BASE Annual Report 2017

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BASE – Collaboration

- **Mainz**: Measurement of the magnetic moment of the proton (Mooser, Ulmer, Blaum, Walz, Quint).

- **CERN-AD**: Measurement of the magnetic moment of the antiproton and proton/antiproton q/m ratio (Ulmer, Smorra, Yamazaki, Blaum, Matsuda).

- **Hannover/PTB**: QLEDS-laser cooling project (Ospelkaus, Ulmer)

**Institutes**: RIKEN Ulmer IRU, RIKEN APL, Max Planck Society, CERN, University of Mainz, Tokyo University, GSI Darmstadt, University of Hannover, PTB Braunschweig

C. Smorra et al., EPJ-Special Topics, The BASE Experiment, (2015)
Observation of spin flips with a single trapped proton

Application of the double Penning-trap technique

Most precise proton g-factor measurement

Precise CPT test with baryons

Most precise antiproton g-factor measurement

Observation of spin flips with a single trapped proton

Most precise proton g-factor measurement

Precise CPT test with baryons

Most precise antiproton g-factor measurement

Partly comparable work by J. DiSciacca, G. Gabrielse et al. (ATRAP/TRAP collaboration)
Outline

• introduction & motivation
• basic concepts
• antiproton and proton magnetic moment measurements
• progress 2017-run

- the measurement of the antiproton magnetic moment with a fractional precision of 0.8 p.p.m. This improved the previous best determination [2] of the antiproton magnetic moment by a factor of six.
  H. Nagahama et al., Nat. Commun 8, 14084 (2017) [1].

- the first observation of spin flips with a single-trapped antiproton. This measurement constitutes the first non-destructive observation of spin quantum transitions in baryonic antimatter.

- the storage of an antiproton cloud for 405 days, which improves limits on the directly measured antiproton lifetime by a factor of 7.

- the measurement of the antiproton magnetic moment with a fractional precision of 1.5 p.p.b., based on a new method invented by BASE. In this measurement, the measurement [1] has been improved by a factor of about 350. Results by other groups [2] have been improved by a factor of more than 2000.

- the measurement of the proton magnetic moment with a fractional precision of 0.3 p.p.b., which improved the previous best value [6], also measured by BASE, by a factor of 11.
  G. Schneider et al., Science 358, 1081 (2017) [7].
Motivation

• 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

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

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

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

Pseudo-magnetic field, with exclusive coupling to antimatter

sensitive: comparisons of particle/antiparticle magnetic moments in traps
## Precision in Proton/Antiproton Magnetic Moment Measurements

<table>
<thead>
<tr>
<th>Year</th>
<th>Proton ( g_p/2 )</th>
<th>Antiproton ( g_{\bar{p}}/2 )</th>
<th>Collaboration</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>2.792 847 353 (28)</td>
<td>2.786 2 (83)</td>
<td>Pask (ASACUSA)</td>
<td>MASER / Exotic Atoms</td>
</tr>
<tr>
<td>2012</td>
<td>2.792 846 (7)</td>
<td></td>
<td>diSciacca (ATRAP)</td>
<td>Single Penning-trap</td>
</tr>
<tr>
<td>2013</td>
<td>2.792 845 (12)</td>
<td></td>
<td>diSciacca (ATRAP)</td>
<td>Single Penning-trap</td>
</tr>
<tr>
<td>2014</td>
<td><strong>2.792 847 349 8 (93)</strong></td>
<td></td>
<td>Mooser (BASE)</td>
<td>Double Penning-trap</td>
</tr>
<tr>
<td>2015</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td></td>
<td>2.792 846 5 (23)</td>
<td>Nagahama (BASE)</td>
<td>Single Penning-trap</td>
</tr>
<tr>
<td>2017</td>
<td><strong>2.792 847 344 62 (82)</strong></td>
<td><strong>2.792 847 344 1 (42)</strong></td>
<td>Schneider / Smorra (BASE)</td>
<td>Double Penning-trap / TTM</td>
</tr>
</tbody>
</table>

