Testing the Symmetries and Most Precise Prediction of the Standard Model with a Single Particle or Antiparticle

Gerald Gabrielse
Leverett Professor of Physics, Harvard University
Spokesperson of the CERN ATRAP Collaboration

Supported by NSF and AFOSR

27 Years Since We First Trapped and Then Cooled Antiprotons

1981 – came to Fermilab wanting to do this in the electron cooler ring → found "TEV or Bust" (and Bill Kells)

1986 – headed to CERN

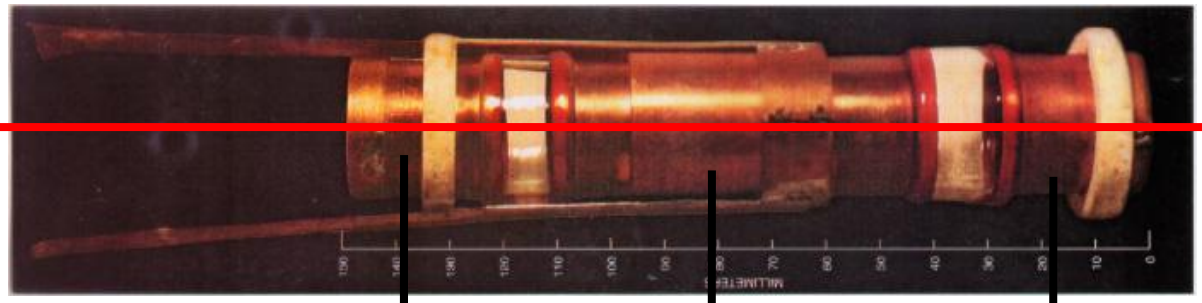
27 Years Since We First Trapped and Then Cooled Antiprotons

TRAP Collaboration
at CERN's LEAR

1 cm

magnetic field

21 MeV antiprotons



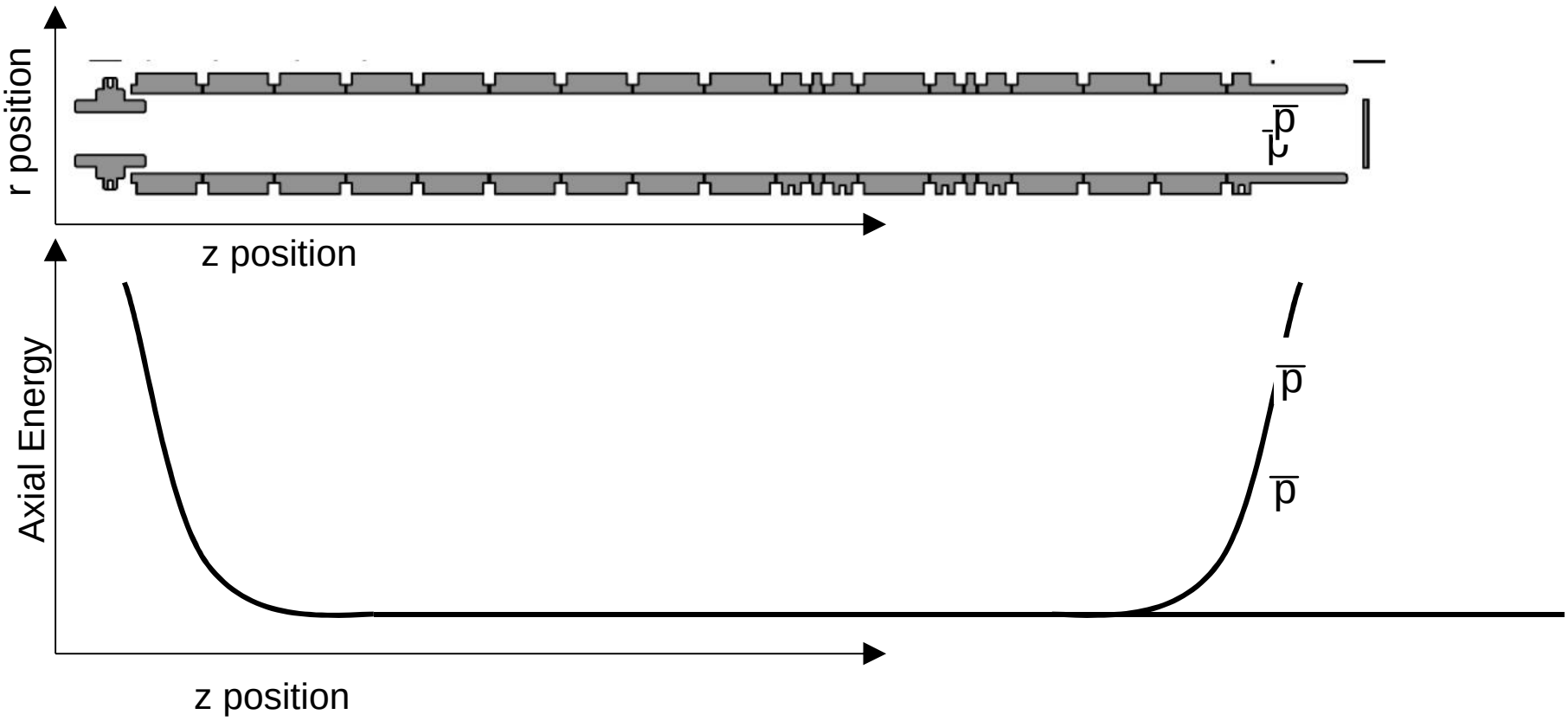
10^{-10} energy reduction

– + –

- **Slow antiprotons in matter**
- **Capture antiprotons in flight**
- **Electron cooling → 4.2 K**
- **5 x 10^{-17} Torr**

Now used by 5 collaborations
at the CERN AD
ATRAP, ALPHA, ASACUSA,
AEGIS, BASE

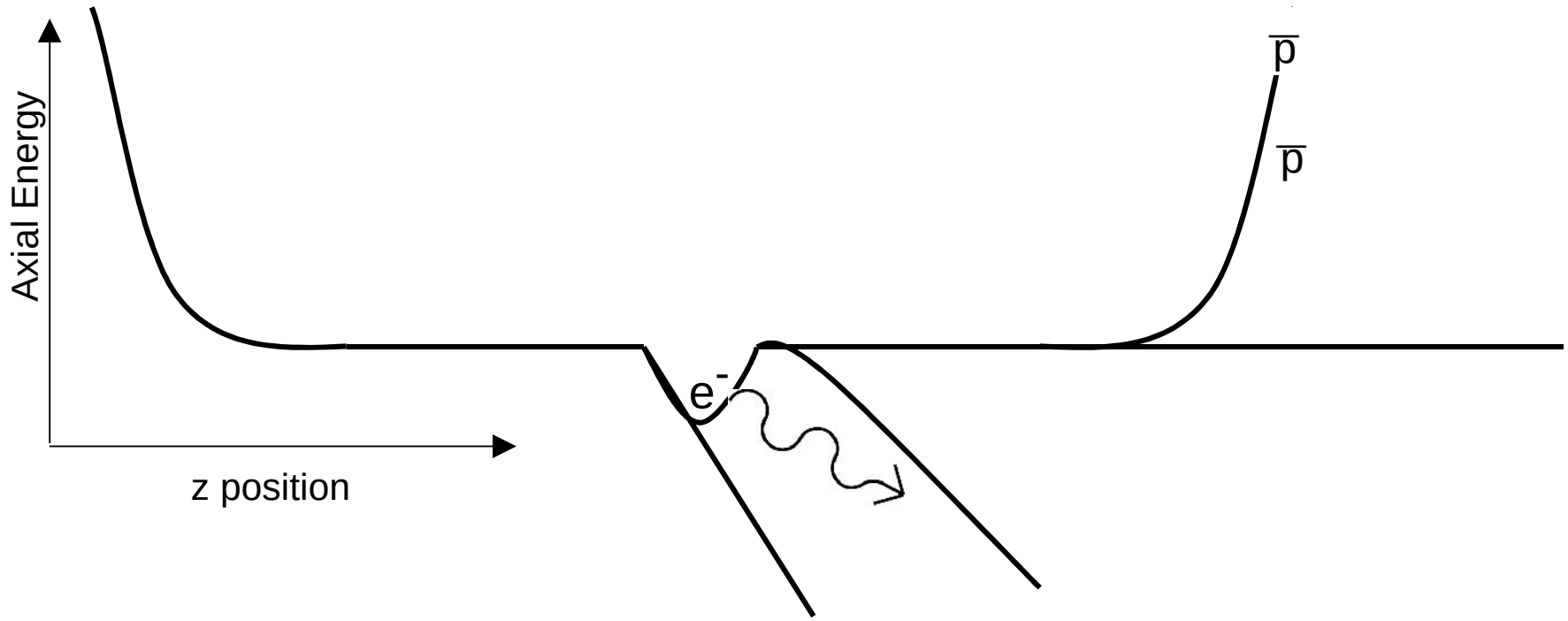
Antiproton Capture – the Movie



"First Capture of Antiprotons in a Penning Trap: A KeV Source",
G. Gabrielse, X. Fei, K. Helmerson, S.L. Rolston, R. Tjoelker, T.A. Trainor, H. Kalinowsky, J. Haas, and W. Kells;
Phys. Rev. Lett. 57, 2504 (1986).

Electron-Cooling of Antiprotons – in a Trap

- Antiprotons cool via collisions with electrons
- Electrons radiate away excess energy



"Cooling and Slowing of Trapped Antiprotons Below 100 meV",
G. Gabrielse, X. Fei, L.A. Orozco, R. Tjoelker, J. Haas, H. Kalinowsky, T.A. Trainor, W. Kells;
Phys. Rev. Lett. 63, 1360 (1989).

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. ..."

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- **Use accurate laser spectroscopy to compare antihydrogen and hydrogen**

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  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)

Why Compare Matter and Antimatter

Start general

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

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

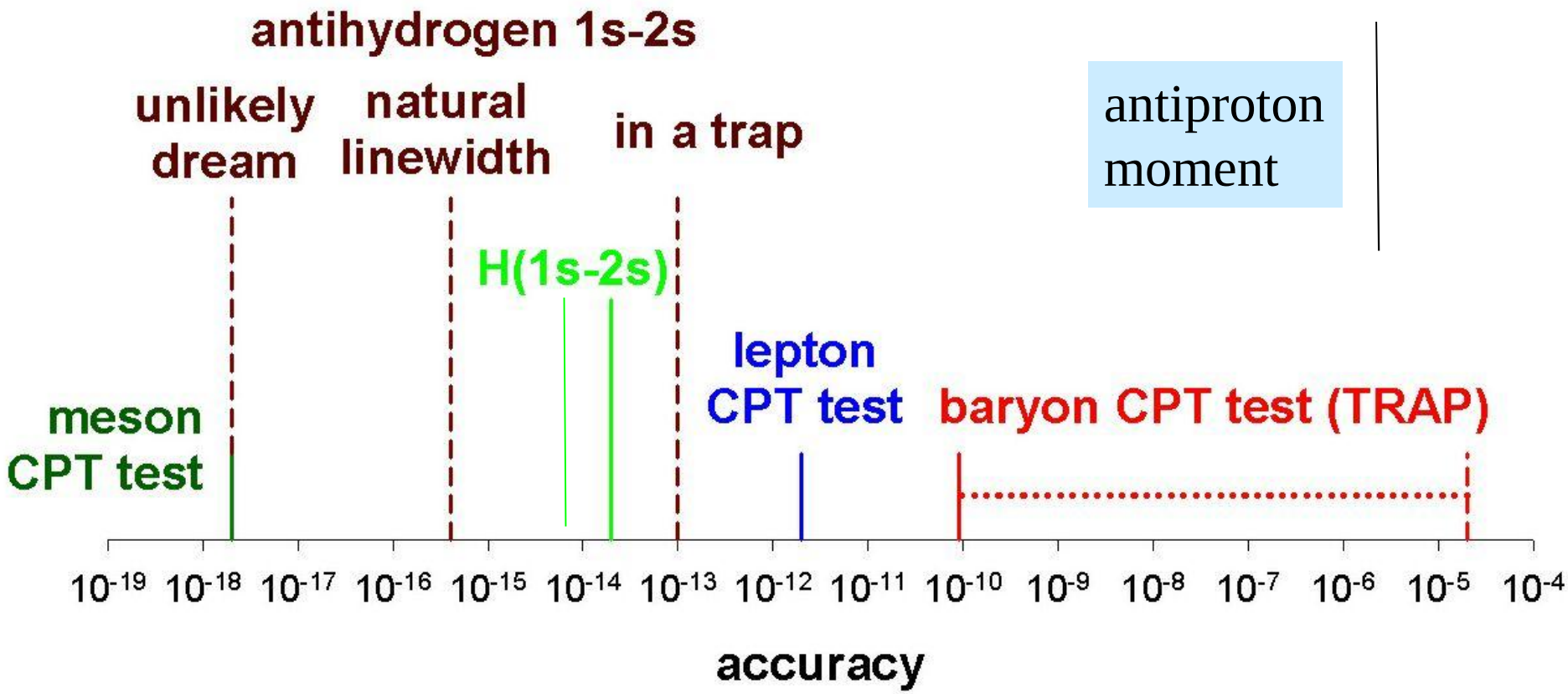
Warning – without CPT violation models it is hard to compare

3 fundamentally different types of particles

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

improve with antihydrogen

Seek to Improve Lepton and Baryon CPT Tests



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

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).

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

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

(most precise result of CERN's antiproton program)

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

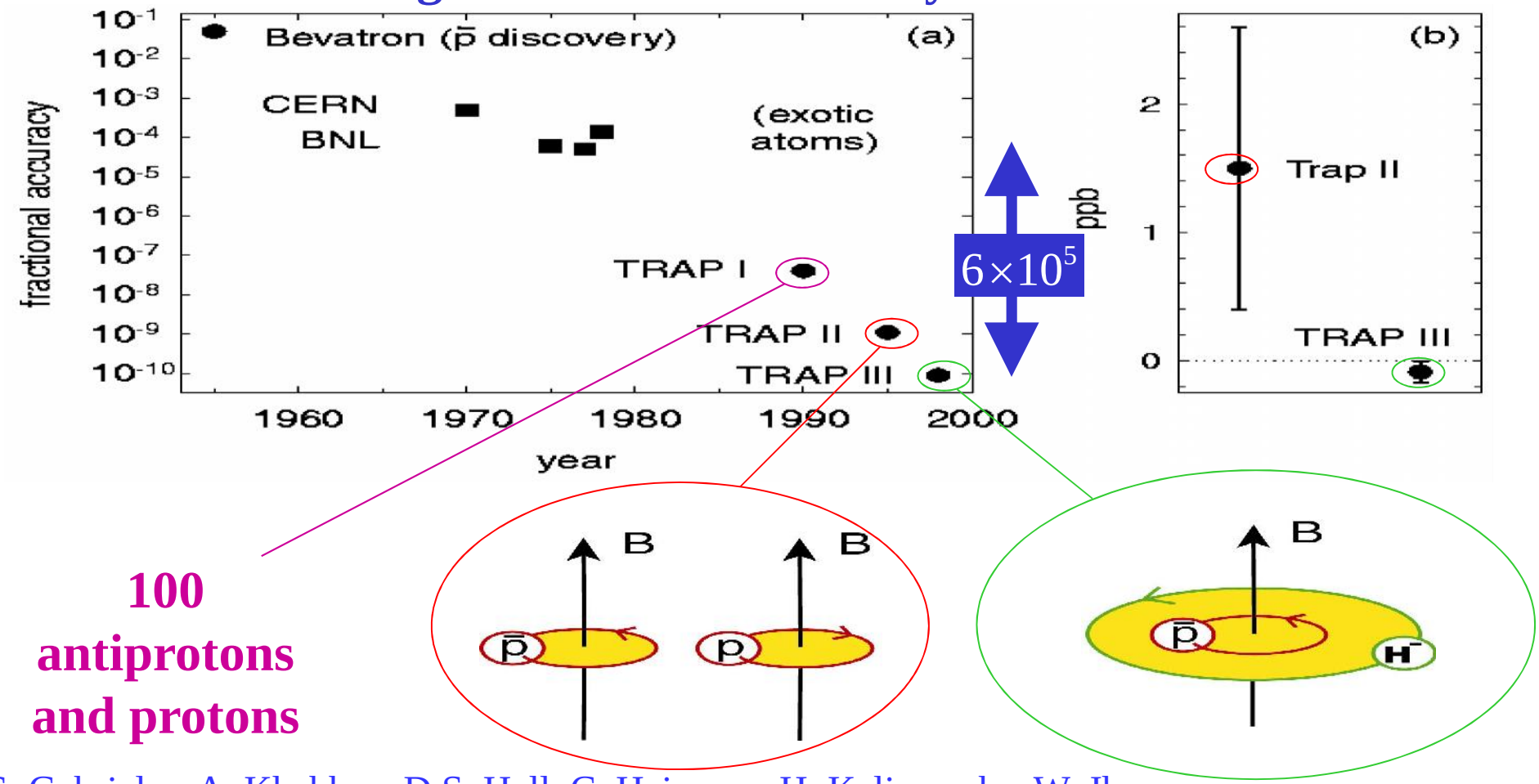
Gabrielse

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

$$\frac{q/m\ \text{(antiproton)}}{q/m\ \text{(proton)}} = -0.999999999\,91(9)$$

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

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).

