Antimatter Under the Microscope

High-Precision Comparisons of the Fundamental Properties of Antiprotons and Protons

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Spokesperson BASE collaboration, CERN

2019 / 10 / 21
BASE – Collaboration

- **Mainz**: Measurement of the magnetic moment of the proton, implementation of new technologies. (see poster Matt Bohman)

- **CERN-AD**: Measurement of the magnetic moment of the antiproton and proton/antiproton q/m ratio (see poster Elise Wursten)

- **Hannover/PTB**: QLEDS-laser cooling project, new technologies

**Institutes**: RIKEN, MPIK, CERN, University of Mainz, Tokyo University, GSI Darmstadt, University of Hannover, PTB Braunschweig

C. Smorra et al., EPJ-Special Topics, The BASE Experiment, (2015)
BASE achievements since 2011

**Most precise proton g-factor measurement**


\[ g/2 = 2.792\,847\,350 (9) \]

First direct high precision measurement of the proton magnetic moment.


**Precise CPT test with baryons**


\[ 1 + \frac{(q/m)_p}{(q/m)_p} = 1(69) \times 10^{-12} \]

\[ R_{exp} = 1.001\,089\,218\,755 (64) (26) \]

To be improved by another factor of 10 to 100

**Reservoir trap for antiprotons**


Idea: Enable operation with antiprotons independent of accelerator run times.

**Most precise antiproton g-factor measurement**


\[ g/2 = 2.792\,846\,5 (23) \]

Sixfold improvement compared to previous measurement

**Reservoir trap for antiprotons**


Idea: Enable operation with antiprotons independent of accelerator run times.

**Reservoir trap for antiprotons**


Idea: Enable operation with antiprotons independent of accelerator run times.

Partly comparable work by J. DiSciaccia, G. Gabrielse et al. (ATRAP/TRAP collaboration)
Problem: Big Bang Scenario and Consequences

1. A cosmic microwave background should exist as a fire-ball remnant of the Big Bang
   1.1 1965 Penzias and Wilson observed CMWB with a black body spectrum of 2.73(1)K, by far too intense to be of stellar origin.

2. Understandable Big Bang nucleosynthesis scenario describes exactly the observed light element abundances as found in «cold» stellar nebulae.

3. Using the models which describe 1. and 2.:

<table>
<thead>
<tr>
<th>Prediction</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baryon/Photon Ratio</td>
<td>Baryon/Photon Ratio</td>
</tr>
<tr>
<td>$10^{-18}$</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>Baryon/Antibaryon Ratio</td>
<td>Baryon/Antibaryon Ratio</td>
</tr>
<tr>
<td>1</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

Following the current Standard Model of the Universe our predictions of baryon to photon ratio are wrong by about 9 orders of magnitude
WE HAVE A PROBLEM

mechanisms which created the obvious baryon/antibaryon asymmetry in the universe have yet to be understood

One strategy: Compare the fundamental properties of matter / antimatter conjugates with ultra high precision
A special place (in the universe?) – the BASE trap

- We have
  - A vacuum of $5\times10^{-19}$ mbars
    - comparable to pressures in the interstellar medium
  - Antiproton storage times of several 10 years.
  - Not more than 3000 atoms in a vacuum volume of 0.5l
  - Order 100 to 1000 trapped antiprotons
  - A local inversion of the baryon asymmetry

---

**BASE ANTIMATTER INVERSION**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>local volume</td>
<td>0.0001$^3$ m$^3$</td>
</tr>
<tr>
<td>Baryons in local trap volume</td>
<td>1.65$\times10^{-7}$</td>
</tr>
<tr>
<td>Antibaryon in local trap volume</td>
<td>100</td>
</tr>
<tr>
<td><strong>Antibaryon/Baryon Ratio</strong></td>
<td>5.9$\times10^8$</td>
</tr>
<tr>
<td><strong>Ratio Inversion</strong></td>
<td>3.8$\times10^{12}$</td>
</tr>
</tbody>
</table>

With this instrument: Investigate properties of antimatter very precisely.
CPT tests based on particle/antiparticle comparisons

