)$$

$$9\times10^{-11} = 90\,\text{ppt}$$

most stringent CPT test with baryons

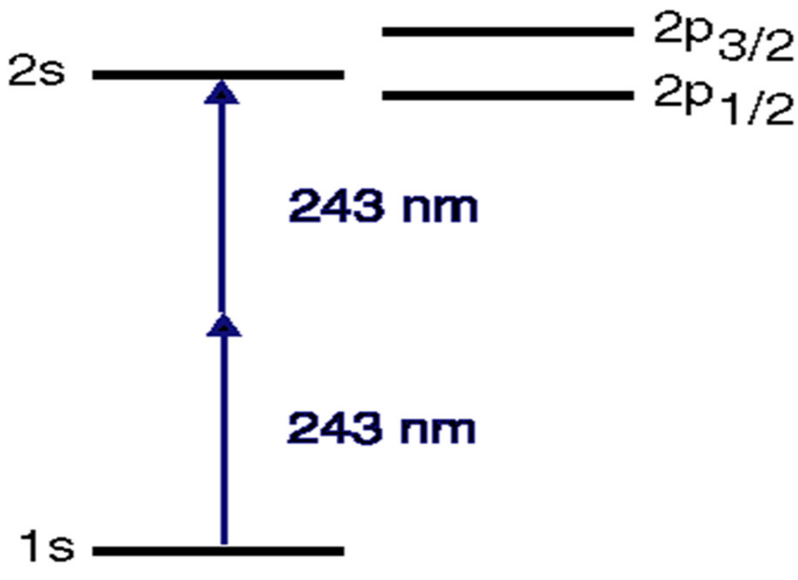


100 antiprotons and protons

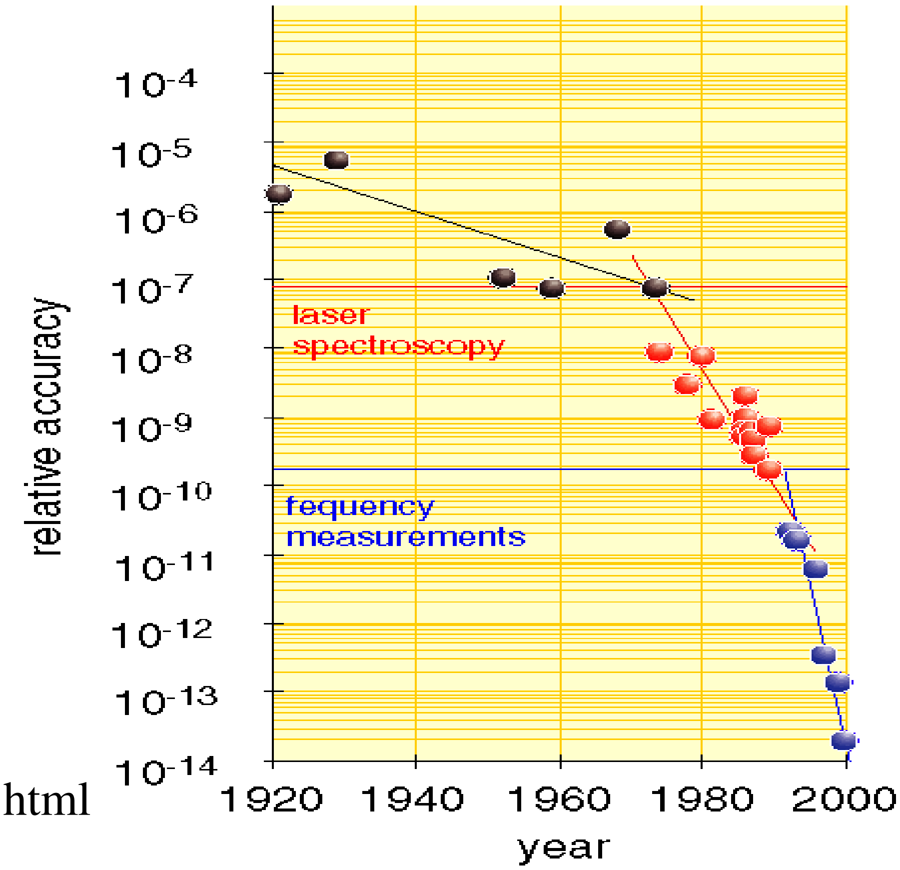
G. Gabrielse, A. Khabbaz, D.S. Hall, C. Heimann, H. Kalinowsky, W. Jhe;
Phys. Rev. Lett. **82**, 3198 (1999).

Gabrielse

Ultimate Goal: Hydrogen 1s – 2s Spectroscopy



(Haensch, et al., Max Planck Soc., Garching)
http://www.mpq.mpg.de/~haensch/hydrogen/h.html



Many fewer antihydrogen atoms will be available

Summary

Antiproton magnetic moment

Build on our observations of single proton spin flips to make it possible to make more accurate measurements – during the shutdown.

Be ready to make more precise antiproton measurements when antiprotons are again available.

Antihydrogen

Produce and test a vacuum enclosure for the Ioffe trap.

Be ready to trap antihydrogen in the second generation Penning-Ioffe trap, and then move toward Lyman alpha cooling of trapped antiydrogen atoms