Precision Measurements with Antimatter and Matter

what may be possible

Antiproton-Proton Comparisons

- q/m TRAP x 100
- gravity x 100
- q and m TRAP and ASACUSA (indirect)
- magnetic moment ATRAP x 10000

Positron-Electron Comparisons

- magnetic moment UW
- magnetic moment Harvard (in progress) x 15

Antihydrogen-Hydrogen Comparisons – no interesting comparisons

Digression: 12 time more precise measurement of the electron EDM (electric dipole moment) x 30

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Direct Comparison of Antimatter and Matter Gravity

Does antimatter and matter accelerate at the same rate in a gravitational field?

$$g_{antimatter} =© g_{matter}$$

acceleration due to gravity for antimatter

acceleration due to gravity for matter

The Most Precise Experimental Answer is "Yes" → to at lease a precision of 1 part per million

Gravitational red shift for a clock: $\Delta\mu / \mu = g\,h / c^2$

→ Antimatter and matter clocks run at different rates if g is different for antimatter and matter

$$\frac{\Delta\mu_c}{\mu_c} = 3(© - 1)\frac{U}{c^2}$$

Hughes and Holzscheiter, Phys. Rev. Lett. 66, 854 (1991).

for tensor gravity (would be 1 for scalar gravity)

grav. pot. rnergy difference between empty flat space time and inside of hypercluster of galaxies

Experiment: TRAP Collaboration, Phys. Rev. Lett. 82, 3198 (1999).

$$\frac{\Delta\mu_c}{\mu_{\partial c}} < 10^{-10} \quad --> \quad © = 1 \pm \ (< 10^{-6})$$

Comparable limit to that on neutrinos and antineutrinos 1987A

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Hard to Get the Part per Million Precision of the Redshift Limit with Antihydrogen and Hydrogen

$$g_{antimatter} = © \, g_{matter}$$

Our TRAP gravitational redshift: $\frac{\Delta\mu_c}{\mu_{\partial c}} < 10^{-10}$

$$--> \quad 0.999999 < © < 1.000001$$

ALPHA trapped antihydrogen released (2013): $-110 < © < 110$

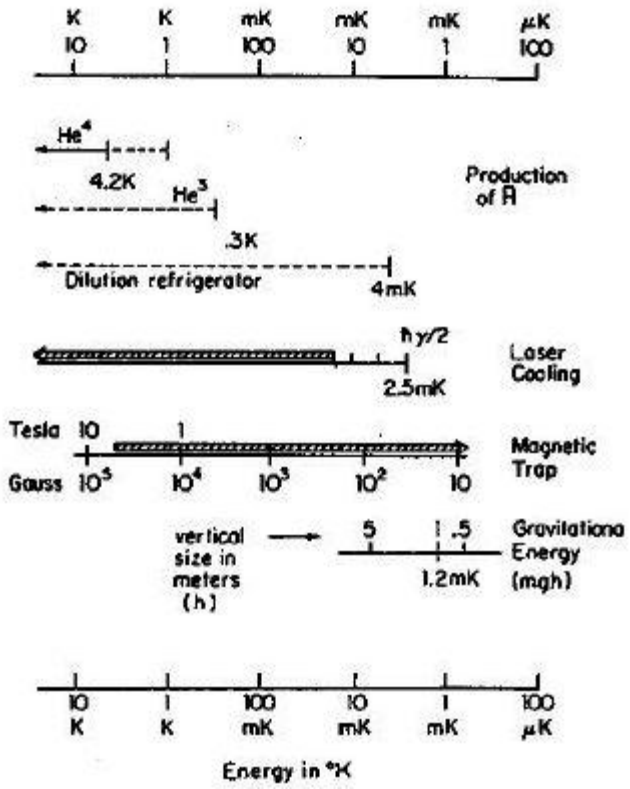
Gravity and Antihydrogen

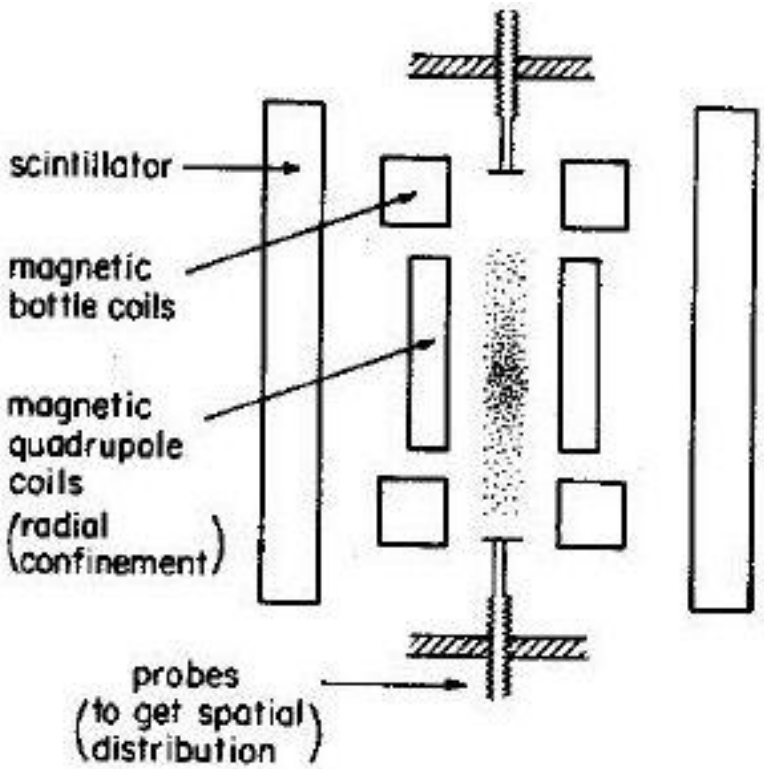
Hyperfine Interactions 44 (1988) 349–356

TRAPPED ANTIHYDROGEN FOR SPECTROSCOPY AND GRAVITATION STUDIES: IS IT POSSIBLE?

G. GABRIELSE

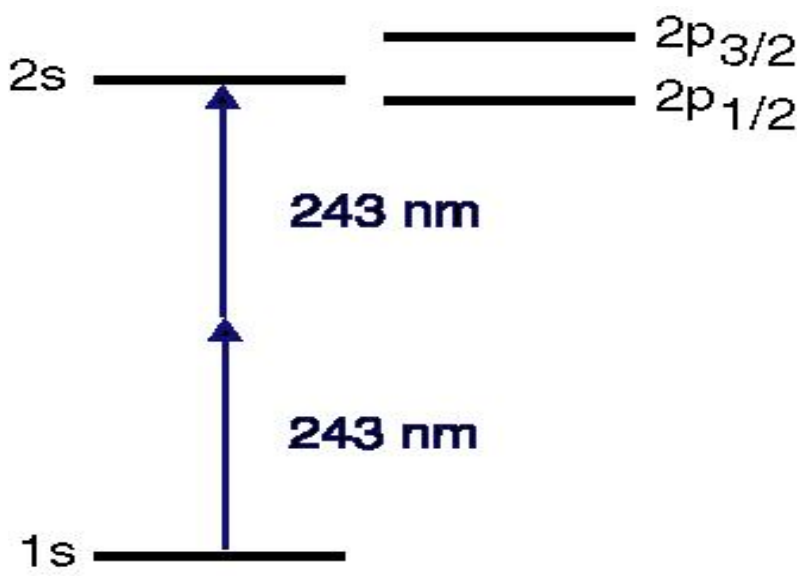
Department of Physics, Harvard University, Cambridge, MA 02138, U.S.A.

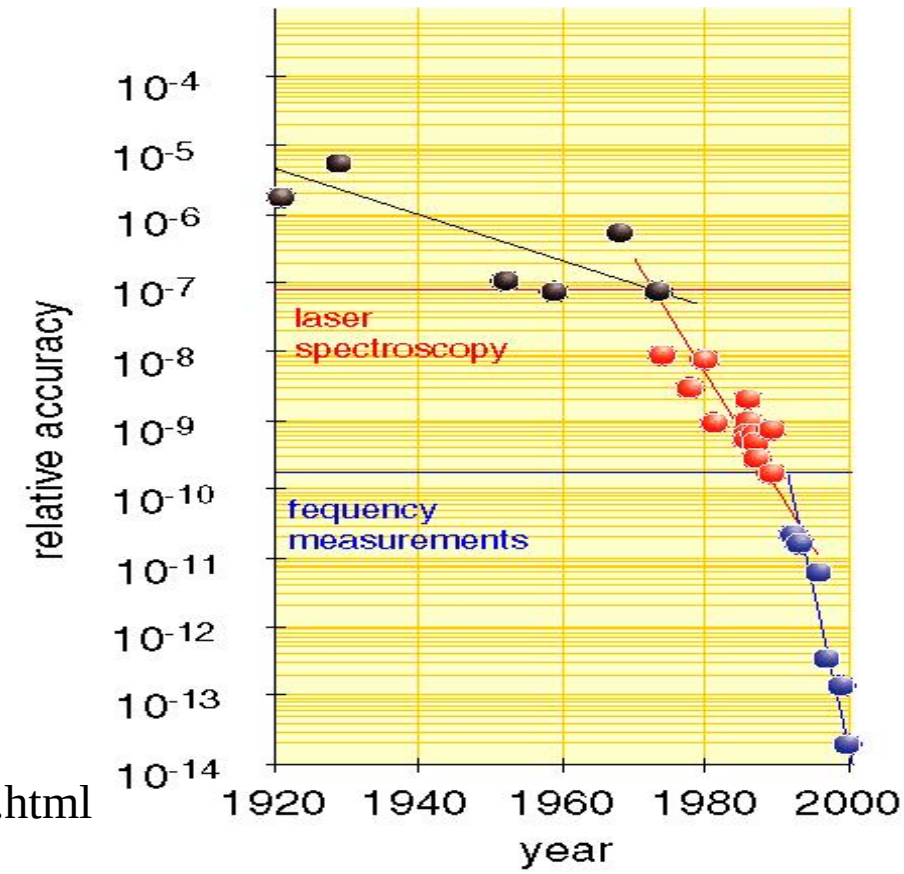




Antihydrogen Hope for the Future

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

Proposal to Trap Cold Antihydrogen – 1986

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Magnetic Moments
Can be Measured Very Precisely

e.g. Electron magnetic moment is the most precisely measured property of an elementary particle

Electron Magnetic Moment

electron magnetic moment

$$\vec{\mu} = -g\mu_B \frac{\vec{L}}{\hbar}$$

angular momentum

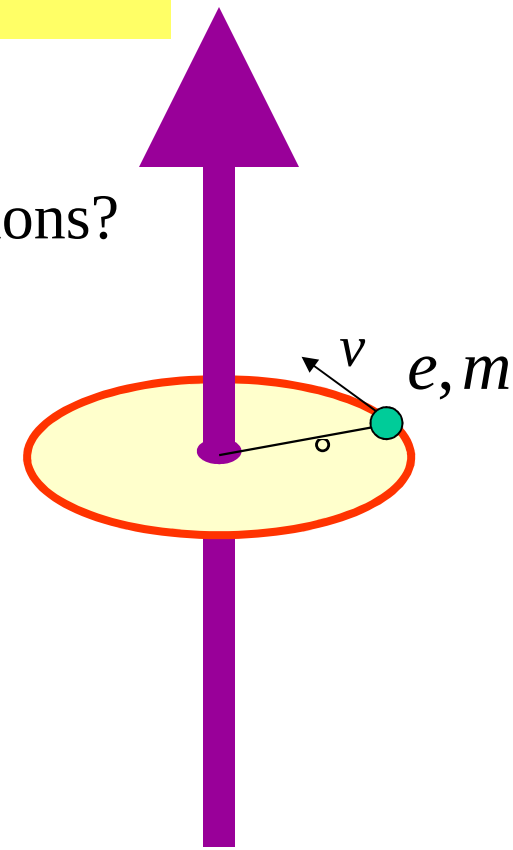
Bohr magneton $\frac{e\hbar}{2m}$

e.g. What is g for identical charge and mass distributions?

$$\mu = IA = \frac{-e}{\left(\frac{2\pi r}{v}\right)}(\pi r^2) = -\frac{ev r}{2}\frac{L}{mvr} = -\frac{e}{2m}L = -\frac{e\hbar}{2m}\frac{L}{\hbar}$$

μ_B

$$\rightarrow \quad g = 1$$



Electron Magnetic Moment

magnetic moment $\vec{\mu} = -\frac{g}{2}\mu_B \frac{\vec{S}}{\hbar/2}$ ← angular momentum

Bohr magneton $\frac{e\hbar}{2m}$

g/2 = magnetic moment in Bohr magnetons for spin 1/2

$g = 1$ mechanical model with identical charge and mass distribution

$g = 2$ spin for simple Dirac point particle

$g = 2.002\ 319\ 304\ ...$ simplest Dirac spin, plus QED

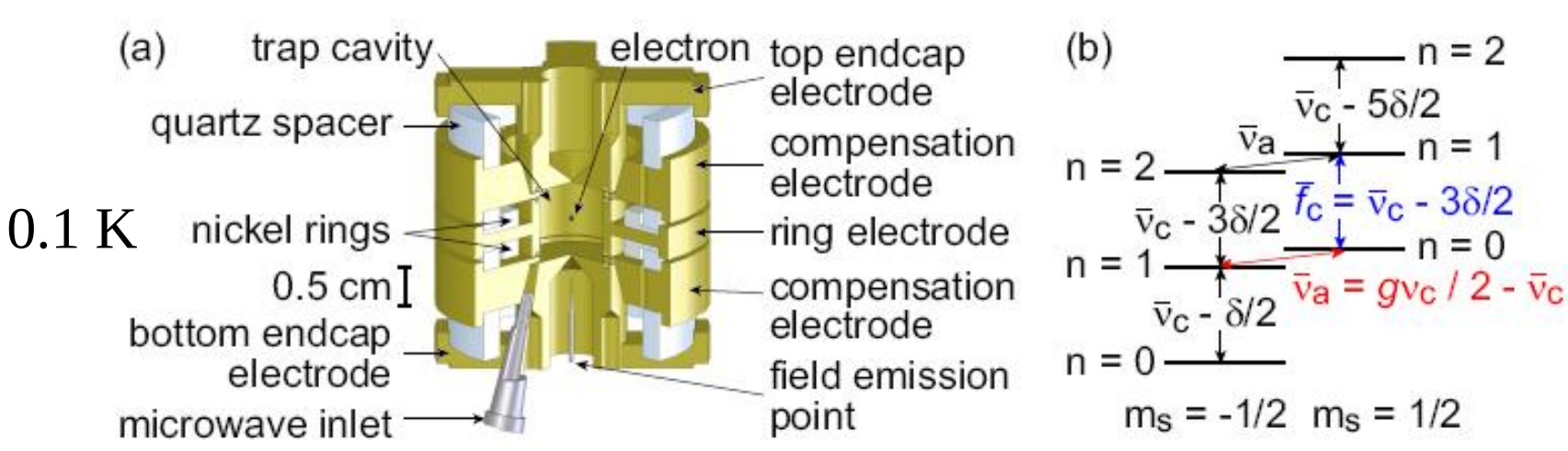
(if electron g is different → electron has substructure)

Proton and Antiproton Magnetic Moments are Much Smaller

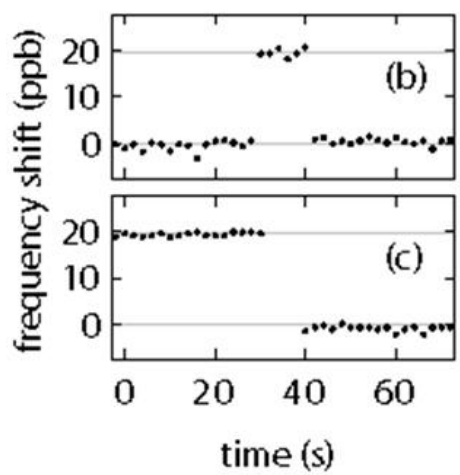
Harder: nuclear magneton rather than Bohr magneton

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

One Electron: Resolve One-Quantum Excitation



QND observations of one-quantum transitions



one quantum cyclotron excitation

spin flip

"Single-Particle Self-excited Oscillator",
B. D'Urso, R. Van Handel, B. Odom and G. Gabrielse
Phys. Rev. Lett. **94**, 113002 (2005).