G. Gabriesle et al., PRL 82, 3199(1999).
Limits on Exotic Physics – ONE example

• Test the Standard Model (CPT invariance) by comparing the fundamental properties of protons and antiprotons with high precision

\[
H \psi = (H_0 + V_{\text{exotic}}) \psi
\]

\[
\Delta E_{\text{exotic}} = \langle \psi | V_{\text{exotic}} | \psi \rangle
\]

\[
b_\mu \gamma_5 \gamma^\mu \to b_x \begin{pmatrix} -\sigma_x & 0 \\ 0 & \sigma_x \end{pmatrix} + b_y \begin{pmatrix} -\sigma_y & 0 \\ 0 & \sigma_y \end{pmatrix} + b_z \begin{pmatrix} -\sigma_z & 0 \\ 0 & \sigma_z \end{pmatrix}
\]

Dirac equation CPT-odd modifications

Pseudo-magnetic field, with different coupling to matter and antimatter, respectively

\[
\Delta V_{\text{int}} = \tilde{b}_{z,\nu} \begin{pmatrix} 0 & 0 \\ 0 & \pm \sigma_z \end{pmatrix}
\]

Would correspond to the discovery of a boson field which exclusively couples to antimatter.

sensitive: comparisons of particle/antiparticle magnetic moments in traps

The AD/ELENA-facility

Six collaborations, pioneering work by Gabrielse, Oelert, Hayano, Hangst, Charlton et al.

BASE, ATRAP,
Fundamental properties of the antiproton

ALPHA, ATRAP,
Spectroscopy of 1S-2S in antihydrogen

ASACUSA, ALPHA
Spectroscopy of GS-HFS in antihydrogen

ASACUSA
Antiprotonic helium spectroscopy

ALPHA, AEgIS, GBAR
Test free fall/equivalence principle with antihydrogen

Main Tool: Penning Trap

radial confinement: \( \vec{B} = B_0 \hat{z} \)

axial confinement: \( \Phi(\rho, z) = V_0 c z \left( z^2 - \frac{\rho^2}{2} \right) \)

Invariance-Relation
\[
\nu_c = \sqrt{\nu^2_+ + \nu^2_- + \nu^2_z}
\]

Cyclotron Frequency
\[
\nu_c = \frac{1}{2\pi} \frac{q_{ion}}{m_{ion}} B
\]

Cyclotron frequency connects measurable quantity to fundamental properties of trapped charged particle

<table>
<thead>
<tr>
<th>Component</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial</td>
<td>( \nu_z = 680 \text{kHz} )</td>
</tr>
<tr>
<td>Magnetron</td>
<td>( \nu_- = 8 \text{kHz} )</td>
</tr>
<tr>
<td>Modified Cyclotron</td>
<td>( \nu_c = 28.9 \text{MHz} )</td>
</tr>
</tbody>
</table>
Measurements in Penning traps

Cyclotron Motion

\[
\omega_c = \frac{e}{m_p} B
\]

g: mag. Moment in units of nuclear magneton

Larmor Precession

\[
\omega_L = g \frac{e}{2m_p} B
\]

difficult

Determinations of the q/m ratio and g-factor reduce to measurements of frequency ratios -&gt; in principle very simple experiments -&gt; full control, (almost) no theoretical corrections required.

S. Ulmer, A. Mooser et al. PRL 106, 253001 (2011)
S. Ulmer, A. Mooser et al. PRL 107, 103002 (2011)
Experiment
THE BASE EXPERIMENT

dedicated to the highest level of precision! This innovative experiment can be operated with protons and/or antiprotons. It allows single particle control leading to the determination of the g-factor or the charge-to-mass ratio with outrageous sensitivity.