Most precisely measured property of an elementary particle

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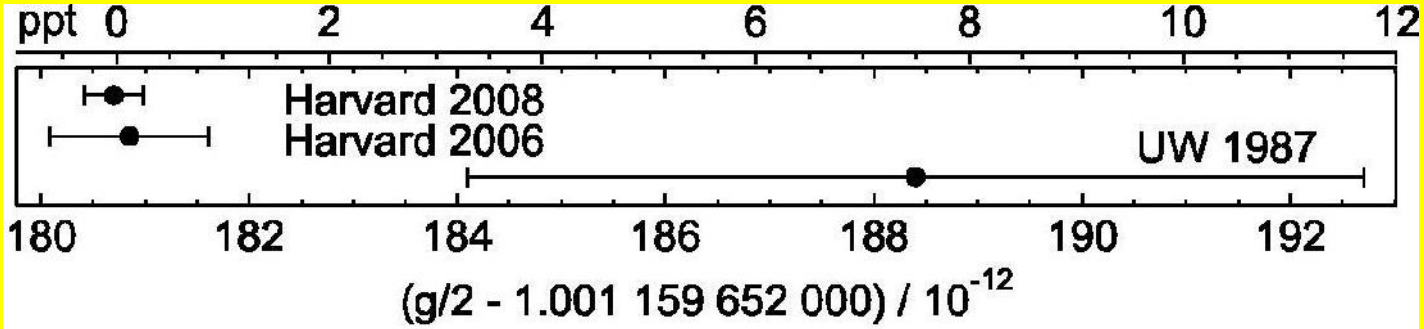
Electron Magnetic Moment Measured to 3 x 10^{-13}

2.8×10^{-13}



(improved measurement is currently underway)

electron magnetic moment in Bohr magnetons

trying to do as well with a as with an electron

"New Measurement of the Electron Magnetic Moment and the Fine Structure Constant"
D. Hanneke, S. Fogwell and G. Gabrielse,
Phys. Rev. Lett. **100**, 120801 (2008) and arXiv:0801.1134v1 [physics.atom-ph].

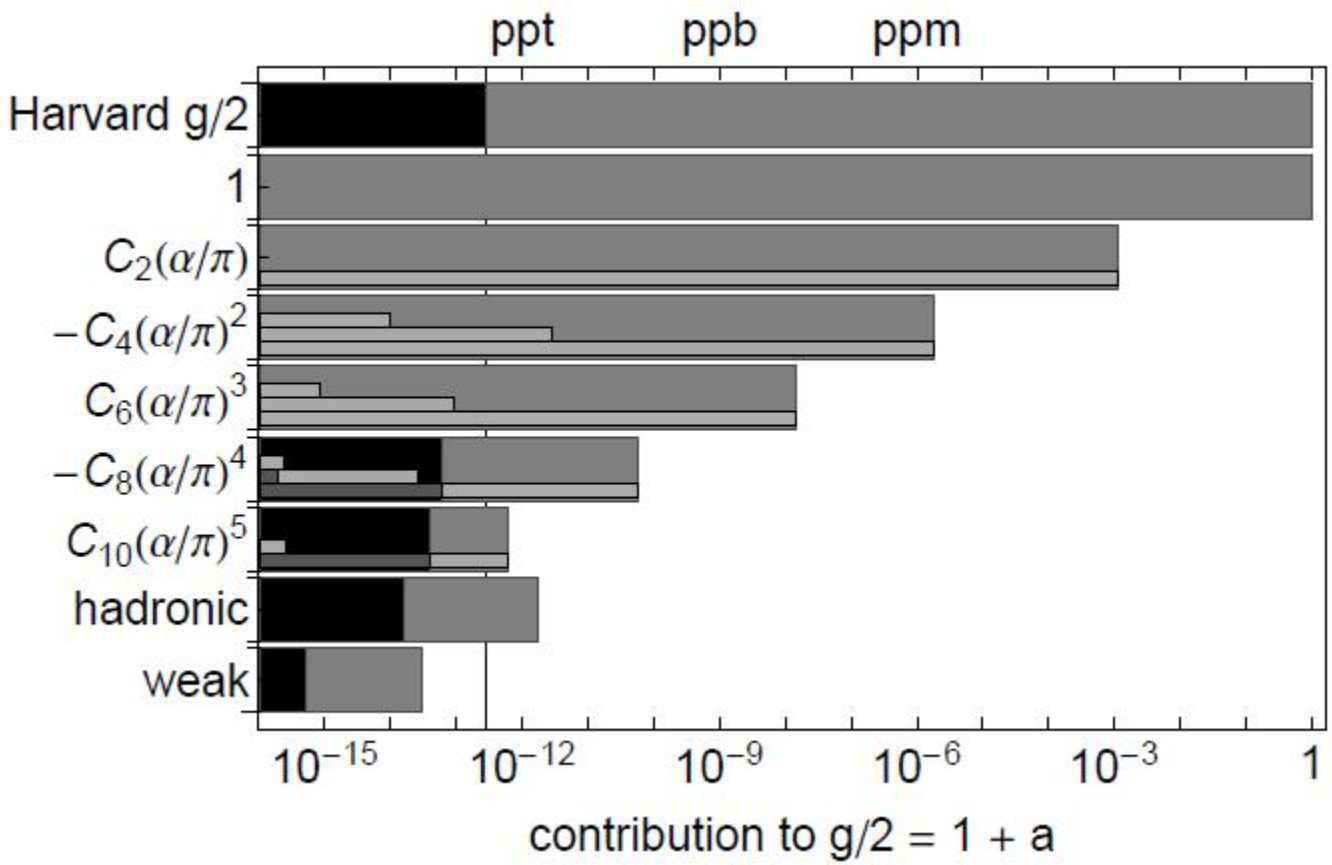
"Cavity Control of a Single-Electron Quantum Cyclotron: Measuring the Electron Magnetic Moment"
D. Hanneke, S. Fogwell Hoogerheide and G. Gabrielse,
Phys. Rev. A **83**, 052122 (2011).

$$\frac{g}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4$$

$$+ C_{10}\left(\frac{\alpha}{\pi}\right)^5 + \ldots + a_{\text{hadronic}} + a_{\text{weak}}$$

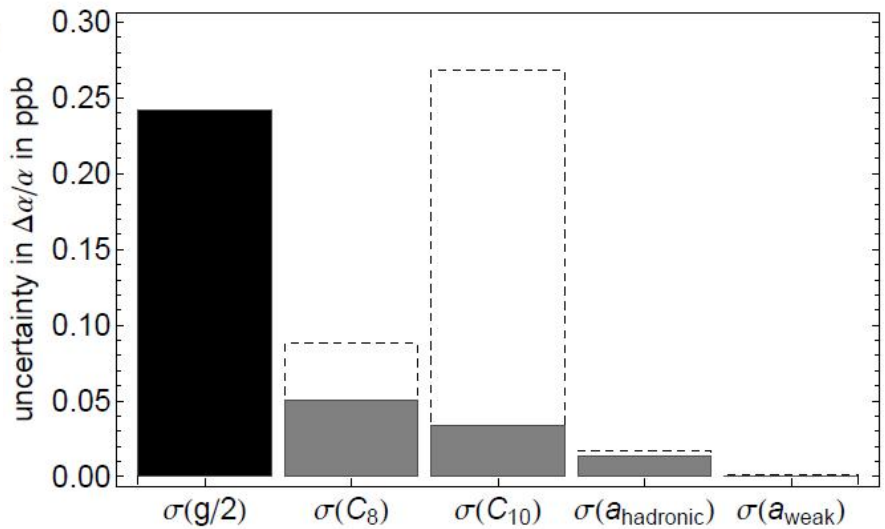
$$\begin{aligned}
C_2 &= 0.500\,000\,000\,000\,00 \text{ (exact)} \\
C_4 &= -\,0.328\,478\,444\,002\,55\,(33) \\
C_6 &= 1.181\,234\,016\,815\,(11) \\
C_8 &= -\,1.909\,7\,(20) \\
C_{10} &= 9.16\,(0.57).
\end{aligned}$$

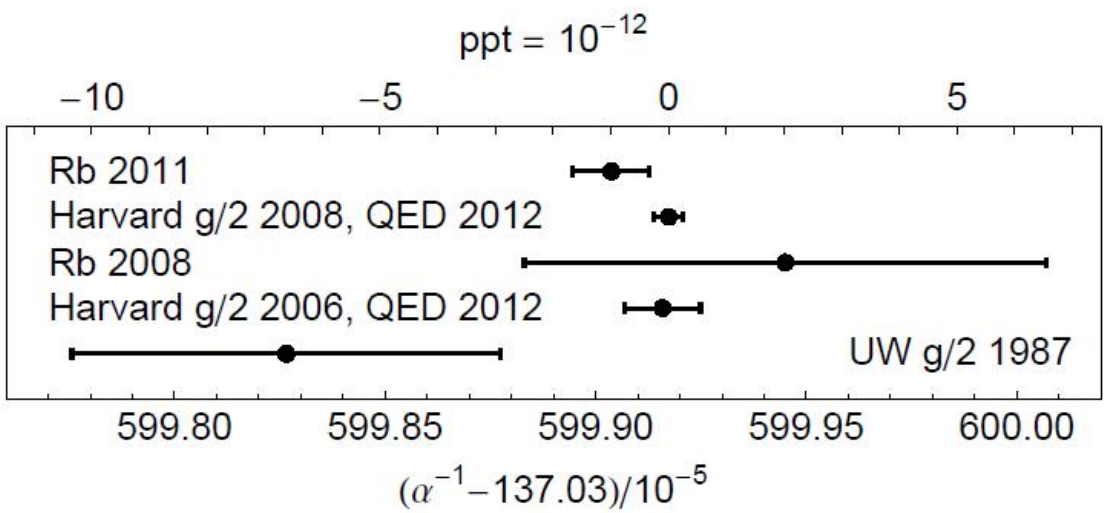
$$a_e^{\text{hadronic}} = 1.677(16) \times 10^{-12}$$


ppt
ppb
ppm
Harvard g/2
1
$C_2(\alpha/\pi)$
$-C_4(\alpha/\pi)^2$
$C_6(\alpha/\pi)^3$
$-C_8(\alpha/\pi)^4$
$C_{10}(\alpha/\pi)^5$
hadronic
weak
10^{-15}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
1
contribution to g/2 = 1 + a

Determine Fine Structure Constant

$$\alpha^{-1} = 137.035\,999\,173\,(33)\,(8) \quad [0.24\text{ ppb}]\,[0.06\text{ ppb}]$$
$$= 137.035\,999\,173\,(34) \qquad [0.25\text{ ppb}],$$





Next Most Precise Way to Determine a

PRL 106, 080801 (2011) PHYSICAL REVIEW LETTERS week ending 25 FEBRUARY 2011

New Determination of the Fine Structure Constant and Test of the Quantum Electrodynamics

Rym Bouchendira,[1] Pierre Cladé,[1] Saïda Guellati-Khélifa,[2] François Nez,[1] and François Biraben[1]
[1]Laboratoire Kastler Brossel, Ecole Normale Supérieure, Université Pierre et Marie Curie, CNRS, 4 place Jussieu, 75252 Paris Cedex 05, France
[2]Conservatoire National des Arts et Métiers, 292 rue Saint Martin, 75141 Paris Cedex 03, France

$$\sim \equiv \frac{1}{4®£_0}\frac{e^2}{hc} \qquad R_\infty \equiv \frac{1}{(4®£_0)^2}\frac{e^4 m_e c}{2h^3c^2}$$

$$\frac{h}{M_{Rb}} = 2c^2\frac{f_{recoil}}{(f)^2}$$

atom recoil velocity from 1000 photons

$$\sim = \frac{2R_\infty}{c}\frac{h}{M_{Rb}}\frac{M_{Cs}}{M_p}\frac{M_p}{m_e}$$

Haensch, …

Myers, …
Pritchard, …
Van Dyck, …

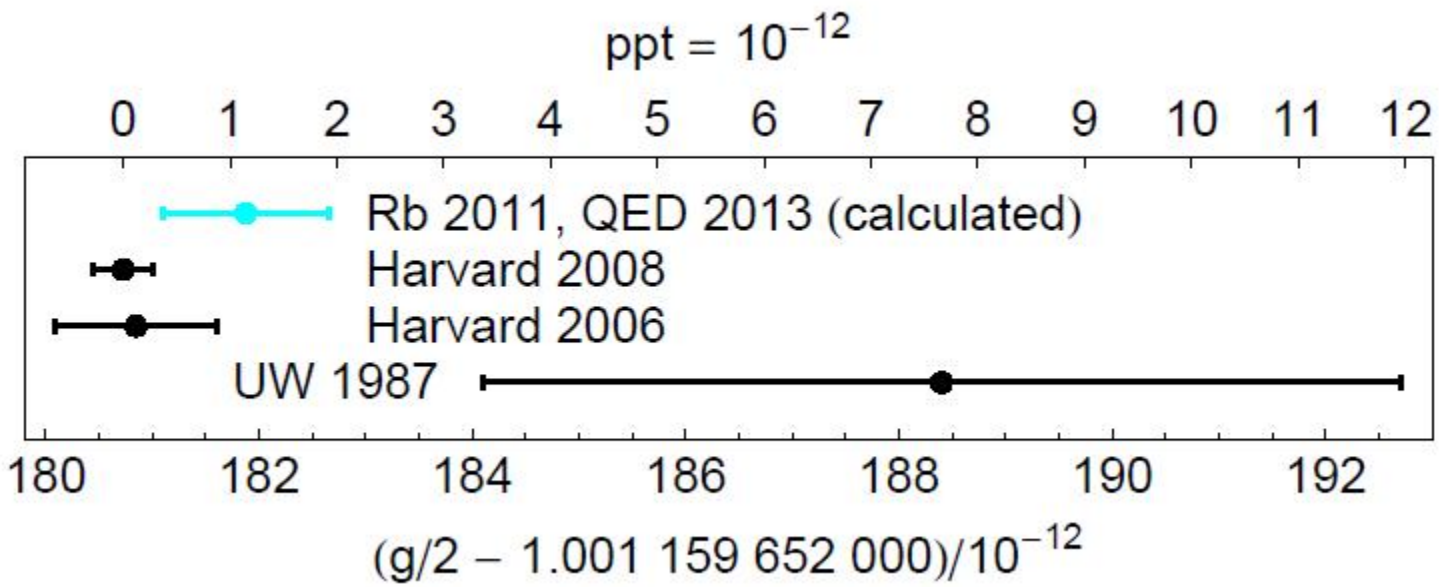
Quint, Blaum, …

Great Triumph of the Standard Model

Measured: $\mu/\mu_B = -g/2 = -1.001\,159\,652\,180\,73\,(28) \quad [0.28\ \text{ppt}].$

"Calculated": $\mu/\mu_B = -g/2 = -1.001\,159\,652\,181\,88\,(78)\ [0.77\ \text{ppt}]$

(Uncertainty from measured fine structure constant)



$$\frac{\mu - \mu(SM)}{\mu} = 0.000\,000\,000\,000\,15\ (82)\ [0.82\ \text{ppt}],$$

$$= 1.5\ (0.8) \times 10^{-12}\ [0.8\ \text{ppt}].$$

Can We Similarly Measure the Antiproton Magnetic Moment?

Proton and Antiproton Magnetic Moments are Much Smaller

Harder: nuclear magneton rather than Bohr magneton

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

Precise Proton Magnetic Moment Measurement

→ Most precise so far (0.01 ppm)

→ 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

MIT

Harvard

2 ppb or 0.7 ppb

UW

direct

bound electron magnetic moment

Mainz

ppb = 10^{-9}

Exotic Atom Measurements

→ Very low precision (3000 ppm)

→ Works only with an antiproton

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

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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

-1

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

we measured
to < 9 x10^{-11}

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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).

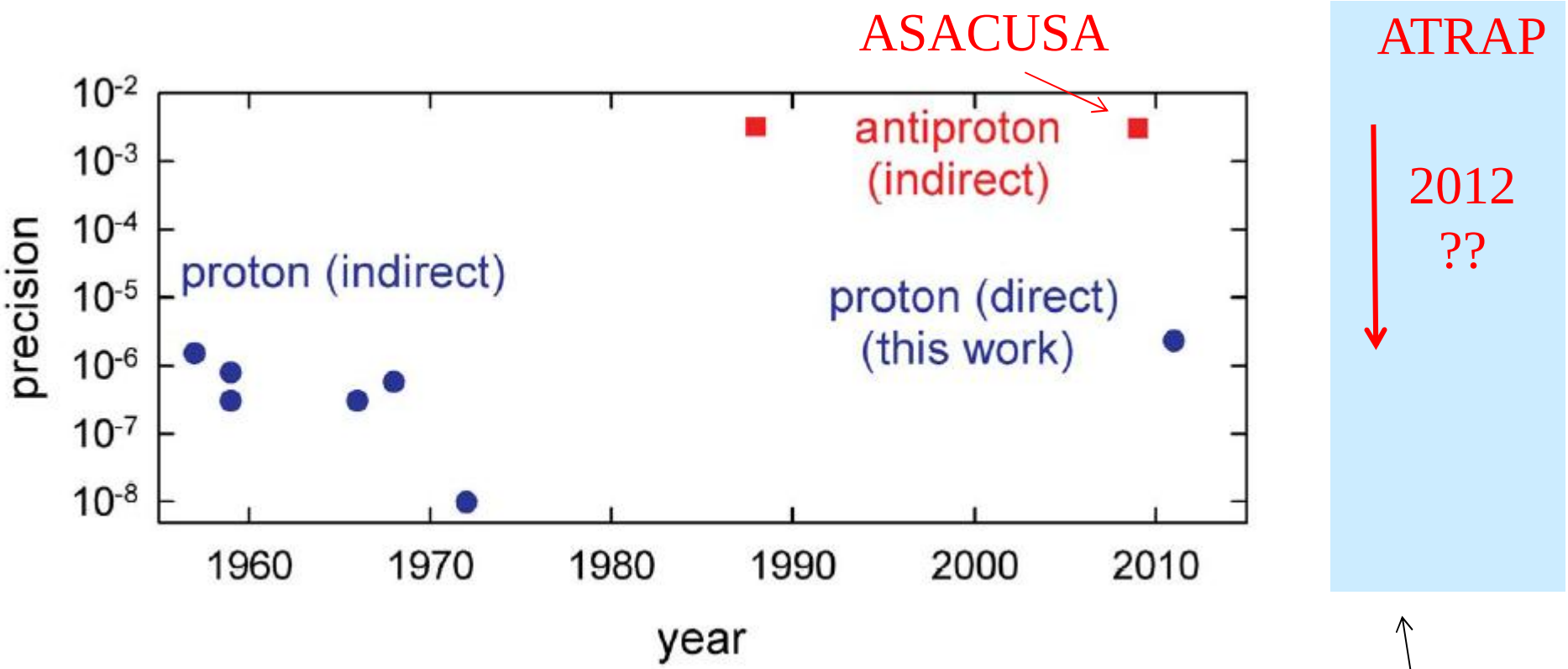
[14] S. Ulmer, C. C. Rodegheri, K. Blaum, H. Kracke, A. Mooser, W. Quint, and J. Walz, Phys. Rev. Lett. **106**, 253001 (2011).

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).

Gabrielse

Suggested Possibility of a Thousand-fold Improved Measurement of the Antiproton Moment



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

Expect to eventually be more precise than all proton measurements

Could We Adapt the Apparatus, Move to CERN, and Make the -- all in 2012?

Decided 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

Gabrielse

ATRAP Collaboration

G. Gabrielse[1], J. DiSciacca, S. Ettenauer, K. Marable, M. Marshall, E. Tardiff, R. Kalra
Department of Physics, Harvard University, Cambridge, MA 02138 USA

Walter Oelert, Dieter Grzonka, Thomas Sefzick, Marcin Zielinski
Institut für Kernphysik, Forschungszentrum Jülich, Germany

Eric Hessels, Cody Storry, Daniel Fitzakerley,
Matthew George, Matthew Weel
Department of Physics and Astronomy, York University,
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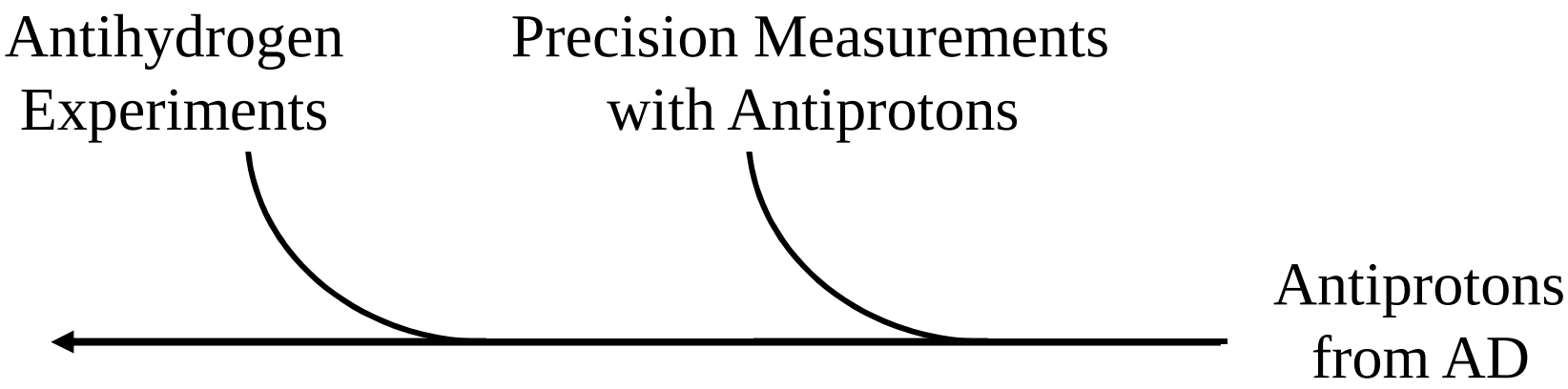
A. Müllers[2], J. Walz[2]
Institute für Physik, Johannes Gutenberg Universität Mainz, D55099, Mainz, Germany

[1]spokesperson,gabrielse@physics.harvard.edu
[2]antihydrogen studies only

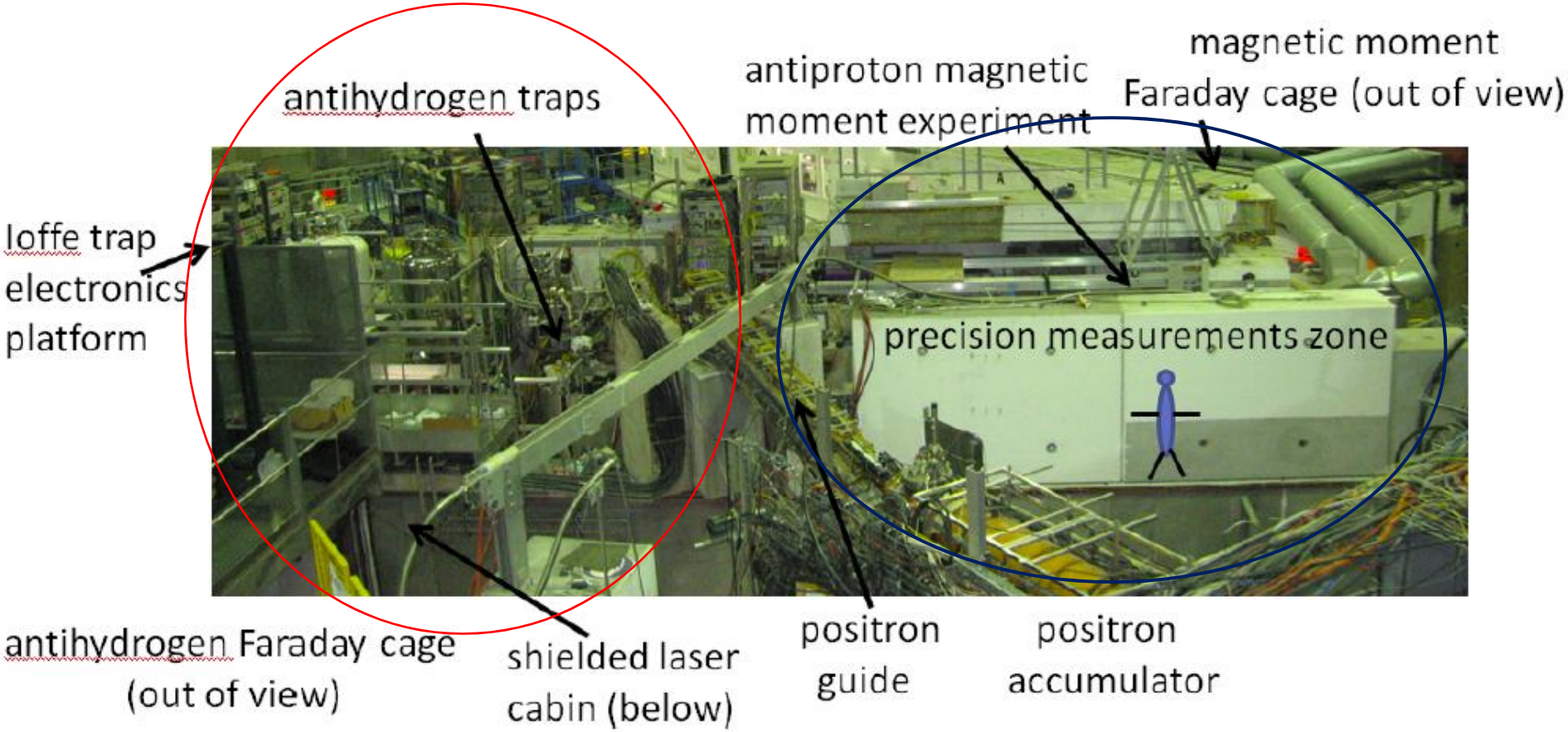
ATRAP Apparatus Built to do Two Types of Experiments Simultaneously



trapped antihydrogen in its ground state

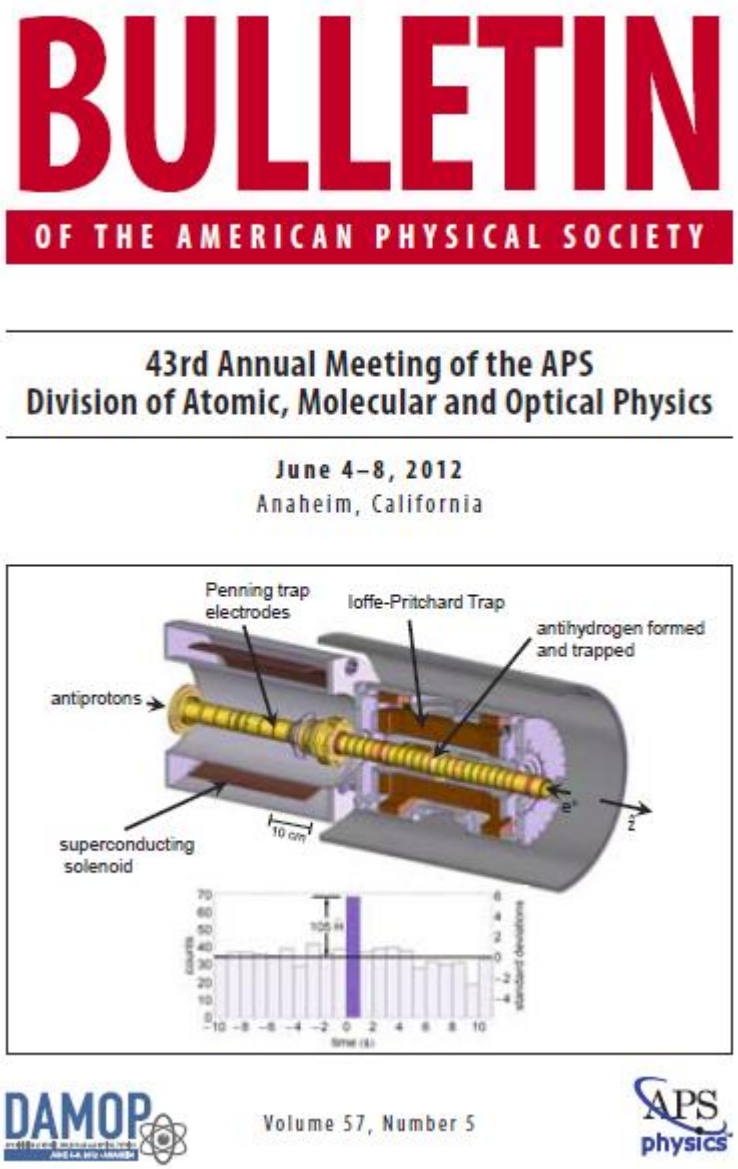
680-fold improved measurement of the antiproton magnetic motion

Simultaneous Antihydrogen Experiments and Precision Measurements



ATRAP Experimental Area

On the Antihydrogen Port:


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

DAMOP
Volume 57, Number 5
APS physics

5 +/- 1 ground state atoms simultaneously trapped

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

Accumulating Cold Antiprotons

(for all antihydrogen experiments as well as for the magnetic moment measurement)

Only Accessible Antiprotons are at CERN

France

Switzerland (Geneva)

- Unusual for AMO experiment to be done over an ocean
- Must conform to accelerator schedule
- Environment not very amenable to precise AMO methods
- No AMO funding source for facility upgrades
- Data rate is very slow

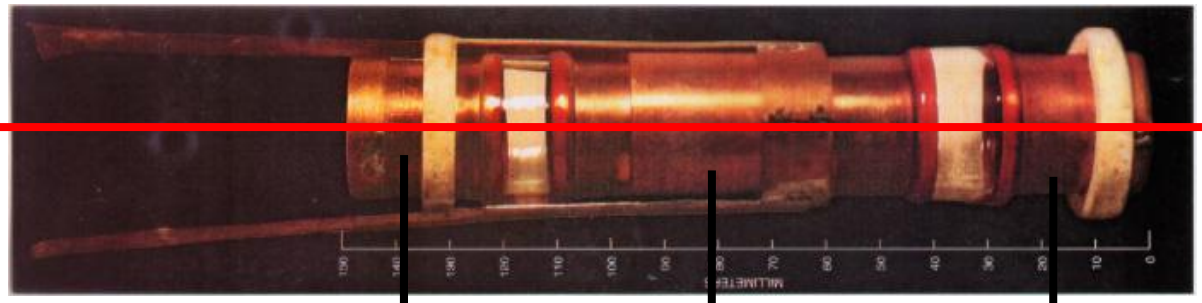
Accumulating Low Energy Antiprotons: Basic Ideas and Demonstrations (1986 – 2000)

TRAP Collaboration
at CERN's LEAR

1 cm

magnetic field

21 MeV antiprotons



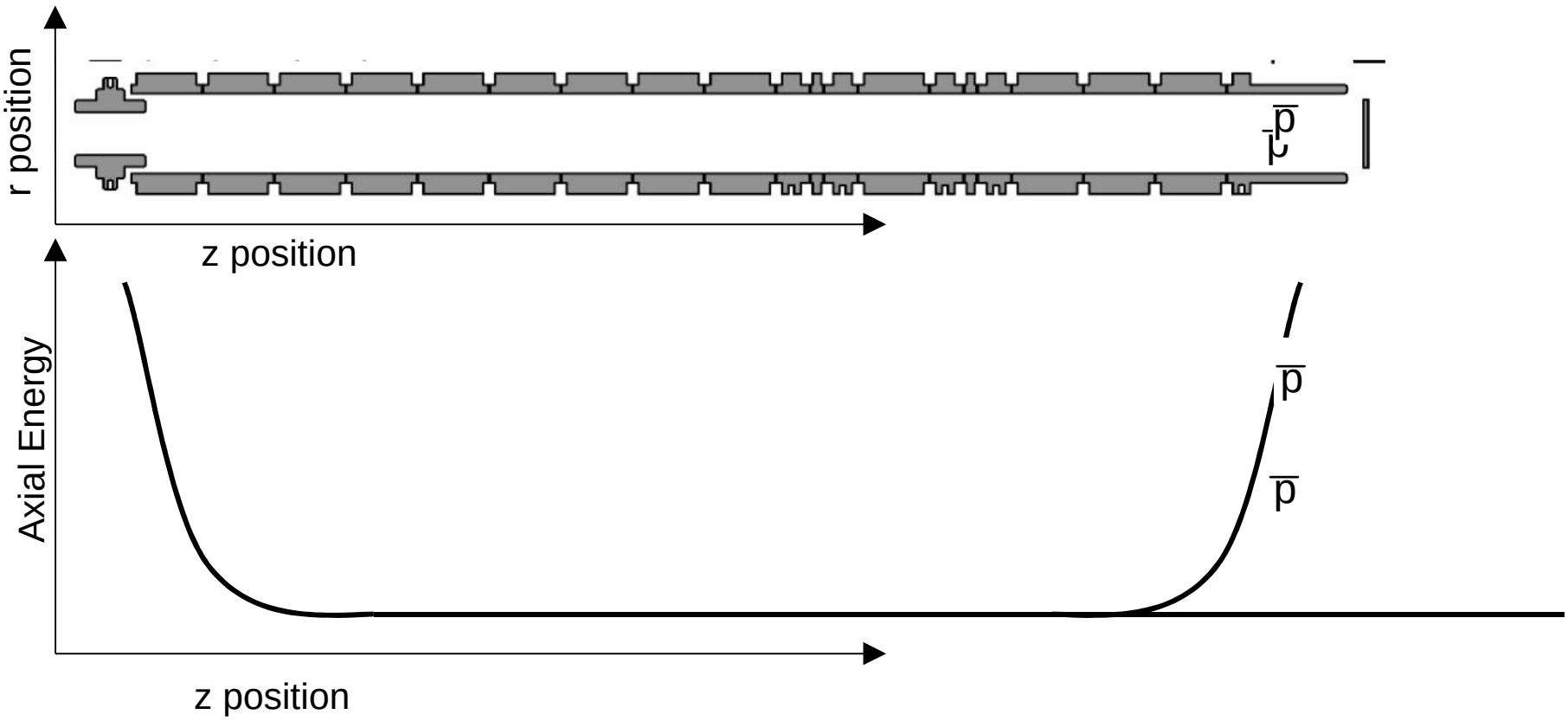
– + –

10^{-10} energy reduction

- **Slow antiprotons in matter**
- **Capture antiprotons in flight**
- **Electron cooling → 4.2 K**
- **5 x 10^{-17} Torr**