PRECISION TRAP
used for the determination of the cyclotron and the Larmor frequency

ANALYSIS TRAP
used for the spin state analysis of the proton or antiproton

 $(\frac{q}{m})_{\bar{p}} \quad (\frac{q}{m})_{p}$

BASE
Antibaryon Baryon Symmetry Experiment

$\mu_{\bar{p}} \quad \mu_p$
BASE-CERN Apparatus (approved 2013)

- Constructed new apparatus
- Integrated in a new experiment zone

Timeline:
- 0 2 4 6 8 10 12
  - Experiments with pbars
  - Commissioning with protons
  - Development of beam monitor
  - Installation of cryosetup
  - Installation of superconducting magnet
  - Commissioning with protons
  - First beam in DES5 line

Thanks to L. Bojtar, F. Butin and team
T Erkisson and team
R. Kersevan and team

Implemented into the AD facility within 12 months – thanks to strong support by CERN
The BASE Trap System

Reservoir Trap: Stores a cloud of antiprotons, suspends single antiprotons for measurements. Trap is “power failure save”.

Precision Trap: Homogeneous field for frequency measurements, $B_2 < 0.5 \, \mu T / \text{mm}^2$ (10 x improved)

Cooling Trap: Fast cooling of the cyclotron motion, $1/\gamma < 4 \, \text{s}$ (10 x improved)

Analysis Trap: Inhomogeneous field for the detection of antiproton spin flips, $B_2 = 300 \, \text{mT} / \text{mm}^2$

S. Ulmer et al., BASE TDR, CDS (2013).

Measurement configuration

Extract antiprotons and H⁻ ions, compare cyclotron frequencies

\[ R = \frac{\nu_{c,\bar{p}}}{\nu_{c,H^-}} = \frac{(q/m)_{\bar{p}}}{(q/m)_{H^-}} \times \frac{B/2\pi}{B/2\pi} = \frac{(q/m)_{\bar{p}}}{(q/m)_{H^-}} \]

\[ m_{H^-} = m_p (1 + 2 \frac{m_e}{m_p} - \frac{E_b}{m_p} - \frac{E_a}{m_p} + \frac{\alpha_{pol,H^-} B_0^2}{m_p}) \]

\[ R_{\text{theo}} = 1.001\ 089\ 218\ 754\ 2(2) \]

Comparison of H⁻/antiproton cyclotron frequencies:

One frequency ratio per 4 minutes with ~ 6 ppb uncertainty

inspired by G. Gabriesle et al., PRL 82, 3199 (1999).
Proton to Antiproton Q/M: Physics

\[
\frac{(q/m)_p}{(q/m)_{\overline{p}}} + 1 = 1(69) \times 10^{-12}
\]

- In agreement with CPT conservation
- Exceeds the energy resolution of previous result by a factor of 4.


- Constrain of the gravitational anomaly for antiprotons:

\[
\frac{\omega_{c,\overline{p}} - \omega_{c,p}}{\omega_{c,p}} = -3(\alpha_g - 1) \frac{U}{c^2}
\]

Our 69ppt result sets a new upper limit of

\[|\alpha_g - 1| < 8.7 \times 10^{-7}\]

- Conclusion: Matter and Antimatter clocks run at the same frequency

- Set limit of sidereal (diurnal) variations in proton/antiproton charge-to-mass ratios to < 0.72 ppb/day
Progress towards a better q/m measurement

Better stabilisation of cryoliquid pressure, temperature improves magnetic stability

J. A. B.-Harrington et al.

Mechanical upgrade: more stable and lower heat load means fewer vibrations

M. J. Borchert et al.

Peak measurement technique

2.5 Hz

25 mHz

New magnetic shielding system

See poster by Elise Wursten

J. Harrington, M. Borchert

J. Devlin, E. Wursten

Next step:

J. Harrington, M. Borchert

J. Devlin, E. Wursten

M. J. Borchert et al.
Future Perspective

• Reached a ratio uncertainty of order 10 p.p.t. to 20 p.p.t.
• What would be the next step?

In the AD hall with accelerator active we would not be able to significantly improve the ratio

Started project to transport antiprotons out of the AD hall (ERC-grant Christian Smorra / BASE-STEP)
A milestone measurement in antimatter physics


The Antiproton Magnetic Moment

The BASE collaboration of CERN has measured the antiproton magnetic moment with extraordinary precision, offering more than 100-fold improved limits on certain tests of charge-parity-time invariance.