Now used by 5 collaborations
at the CERN AD
ATRAP, ALPHA, ASACUSA,
AEGIS, BLAZE

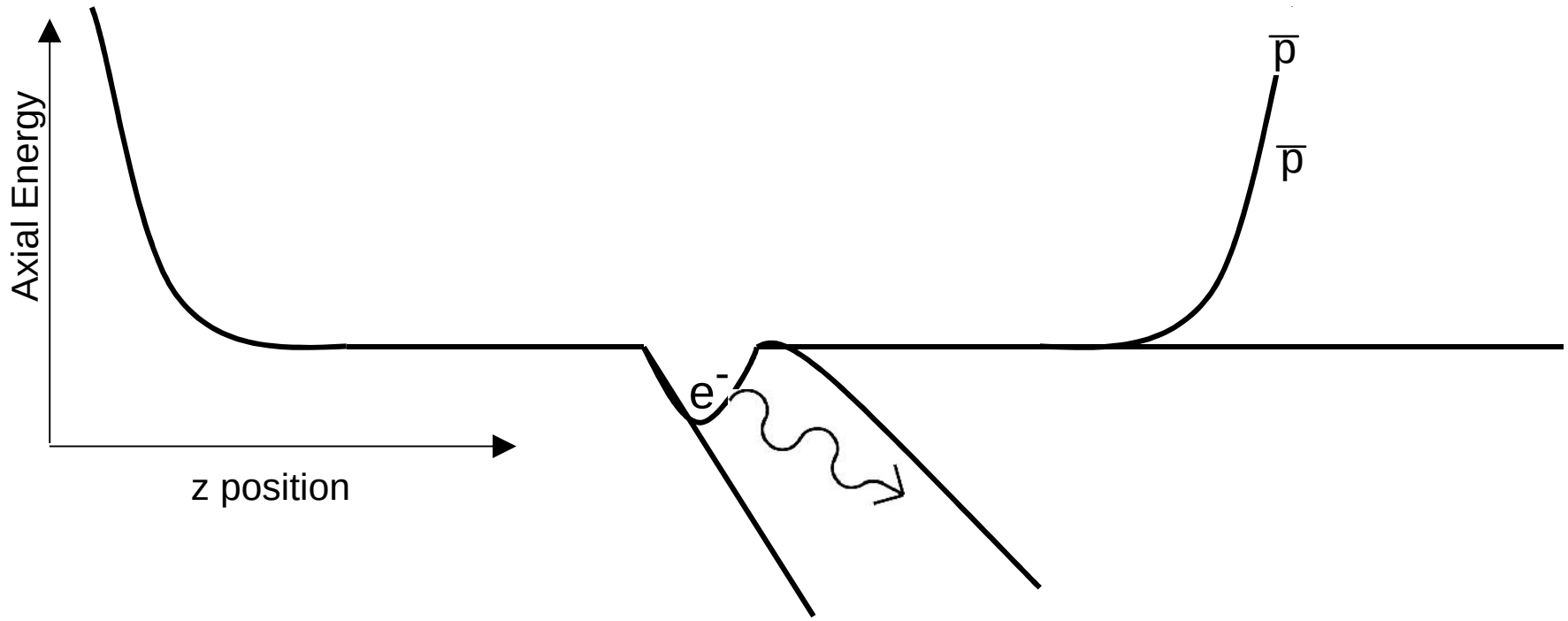
Antiproton Capture – the Movie



"First Capture of Antiprotons in a Penning Trap: A KeV Source",
G. Gabrielse, X. Fei, K. Helmerson, S.L. Rolston, R. Tjoelker, T.A. Trainor, H. Kalinowsky, J. Haas, and W. Kells;
Phys. Rev. Lett. 57, 2504 (1986).

Electron-Cooling of Antiprotons – in a Trap

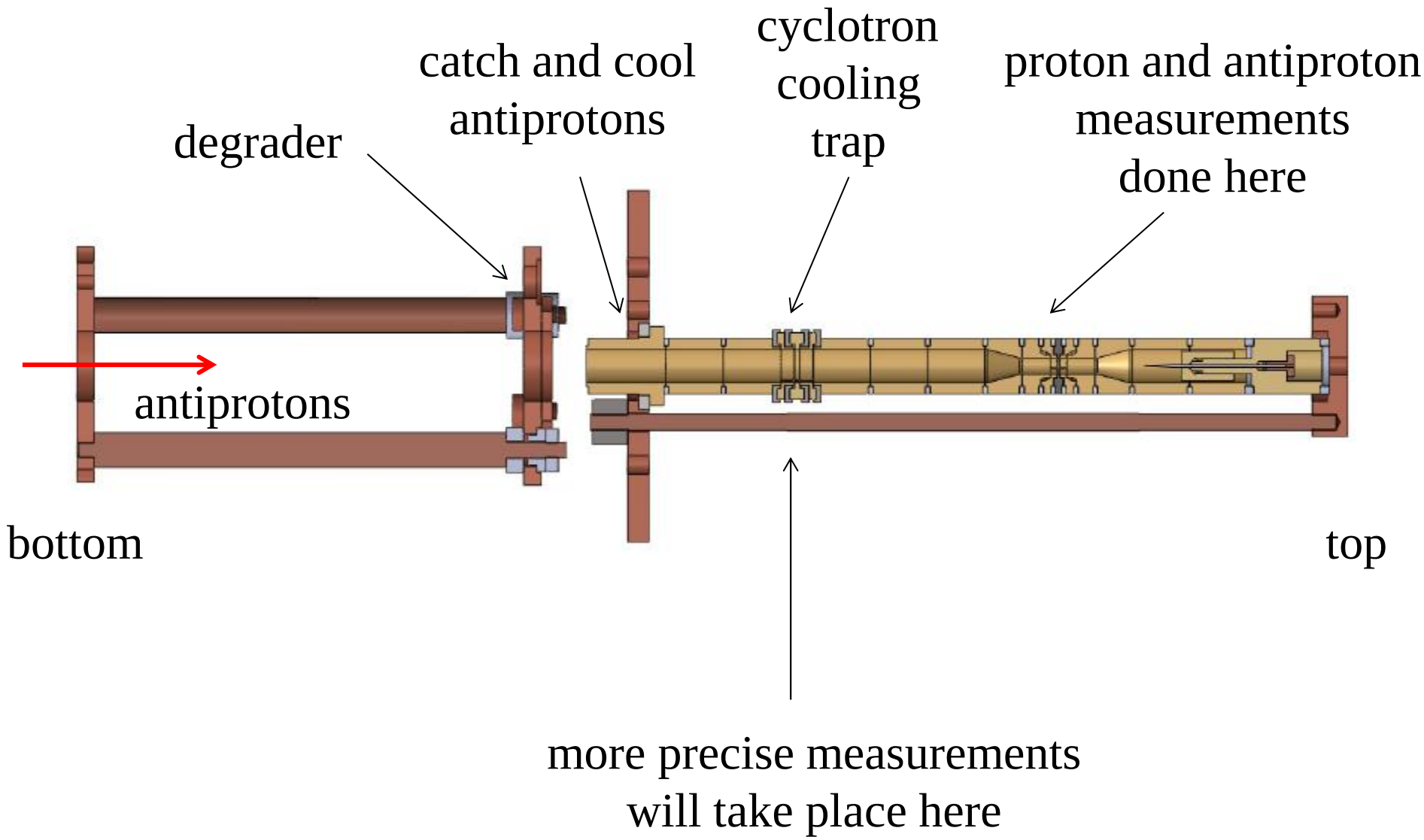
- Antiprotons cool via collisions with electrons
- Electrons radiate away excess energy



"Cooling and Slowing of Trapped Antiprotons Below 100 meV",
G. Gabrielse, X. Fei, L.A. Orozco, R. Tjoelker, J. Haas, H. Kalinowsky, T.A. Trainor, W. Kells;
Phys. Rev. Lett. 63, 1360 (1989).

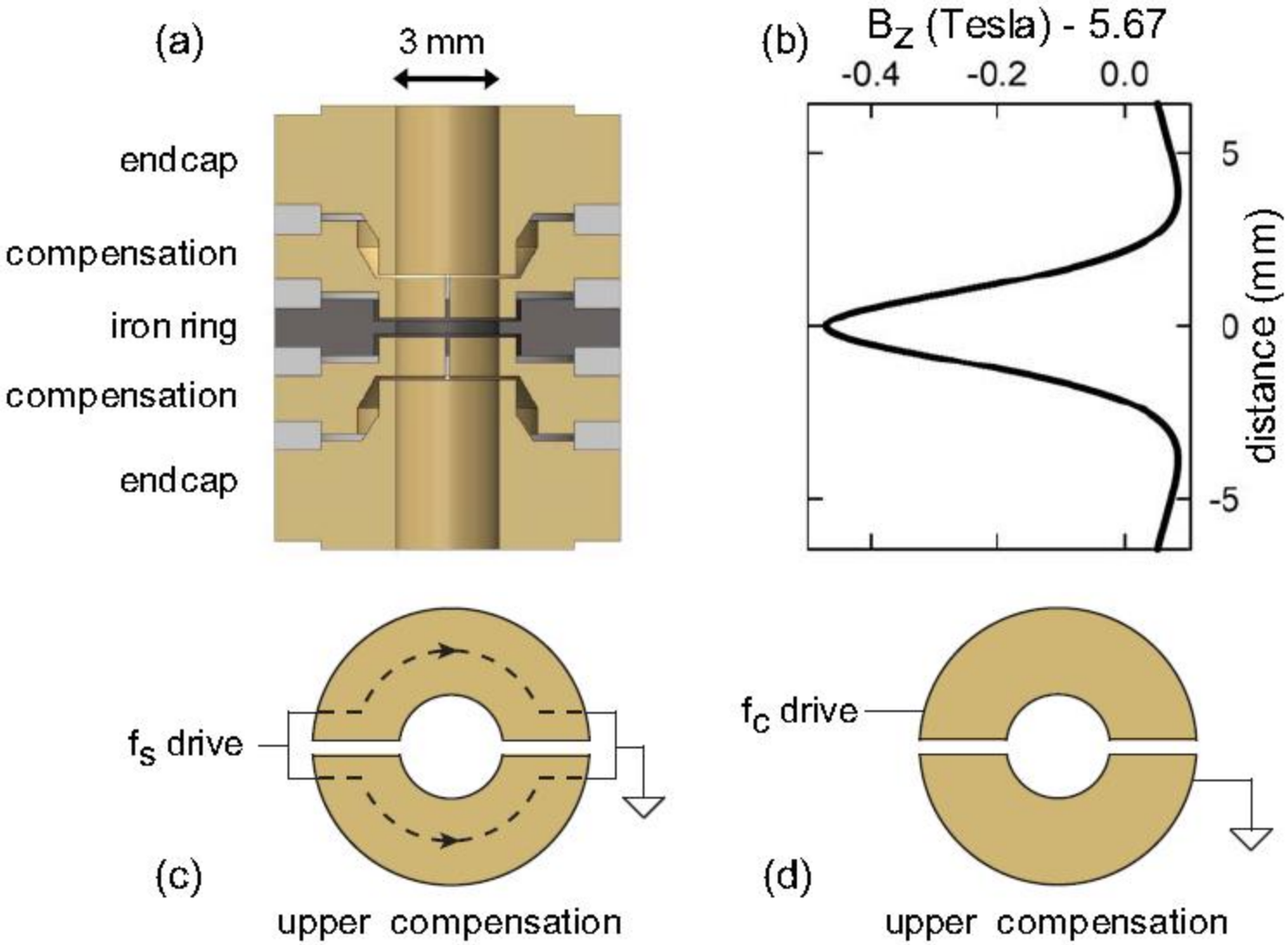
Antiproton Magnetic Moment Apparatus

For Magnetic Moments: Three Antiproton Traps



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

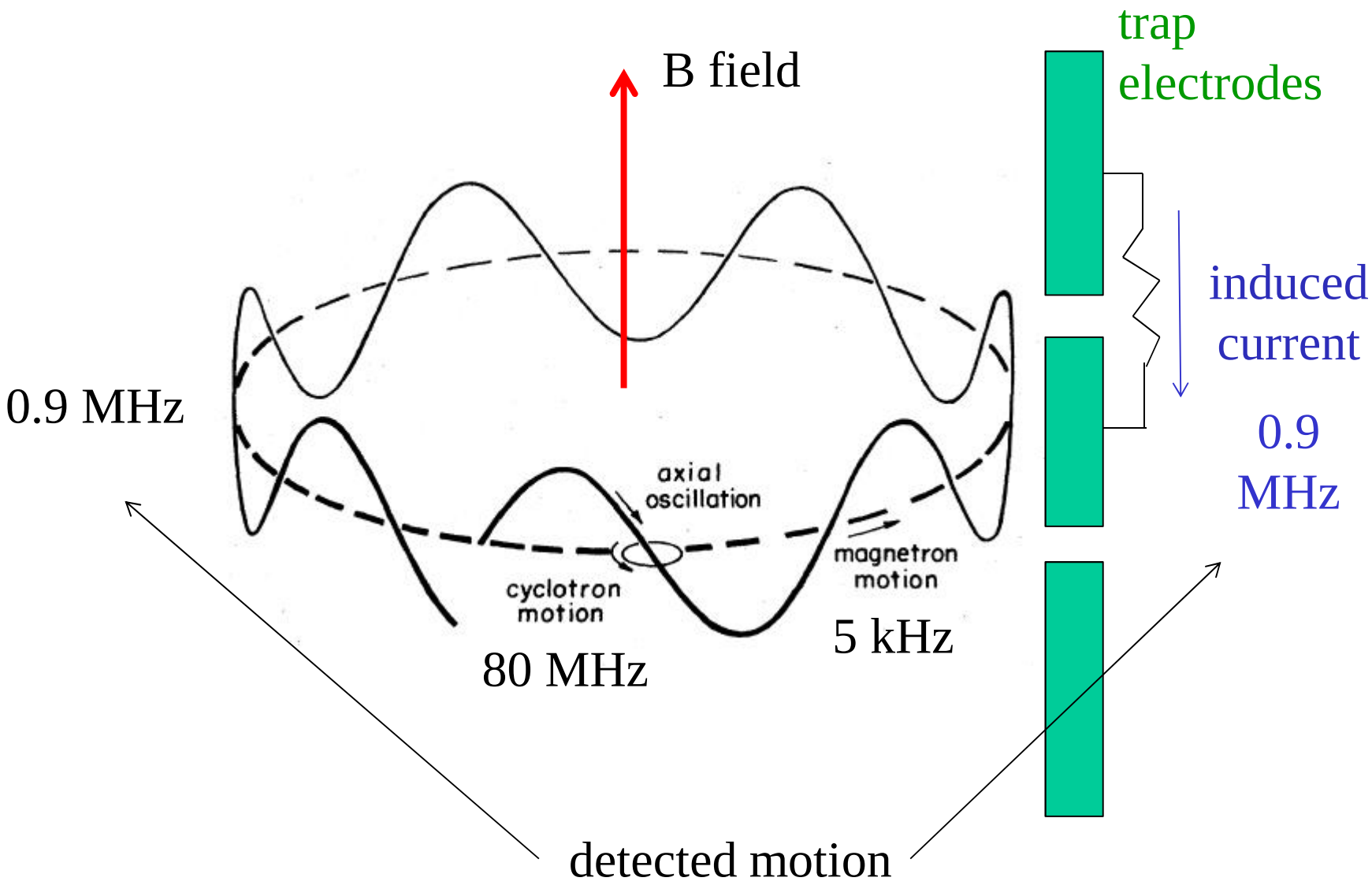
$$\frac{\mu_p}{\mu_N} \equiv \frac{g_p}{2} = \frac{f_s}{f_c}$$

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

Antiproton Orbits in a Penning Trap



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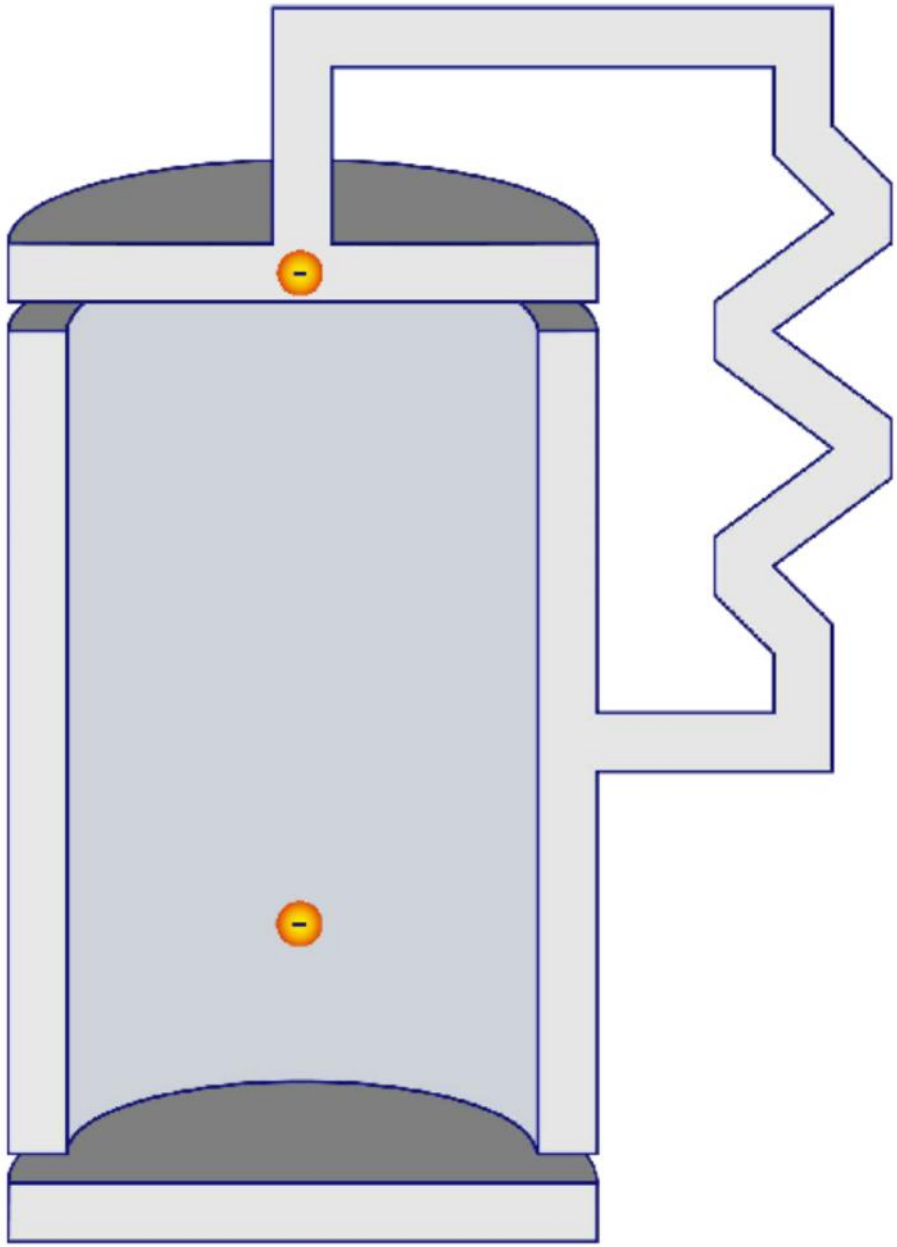
What We Directly Detect (SEO)



axial motion
1 MHz
of
trapped
electron

measure voltage

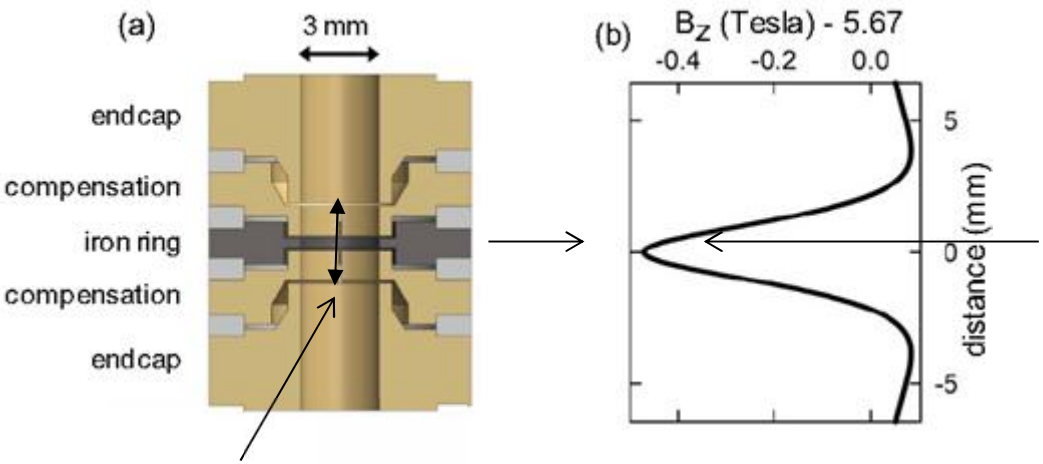
V(t)

I^2R
damping

crucial to limit
the osc. amplitude

amplitude, ϕ

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

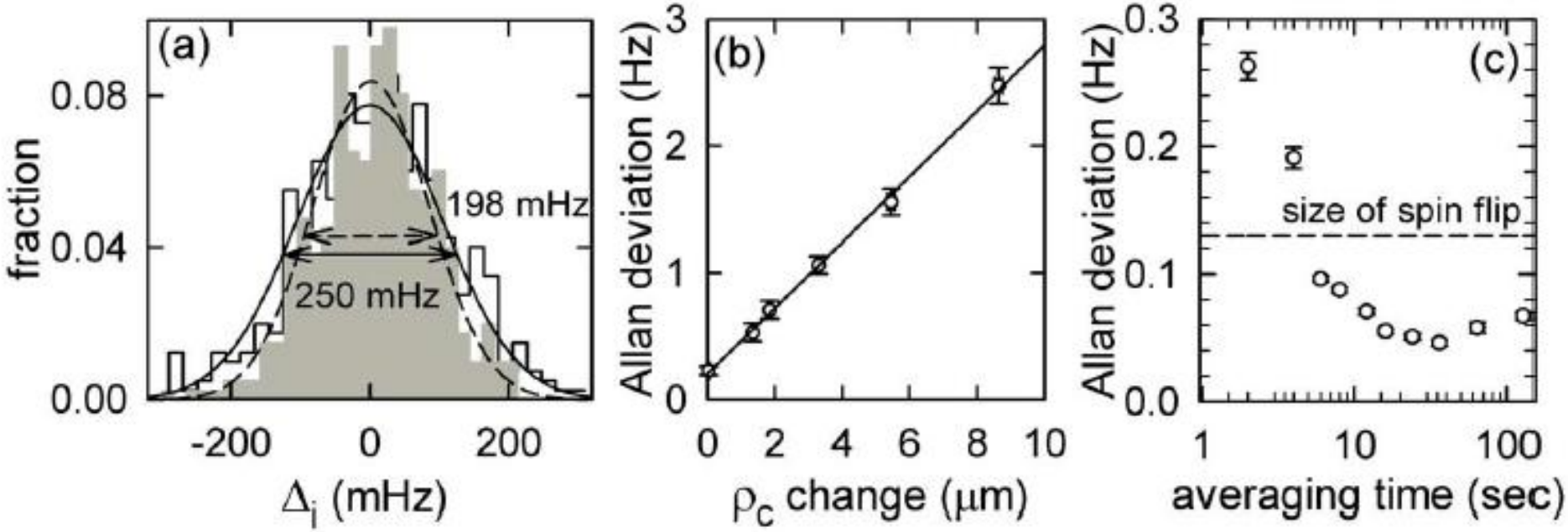
magnetic moment

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

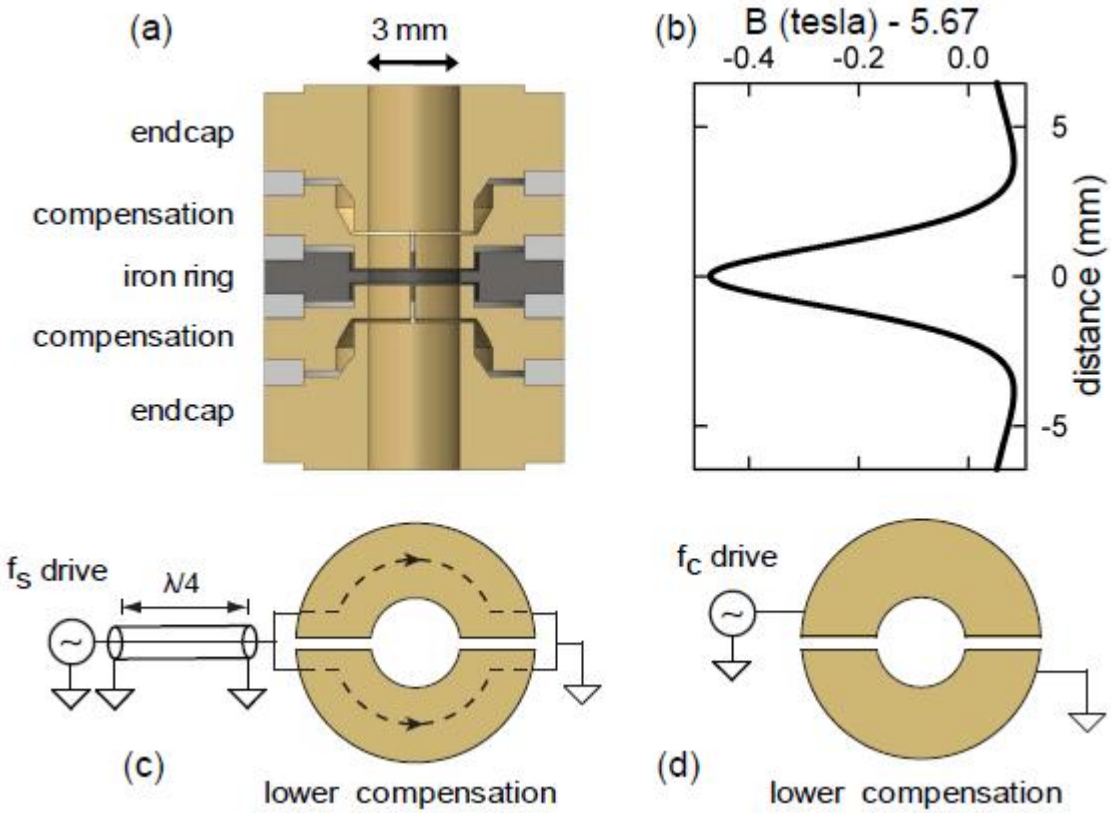
$$\Delta f \sim \mu$$

shift in oscillation frequency

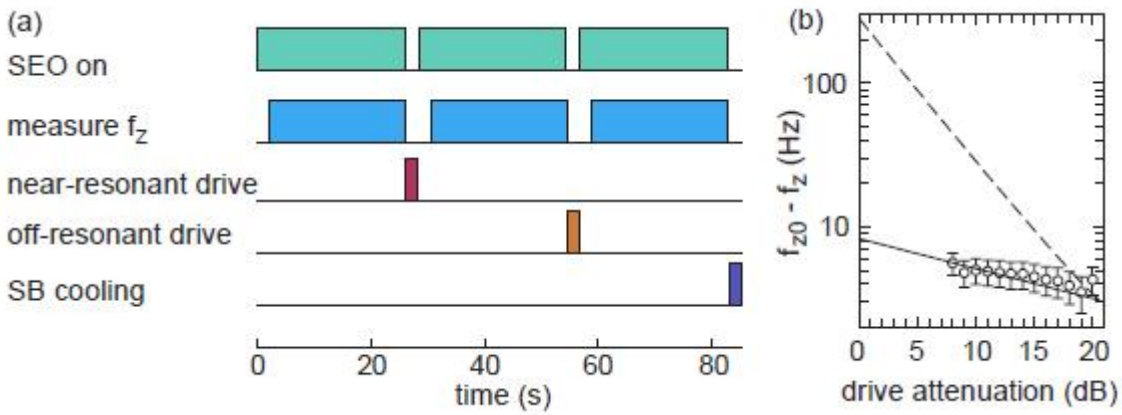
Spin-Flips Increase Allan Deviation



Slightly Improved Apparatus



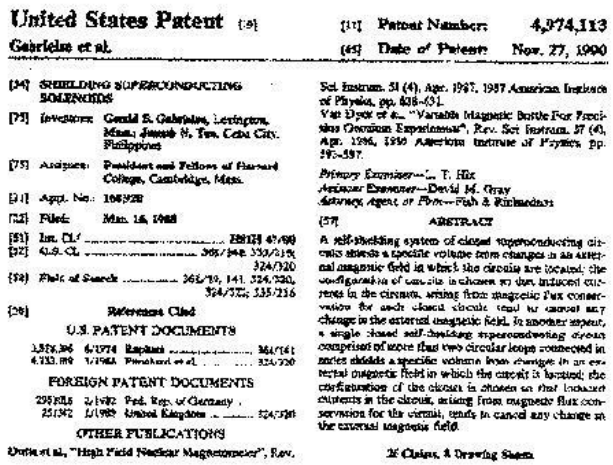
Measurement Sequence – for Spin Measurement



Self-Shielding Solenoid

Flux conservation → Field conservation

Reduces field fluctuations by about a factor > 150


United States Patent [19]
Gabrielse et al.

[11] Patent Number: 4,974,113
[45] Date of Patent: Nov. 27, 1990

[54] SHIELDING SUPERCONDUCTING SOLENOIDS

[75] Inventors: Gerald S. Gabrielse, Lexington, Mass.; Joseph H. Tan, Cebu City, Philippines

[73] Assignee: President and Fellows of Harvard College, Cambridge, Mass.

[21] Appl. No.: 104928

[22] Filed: Mar. 16, 1988

[51] Int. Cl.[4] H01F 6/00

[52] U.S. Cl. 505/846; 335/216; 324/320

[58] Field of Search 361/19, 141; 324/320, 324/322; 335/216

[56] References Cited

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4,733,199 3/1988 Fitzhubert et al. 324/320

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25/342 1/1989 United Kingdom 324/320

OTHER PUBLICATIONS

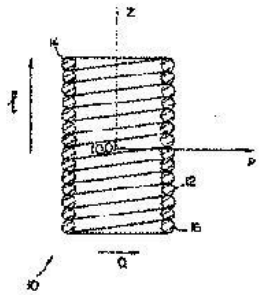
Dutta et al., "High Field Nuclear Magnetometer", Rev. Sci. Instrum. 51 (4), Apr. 1987, 1987 American Institute of Physics, pp. 438–451.
Van Dyck et al., "Variable Magnetic Bottle For Precision Geonium Experiments", Rev. Sci. Instrum. 57 (4), Apr. 1986, 1986 American Institute of Physics, pp. 593–597.

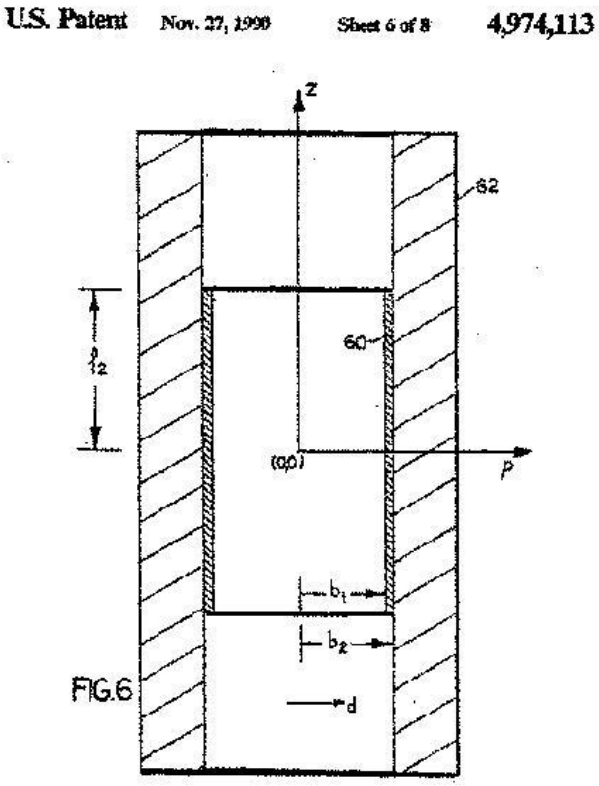
Primary Examiner—L. T. Hix
Assistant Examiner—David M. Gray
Attorney, Agent, or Firm—Fish & Richardson

[57] ABSTRACT

A self-shielding system of closed superconducting circuits shields a specific volume from changes in an external magnetic field in which the circuits are located; the configuration of circuits is chosen so that induced currents in the circuits, arising from magnetic flux conservation for each closed circuit, tend to cancel any change in the external magnetic field. In another aspect, a single closed self-shielding superconducting circuit comprises of more than two circular loops connected in series shields a specific volume from changes in an external magnetic field in which the circuit is located; the configuration of the circuit is chosen so that induced currents in the circuit, arising from magnetic flux conservation for the circuit, tends to cancel any change in the external magnetic field.