The results of the measurement are reported in the paper "The Antiproton Magnetic Moment Measurement at the BASE Experiment," published in Nature. The experiment was carried out at the Antiproton Decelerator at CERN, where antiprotons are produced and trapped in a Penning trap. The measurement was performed by comparing the magnetic moment of antiprotons to that of protons, which is known with high precision.

The BASE experiment is one of several projects worldwide that are aiming to improve our understanding of the fundamental properties of matter. The results of this measurement will contribute to our knowledge of the laws of physics and may have implications for our understanding of the universe.
Continuous Stern-Gerlach Effect

\[ \frac{\mu\tilde{p}}{\mu_N} = \frac{g\tilde{p} e\tilde{p}}{2 m\tilde{p}} \frac{e\tilde{p}}{m\tilde{p}} = \frac{\nu_L}{\nu_c} \]

Image Current Measurements

S. Ulmer et al., PRL 107, 103002 (2011)

Larmor Frequency – extremely hard

Measurement based on continuous Stern Gerlach effect.

Energy of magnetic dipole in magnetic field

\[ \Phi_M = - (\vec{\mu_p} \cdot \vec{B}) \]

Leading order magnetic field correction

\[ B_z = B_0 + B_2 \left( z^2 - \frac{\rho^2}{2} \right) \]

This term adds a spin dependent quadratic axial potential

-> Axial frequency becomes a function of the spin state

\[ \Delta \nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} = \alpha_p \frac{B_2}{\nu_z} \]

- Very difficult for the proton/antiproton system.

\[ B_2 \sim 300000 \, T/m^2 \]

- Most extreme magnetic conditions ever applied to single particle.

\[ \Delta \nu_z \sim 170 \, mHz \]

Single Penning trap method is limited to the p.p.m. level

Frequency Measurement

Spin is detected and analyzed via an axial frequency measurement

S. Ulmer, A. Mooser et al. PRL 106, 253001 (2011)
Antiproton $g$-factor results – single trap

Performed 6 Larmor resonance and 12 cyclotron resonance scans

$g_{\bar{p}}/2 = 2.7928465(23)$

Six fold improved uncertainty of the antiproton magnetic moment

$\frac{g_{\bar{p}}}{g_p} - 1 = -0.31(82) \times 10^{-7}$

Respective limits on SME coefficients for CPT violation improved up to a factor 20


??? How can we do better ???
Next Step: The Double Penning-Trap Method

Invented at Univ. of Mainz by H. Haeffner, W. Quint, G. Werth and company (2000 - 2008)

1.) measure cyclotron $\nu_c$
2.) drive spin transition at $\nu_{\text{rf}}$

Initialize the spin state

analyze the spin state

particle transport

measures spin flip probability as a function of the drive frequency in the homogeneous magnetic field of the precision trap
The holy-grail: single antiproton spin flips

- First non-destructive observation of single antiproton spin quantum transitions.

Heating Rates

- Achieve single spin flip resolution only with cold particles.
- Reason: Heating rates scale with particle energy

\[ \frac{dn_{+,-}}{dt} \approx \frac{q^2}{2m_p h_{+,-}} n_{+,-} \langle \epsilon_n(t), \epsilon_n(t-\tau) \rangle \]

- Cold particle (50mK)
- Hot particle (1K)
- High-fidelity spin state resolution
- Fidelity at 65%, not useful for measurements

Takes hours per preparation cycle

Invented: BASE Two-Particle Method

Idea: divide measurement to two particles

- «cold» cyclotron particle to flip and analyze the spin-eigenstate
- «hot» cyclotron particle which probes the magnetic field in the precision trap

Challenges:
- transport without heating
- more challenging systematics

Pay: measure with two particles at different mode energies

Win: 60% of time usually used for sub-thermal cooling usable for measurements
The Magnetic Moment of the Antiproton

first measurement ever which was more precise for antimatter than for matter conjugate...