26 Claims, 8 Drawing Sheets





"Self-shielding Superconducting Solenoid Systems",
G. Gabrielse and J. Tan, J. Appl. Phys. **63**, 5143 (1988)

Resonance Lines to Determine the "Two" Frequencies

square of extra width

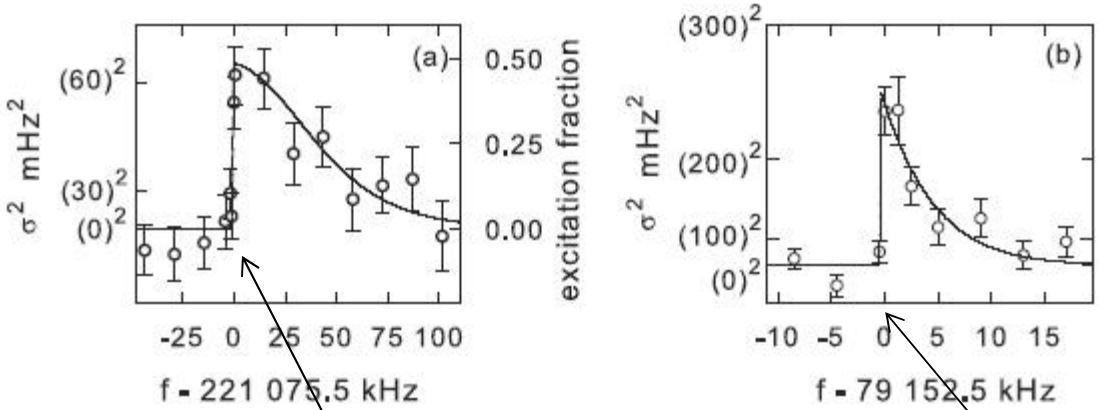


FIG. 4. (a) The spin line. (b)The cyclotron line.

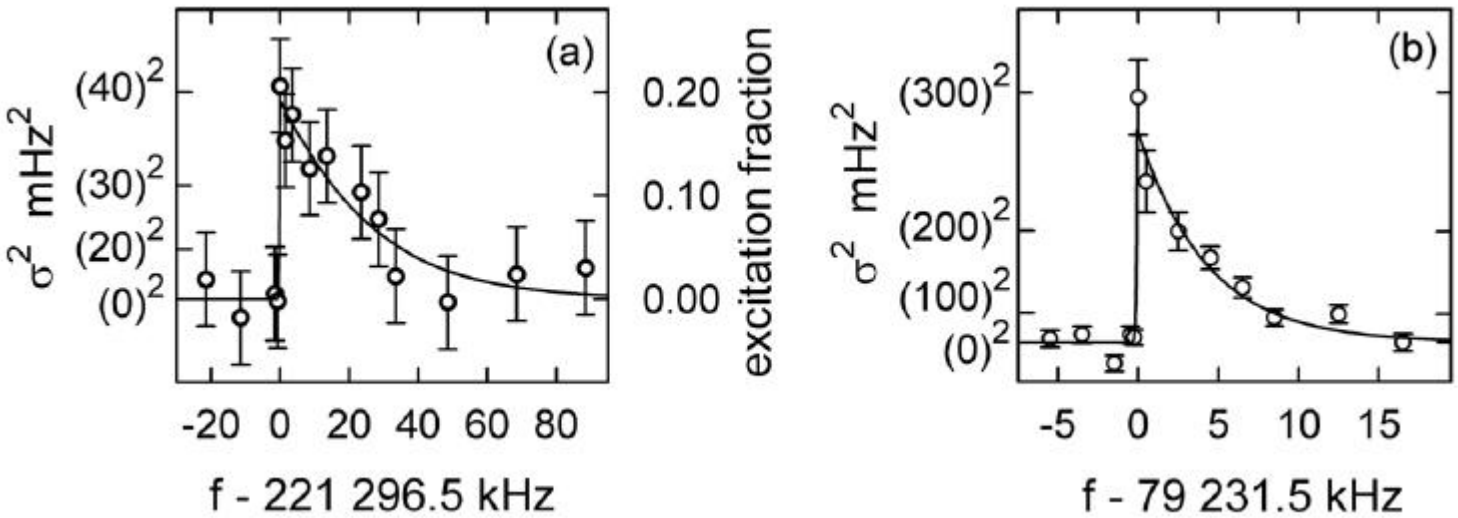
$$\frac{\mu_p}{\mu_N} \equiv \frac{g_p}{2} = \frac{f_s}{f_c}$$

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

Brown-Gabrielse Invariance Theorem

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

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First One-Particle Measurement of the Antiproton Magnetic moment

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

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

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

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

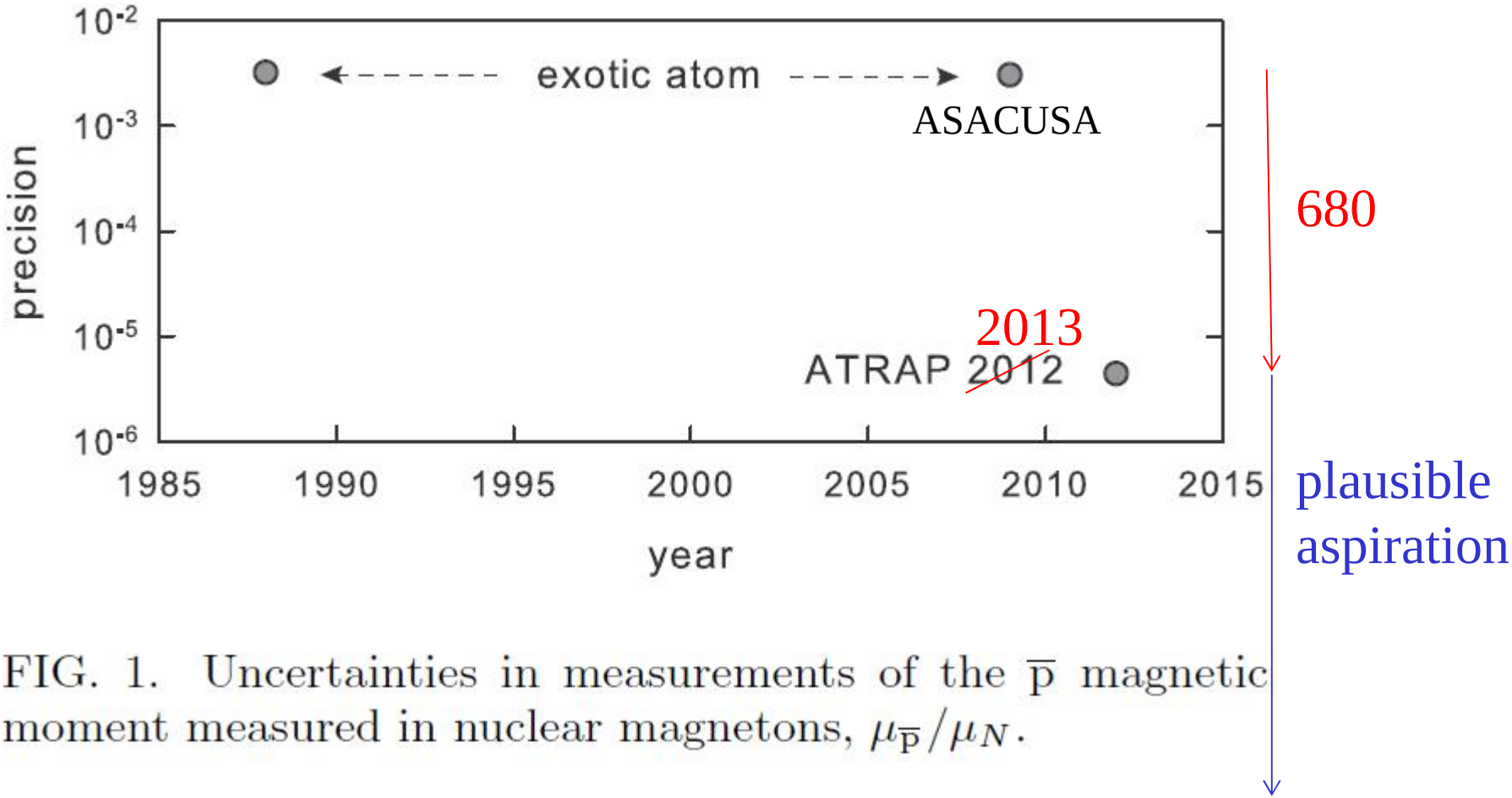

FIG. 1. Uncertainties in measurements of the $\overline{\mathrm{p}}$ magnetic moment measured in nuclear magnetons, $\mu_{\overline{\mathrm{p}}}/\mu_N$.

In press at Physical Review Letters

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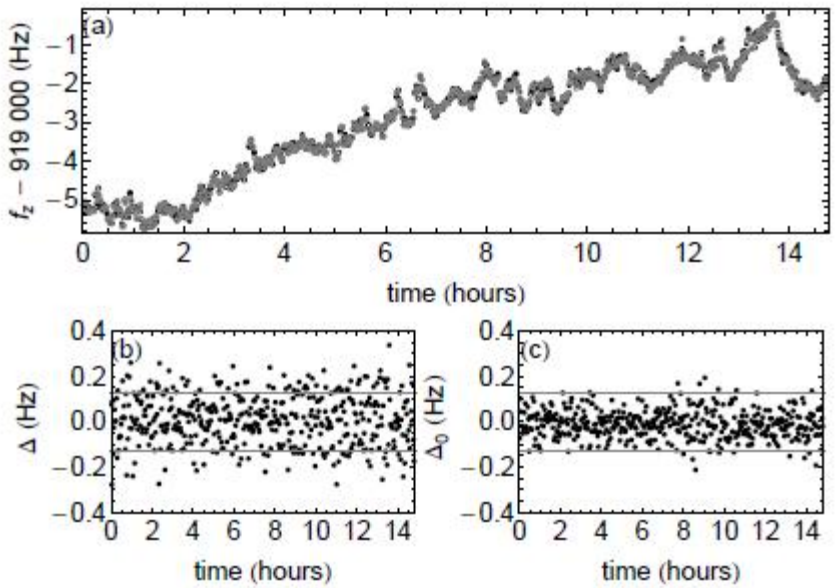
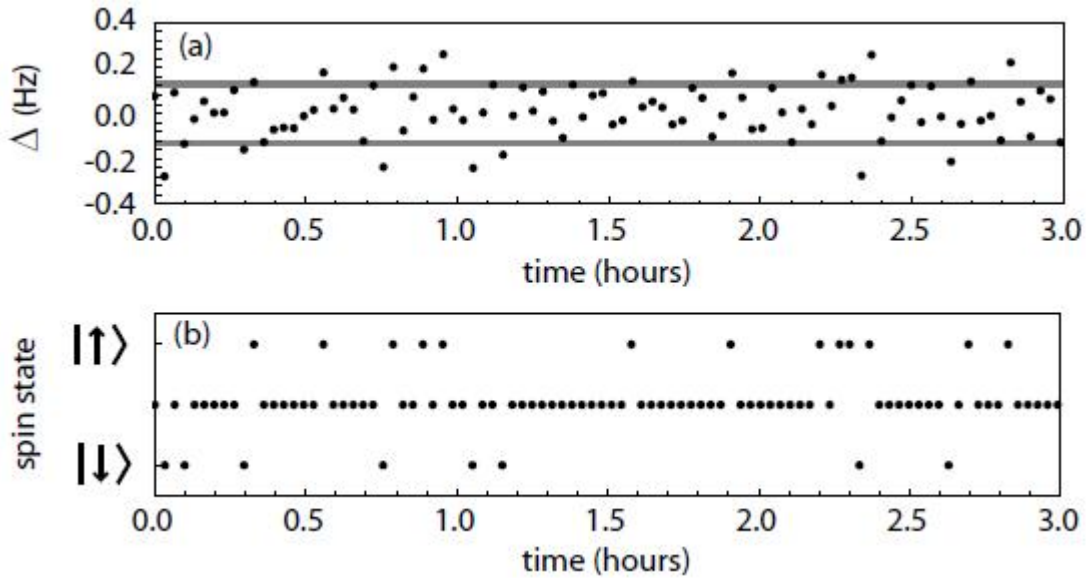
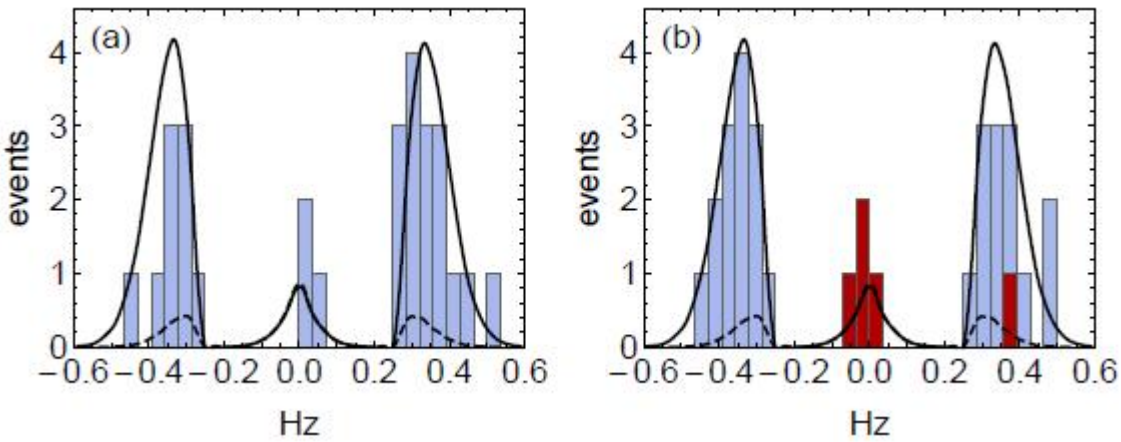
For the Future A 1000 to 10000-fold Improved Precision May be Possible



Single Proton Spin Flips Resolved



Down to Up must follow Up to Down: Correlation Function



Electron Electric Dipole Moment

Does the Electron Also Have an Electric Dipole Moment?