...so how about the proton magnetic moment?

\[
\frac{g_p}{2} = 2.792\ 847\ 350\ (9)
\]

\[
\frac{g_p}{2} = 2.792\ 847\ 344\ 1\ (42)
\]

A. Mooser et al., Nature 509, 596 (2014)

The Magnetic Moment of the Proton

- Plugging all the methods together (in AD)
  - New magnetic shielding system
  - Phase methods
  - Local magnet shims
  - New type of trap (cooling trap)

Reach 0.8 ppb frequency scatter (AD limited)

\[
\frac{g_p}{2} = 2.792 \, 847 \, 344 \, 62 \, (82)
\]

G. Schneider et al., Science 358, 1081 (2017)
| Year   | Proton $g_p/2$       | Antiproton $g_{\overline{p}}/2$ | $CPT \left| \frac{g_p}{g_{\overline{p}}} \right| - 1$ | Collaboration                  |
|--------|----------------------|----------------------------------|-------------------------------------------------|--------------------------------|
| 2011   | 2.792 847 353 (28)   | 2.786 2 (83)                     | 0.002 4 (29)                                   | Pask (ASACUSA)                 |
| 2013   | 2.792 846 (7)        | 2.792 845 (12)                   | 0.000 000 4 (49)                               | diSciacca (ATRAP)              |
| 2014   | 2.792 847 349 8 (93) | 2.792 845 (12)                   | 0.000 000 8 (43)                               | Mooser(BASE)/diSciacca (ATRAP) |
| 2016   | 2.792 847 349 8 (93) | 2.792 846 5 (23)                 | 0.000 000 30 (82)                              | Mooser/Nagahama (BASE)         |
| 2017/1 | 2.792 847 349 8 (93) | 2.792 847 344 1 (42)             | 0.000 000 002 0 (36)                           | Mooser/Smorra (BASE)           |
| 2017/2 | 2.792 847 344 62 (82)| 2.792 847 344 1 (42)             | -0.000 000 000 2 (15)                          | Schneider/Smorra (BASE)        |

\[ \frac{g_p}{g_{\overline{p}}} - 1 = -0.000 \, 000 \, 000 \, 002 \, (15) \]
Summary and Outlook

• Performed a 69 p.p.t. - test of CPT invariance with baryons by comparing proton/antiproton charge-to-mass ratios

• Performed the most precise measurement of the proton magnetic moment with a fractional precision of 0.3 p.p.b.

• Performed the most precise measurement of the antiproton magnetic moment with a fractional precision of 1.5 p.p.b.

• Feasibility to improve Q/M comparison by factor of 5 to 10 demonstrated.
Several open positions available in BASE

- Post Doc and PhD positions to
  - Implement transportable antimatter traps
  - Implement sympathetic cooling of antiprotons
  - Develop advanced magnetic shielding systems
  - Implement new Penning trap architectures

...to investigate matter / antimatter asymmetry with highest precision...
Thanks for your attention!
Moment CPT Tests

| Year | Matter \( g/2 \) | Antimatter \( \bar{g}/2 \) | CPT \( |g/\bar{g}| - 1 \) | System | SME \( |b_L| \) (GeV) | \( f_0^0 \) (\( \mu_B \)) |
|------|----------------|----------------|----------------|---------|----------------|----------------|
| 1987 | 1.001 159 652 188 9 (43) | 1.001 159 652 187 9 (43) | 0.000 000 000 000 5 (21) | electron/positron | 6 \( \times 10^{-25} \) | 2 \( \times 10^{-12} \) |
| 2006 | 1.001 165 921 5 (11) | 1.001 165 920 4 (12) | 0.000 000 001 1 (12) | muon (\( \mu^- \), \( \mu^+ \)) | 1 \( \times 10^{-23} \) | 3 \( \times 10^{-11} \) |
| 2017 | 2.792 847 344 62 (82) | 2.792 847 344 1 (42) | -0.000 000 000 2 (15) | proton/antiproton | 2 \( \times 10^{-24} \) | 6 \( \times 10^{-12} \) |

SME: \[
(i \gamma^\mu D_\mu - m - a_\mu \gamma^\mu - b_\mu \gamma_5 \gamma^\mu) \psi = 0
\]

\[
b_\mu \gamma_5 \gamma^\mu \rightarrow b_x \left( \begin{array}{cc} -\sigma_x & 0 \\ 0 & \sigma_x \end{array} \right) + b_y \left( \begin{array}{cc} -\sigma_y & 0 \\ 0 & \sigma_y \end{array} \right) + b_z \left( \begin{array}{cc} -\sigma_z & 0 \\ 0 & \sigma_z \end{array} \right)
\]

Theoretical framework provided by A. Kostelecky (SME) and Y. Stadnik, V. Flambaum et al.
Sympathetic Cooling of Antiprotons

Goal: Accelerate magnetic moment measurement cycles

Two charged particles trapped in direct vicinity coupled by coulomb interaction.

Of utmost importance for future BASE precision studies

Successfully demonstrated in Paul trap with Be ions

Potential Depth (a.u.)
Distance (a.u.)

\[ U(x_a, x_b) = \frac{1}{4\pi\varepsilon_0 s_0} \frac{q_a q_b}{s_0 - x_a + x_b} \]

\[ \approx \frac{1}{4\pi\varepsilon_0 s_0} \frac{q_a q_b}{s_0} \left( 1 + \frac{x_a - x_b}{s_0} + \frac{x_a^2}{s_0^2} + \frac{x_b^2}{s_0^2} - \frac{2x_a x_b}{s_0^2} \right) \]

Resonant Coupling:

\[ a^\dagger(t) = \exp(i\omega_0 t)(a^\dagger(0) \cos(\Omega_{ex} t) - ib^\dagger(0) \sin(\Omega_{ex} t)) \]

\[ b^\dagger(t) = \exp(i\omega_0 t)(b^\dagger(0) \cos(\Omega_{ex} t) - ia^\dagger(0) \sin(\Omega_{ex} t)) \]

Effective Energy Exchange


Planned Developments – Sympathetic Cooling of pbars

- Current antiproton magnetic moment measurements are limited by particle preparation time and particle mode temperature
- Expect: With traditional methods another 50-fold improvement is possible, afterwards: limit of traditional methods will be reached!

New Method

Couple protons/antiprotons sympathetically to laser cooled $^9\text{Be}^+$ ions and imprint Doppler temperatures to the antiproton

Potential Depth (a.u.)
Distance (a.u.)
s₀
A B
xB


Effort at University of Mainz

5 trap design implemented and simultaneous detection of $^9\text{Be}^+$ ion and proton in common endcap trap was demonstrated.

C. Smorra, A. Mooser, M. Bohman, M. Wiesinger et al.

Effort at University of Hannover and PTB

Recent dramatic progress: Detection of a single laser cooled $^9\text{Be}^+$ ion, in a Penning trap system which is fully compatible with the BASE trap system at CERN


>100-fold improved antiproton cooling time seems to be in reach
Why would this make sense?

- BASE demonstrated measurements at a level of 20 parts in a trillion -> 500uHz
- On the other hand:

Feasibility:

- Need to be able to...
  - ...catch and cool antiprotons
  - ...store antiprotons for quasi-infinite amount of time
  - ...extract small amount of antiprotons from a large reservoir
  - ...shuttle antiprotons between traps

Yet to be developed: Transport trap and transfer to another trap experiment

For measurements at sub-p.p.t. precision particles need to be moved to a dedicated high-precision laboratory.

Exciting potential to multiply the antiproton physics program
Single Trap – Double Trap – Triple Trap

**Single-trap method**

\[
\frac{B_{2,AT}}{B_{2,PT}} > 10^6
\]