Magnetic moment: $\vec{\mu} = -\mu \dfrac{\vec{S}}{\hbar/2}$

(exists and well-measured)

Electric dipole moment: $\vec{d} = -d \dfrac{\vec{S}}{\hbar/2}$

(d is extremely small)

No Electron EDM Detected so Far

Commins limit (2002)

$$|d_e| \leq 1.6 \times 10^{-27} e \text{ cm}$$

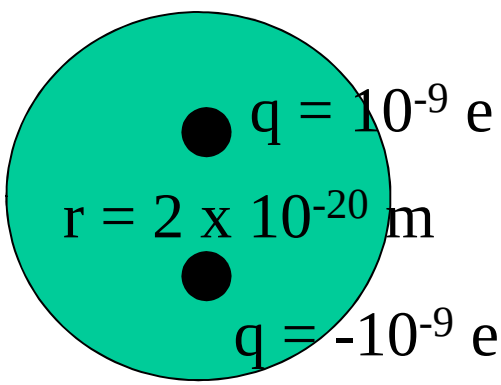
Regan, Commins, Schmidt, DeMille,
Phys. Rev. Lett. **88**, 071805 (2002)

Imperial College (2011)

$$|d_e| < 10.5 \times 10^{-28} e \text{ cm}$$

Hudson, Kara, Smallman, Sauer, Tarbutt, Hinds,
Nature **473**, 493 (2011)

Tl



YbF

Advanced Cold-Molecule Electron EDM

Gerald Gabrielse
Leverett Professor of Physics
Harvard University

Harvard University
John Doyle Group
Gerald Gabrielse Group

Yale University
David DeMille Group

1. Electron and its EDM
2. Measuring an EDM
3. Molecules and ThO?
4. Experimental progress

Funding from NSF

No Particle EDM Has Yet Been Detected

Electron EDM limit $|d_e| < 10.5 \times 10^{-28} e\,\mathrm{cm}$

Hudson, Kara, Smallman, Sauer, Tarbutt, Hinds,
Nature **473**, 493 (2011)

Neutron EDM limit $|d_n| < 2.9 \times 10^{-26} e\ \mathrm{cm}$

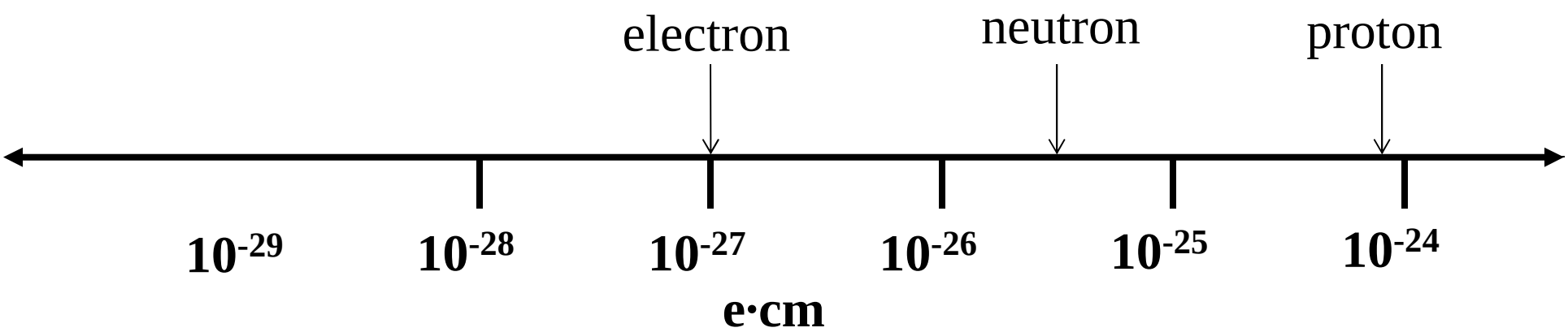
IIL Grenoble,
PRL **97**, 131801 (2006)

Proton EDM limit $|d_p| < 7.9 \times 10^{-25}\ e\,\mathrm{cm}$

Heckel, Fortson, …
PRL **102**, 101601 (2009)

from $|d(^{199}\mathrm{Hg})| < 3.1 \times 10^{-29}\ e\,\mathrm{cm}$

also sets $|d_n| < 5.8 \times 10^{-26}\ e\,\mathrm{cm}$



EDM Measurements – Important Since 1950

On the Possibility of Electric Dipole Moments for Elementary Particles and Nuclei

E. M. Purcell and N. F. Ramsey
Department of Physics, Harvard University, Cambridge, Massachusetts
April 27, 1950

It is generally assumed on the basis of some suggestive theoretical symmetry arguments[1] that nuclei and elementary particles can have no electric dipole moments. It is the purpose of this note to point out that although these theoretical arguments are valid when applied to molecular and atomic moments whose electromagnetic origin is well understood, their extension to nuclei and elementary particles rests on assumptions not yet tested.

parity conservation

This was well before parity violation was

- considered by Lee and Yang (1957) for kaon decay, etc.
- demonstrated experimentally by Wu (1957)

Particle EDM Requires Both P and T Violation

Magnetic moment:

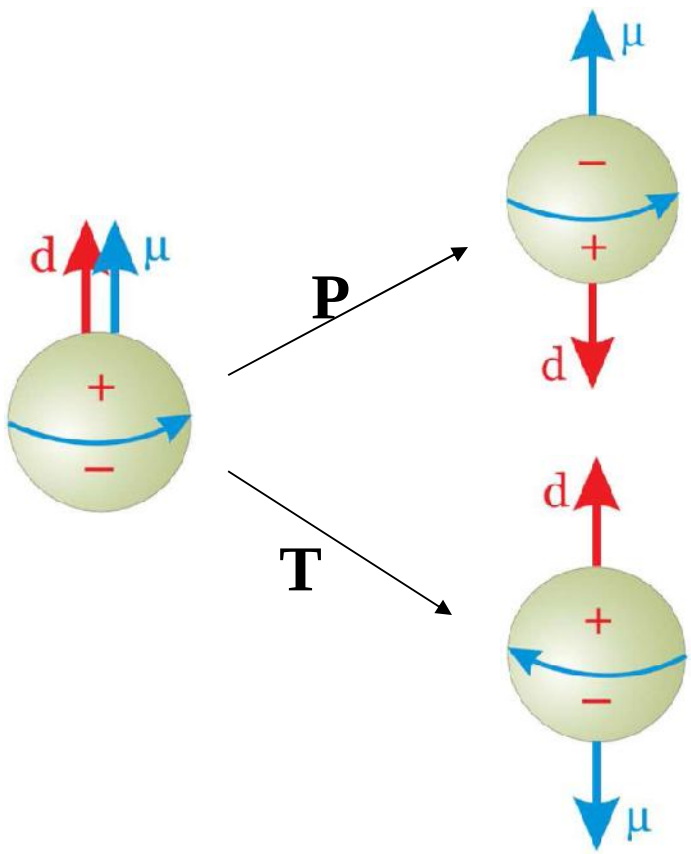
$$\vec{\mu} = -\mu \frac{\vec{S}}{\hbar/2}$$

(exists and well-measured)

Electric dipole Moment:

$$\vec{d} = -d \frac{\vec{S}}{\hbar/2}$$

(d is extremely small)



If reality is invariant under parity transformations **P**

→ **d = 0**

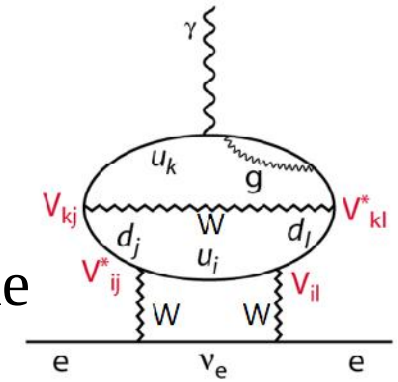
If reality is invariant under time reversal transformations **T**

→ **d = 0**

Standard Model of Particle Physics
→ Predicts a Non-zero Electron EDM

Standard model: d ~ 10^{-38} e-cm

Too small to measure by orders of magnitude
best measurement: d ~ 2 x 10^{-27} e-cm



four-loop level in perturbation theory

M. Pospelov and I. B. Khriplovich, "Electric dipole moment of the W boson and the electron in the Kobayashi-Maskawa model," Sov. J. Nucl. Phys. **53**, 638–640 (1991).

Weak interaction couples quark pairs (generations) $\begin{pmatrix} u \\ d' \end{pmatrix}, \begin{pmatrix} c \\ s' \end{pmatrix}, \begin{pmatrix} t \\ b' \end{pmatrix}$

CKM matrix relates to d, s, b quarks
(Cabibbo-Kabayashi-Maskawa matrix)

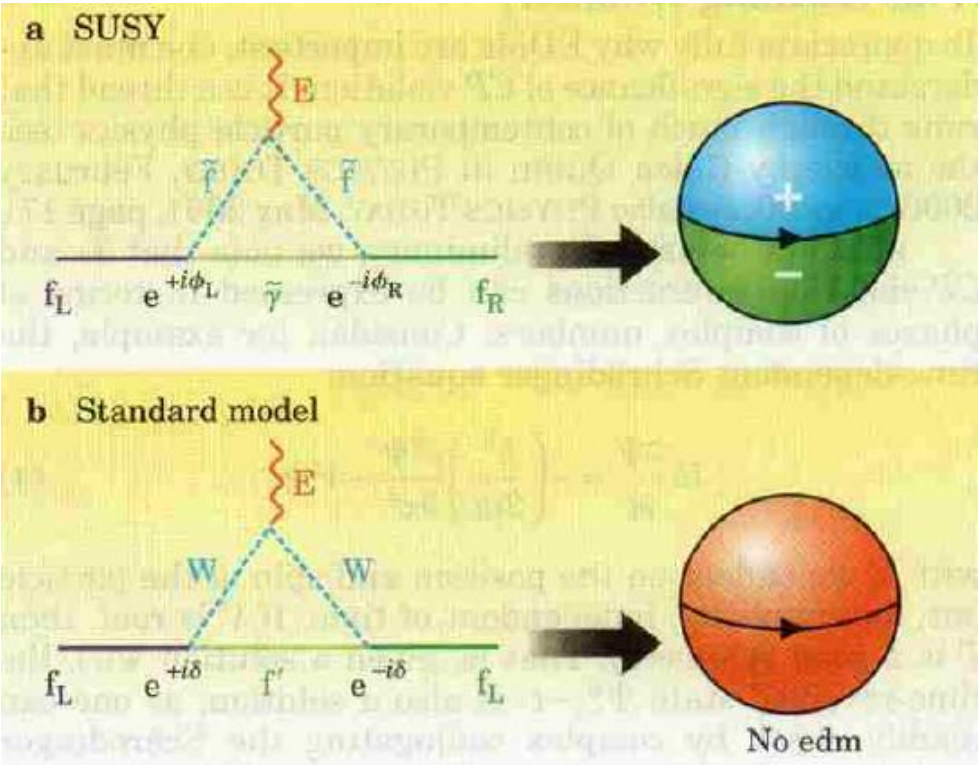
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

almost the unit matrix

$$\begin{pmatrix} 0.974 & 0.227 & 0.004 \\ 0.227 & 0.973 & 0.042 \\ 0.008 & 0.042 & 0.999 \end{pmatrix}$$

Extensions to the Standard Model
→ Measureable Electron EDM

An example



Low order contribution
→ larger moment

Low order contribution
→ vanishes

From Fortson, Sandars and Barr, Physics Today, 33 (June 2003)

Relationship to LHC Physics

The LHC is exciting and important but EDMs also play a role

- should get an improved electron EDM on the LHC time scale
- If the LHC sees new particles, is CP violation involved?
- If the LHC sees nothing, EDM game is the only one in town

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Promising Molecules

PHYSICAL REVIEW A **78**, 010502(R) (2008)

Prospects for an electron electric-dipole moment search in metastable ThO and ThF^+

Edmund R. Meyer* and John L. Bohn
JILA, NIST, and University of Colorado, Department of Physics, Boulder, Colorado 80309-0440, USA
(Received 1 May 2008; published 11 July 2008)

Molecular calc. project on atom basis

Molecule	Published	Old [14]	New
BaF	7.4 [9]	5.1	6.1
YbF	26 [10]	43	32
HgF	99 [8]	68	95
PbF	−29 [8]	−36.6	−31
$a(1)$ PbO	26.2 [11]	3.2 [22]	23
HI^+	0.34 [13]	0.57	0.34
HfF^+	24 [15]	18	30
ThO	N/A	N/A	104
ThF^+	N/A	N/A	90

Imperial

Oklahoma

Yale

JILA

Harvard - Yale

GV/cm

Thallium atom Experiment used used 120 kV/cm

Why ThO?

Omega doublets in excited H state → closely spaced levels with opposite parity → high internal electric field with weak lab field

Molecule is "easier to understand" than some
Hunds case c → leads to rigid rotor states
(despite the inclusion of electronic ang. mom. J)

Excited H state is triplet, with ground state singlet → long-lived as needed for a beam

Excited H state has small magnetic moment (0.01 Bohr magnetons)
→ not very vulnerable to magnetic field noise

Th has high Z → escape the Schiff theorem (and get enhancement)

Excitation lasers can be tuned to change the direction of the molecular polarization
(i.e. the direction of the internal E with respect to the laboratory E)

All transitions accessible with diode lasers

Old spectroscopy papers made it easier to find the states

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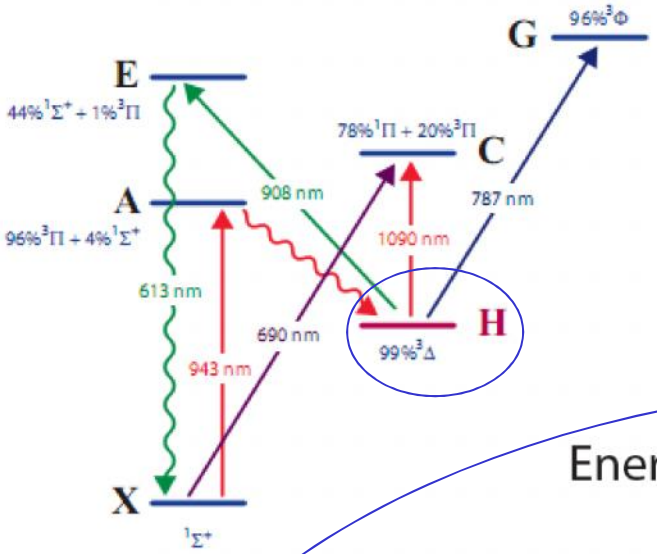
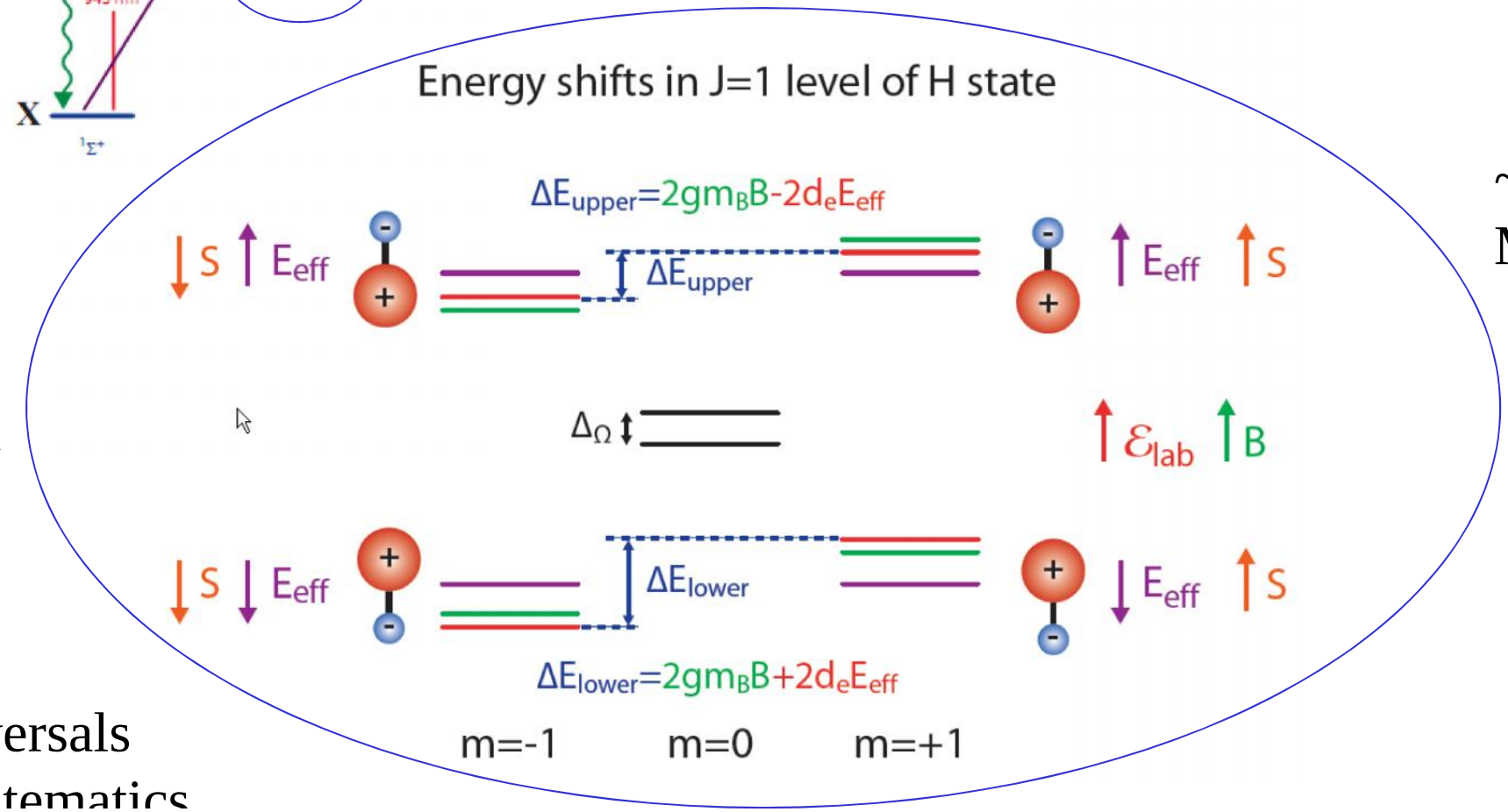
Metastable H State of ThO



Long-lived to make a beam
triplet → singlet ground state

Omega doublet – closely spaced levels
with opposite parity



$^3\Delta_1$

~100 MHz

reversals

systematics

Gabrielse

Summary

Antiproton magnetic moment

4.4 ppm (factor of 680 improvement)

Not so often that one gets to make such a step

Aspire to get 1000 to 10000 times better

Then will have a second extremely precise test of CPT with baryon/antibaryon system