**Multi-trap method**

Two years compared to two months...
### Systematics

**Table 1 | Error budget of the antiproton magnetic moment measurement**

<table>
<thead>
<tr>
<th>Effect</th>
<th>Correction (p.p.b.)</th>
<th>Uncertainty (p.p.b.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image-charge shift</td>
<td>0.05</td>
<td>0.001</td>
</tr>
<tr>
<td>Relativistic shift</td>
<td>0.03</td>
<td>0.003</td>
</tr>
<tr>
<td>Magnetic gradient</td>
<td>0.22</td>
<td>0.020</td>
</tr>
<tr>
<td>Magnetic bottle</td>
<td>0.12</td>
<td>0.009</td>
</tr>
<tr>
<td>Trap potential</td>
<td>−0.01</td>
<td>0.001</td>
</tr>
<tr>
<td>Voltage drift</td>
<td>0.04</td>
<td>0.020</td>
</tr>
<tr>
<td>Contaminants</td>
<td>0.00</td>
<td>0.280</td>
</tr>
<tr>
<td>Drive temperature</td>
<td>0.00</td>
<td>0.970</td>
</tr>
<tr>
<td>Spin-state analysis</td>
<td>0.00</td>
<td>0.130</td>
</tr>
<tr>
<td>Total systematic shift</td>
<td>0.44</td>
<td>1.020</td>
</tr>
</tbody>
</table>

The table lists the relative systematic shifts (column 2) by which the measured magnetic-moment value was corrected; column 3 is the uncertainty of the correction. Details of these systematic effects and their quantification are given in Methods.

This dominant error is not present in double trap measurements. Has been estimated with the conservative 95% C.L.
The Magnetic Moment of the Proton

- Compared to the CERN experiment, the Mainz experiment has:
  - more homogeneous magnetic field
  - magnetic field has higher stability
  - shallower heating rate scaling
  - lower detector temperature

- double-trap measurement at (compare 2014)
  A. Mooser et al., Nature 509, 596 (2014)
  - improved magnetic field homogeneity
  - improved magnetic field stability (SSC)
  - improved cyclotron cooler
  - elimination of main systematic limitations

Note: At this level of precision a factor of 11 required 3 years

\[ \frac{g_p}{2} = 2.792 \times 10^{-3} \]

G. Schneider et al., Science 358, 1081 (2017)

methods developed to improve antiproton moment by at least a factor of 5
Momentum in the AD community since 2013

- Summarized in CERN courier, issue 2018/03
- J. Hangst – «Illuminating Antimatter»
- S. Ulmer – «Experiment of the Moment»
Antiprotons – CERN

5.3 MeV antiprotons

3.5 GeV/c antiprotons

25 GeV/c protons

- Degrader -> 1keV
- Electron cooling -> 0.1 eV
- Resistive cooling -> 0.000 3 eV
- Feedback cooling -> 0.000 09 eV

Within a production/deceleration cycle of 120s + 300s of preparation time we bridge 14 orders of magnitude
Limits on Exotic Physics – ONE example

- Test the Standard Model (CPT invariance) by comparing the fundamental properties of protons and antiprotons with high precision

\[
(i\gamma^\mu D_\mu - m - a_\mu\gamma^\mu - b_\mu\gamma_5\gamma^\mu)\psi = 0
\]

Dirac equation, CPT-odd modifications

\[
b_\mu\gamma_5\gamma^\mu \rightarrow b_x \begin{pmatrix} -\sigma_x & 0 \\ 0 & \sigma_x \end{pmatrix} + b_y \begin{pmatrix} -\sigma_y & 0 \\ 0 & \sigma_y \end{pmatrix} + b_z \begin{pmatrix} -\sigma_z & 0 \\ 0 & \sigma_z \end{pmatrix}
\]

Pseudo-magnetic field, with different coupling to matter and antimatter, respectively

\[
\Delta V_{\text{int}} = b_{z,D} \begin{pmatrix} 0 & 0 \\ 0 & \pm \sigma_z \end{pmatrix}
\]


Would correspond to the discovery of a boson field which exclusively couples to antimatter.

sensitive: comparisons of particle/antiparticle magnetic moments in traps
Frequency Measurements

- Measurement of tiny image currents induced in trap electrodes

\[ \Delta \nu = \frac{1}{2\pi} \frac{R}{m} \left( \frac{q}{D} \right)^2 \cdot N \]

- In thermal equilibrium:
  - Particles short noise in parallel
  - Appear as a dip in detector spectrum
  - Width of the dip \( \rightarrow \) number of particles

- Measurements in thermal equilibrium \( \rightarrow \) tiny volumina / homogeneous conditions