### Fractional Uncertainty

<table>
<thead>
<tr>
<th>Year</th>
<th>Proton</th>
<th>Antiproton</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>10^{-12}</td>
<td></td>
</tr>
<tr>
<td>2017</td>
<td>10^{-9}</td>
<td></td>
</tr>
</tbody>
</table>
Main Tool: Penning Trap

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

Axial confinement: \( \Phi(\rho, z) = V_0 c_2 \left( z^2 - \frac{\rho^2}{2} \right) \)

Axial confinement: \( \nu_z = 680 \text{kHz} \)
Magnetron: \( \nu_\perp = 8 \text{kHz} \)
Modified Cyclotron: \( \nu_\parallel = 28.9 \text{MHz} \)

**Invariance-Relation**

Cyclotron Frequency

\[ v_c = \sqrt{v_\parallel^2 + v_\perp^2 + v_z^2} \]

\[ v_c = \frac{1}{2\pi} \frac{q_{\text{ion}}}{m_{\text{ion}}} B \]

Cyclotron frequency relates measurable quantity to fundamental properties of trapped charged particle.
Continuous Stern-Gerlach Effect

\[ \frac{\mu_p}{\mu_N} = \frac{g_p}{2} \frac{e_p/m_p}{e_p/m_p} = \frac{v_L}{v_c} \]

Image Current Measurements

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

Measurement based on continuous Stern Gerlach effect.

Energy of magnetic dipole in magnetic field

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

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 function of 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.

\[ \Delta \nu_z \sim 170 \, \text{mHz} \]

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

co-magnetometer measurement

- co-magnetometer measurement
- single particle in the magnetic bottle

- measurement
- repeated the scheme in total six times

- task: resolve these two «cut» frequencies

\[
g \mathbf{p}^2 = \frac{\mathbf{v}_L}{c} L \mathbf{c}
\]

- evaluate g-factor
Result and Limitations

Result

• from six independent g-factor measurements

\[ \frac{g_p}{2} = 2.792\,846\,5\,(23) \]

• noise driven random walk in the magnetron mode traces magnetic field.

\[ \frac{dv_c}{v_c} = -\frac{1}{2\pi^2 m_p v_z^2 B_2} \frac{B_2}{B_0} dE = \frac{5.2\,\text{p.p.m.}}{\mu\text{eV}} dE \]

Ultimately limits g-factor measurement to the 1 p.p.m. to 0.1 p.p.m. level
Can we do better?

- probably, by putting a lot of effort in we would be able to reach with the single-trap method the 0.1 p.p.m. level.

- apply alternative measurement schemes: multi-trap methods
"Simplest": The Double Penning-Trap Method

- **Analysis Trap (AT)**
  - \( B_{2,AT} = 276000 \text{Tm}^{-2} \)
  - Inhomogeneous magnetic field for spin state analysis

- **Precision Trap (PT)**
  - \( B_{2,PT} = 0.1 \text{Tm}^{-2} \)

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

- **Comparison**
  - Single-trap method
  - Multi-trap method

\[
\text{spin flip probability} \frac{\nu_L}{\nu_c}
\]

\[
\text{Amplitude (dBm)}
\]
The Double Penning-Trap Method

Initialize the spin state

1.) measure cyclotron $\nu_c$

2.) drive spin transition at $\nu_{rf}$

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

no spin-flip in PT

spin flipped in PT
Challenges – High-Fidelity Single Spin-Flip Resolution

• To conclude in which quantum state the particle leaves / returns from precision trap, the double trap method requires **high-fidelity spin-state resolution**

• this is the game changer...

...where all the work is in...

**SSF resolved**

resolving single antiproton spin flips is a challenge
Challenges – High-Fidelity Single Spin-Flip Resolution

observation of antiproton spin transitions with high-fidelity requires ultra-cold particles

• Physics

  • heating by rf at a noise density of about 100 pV/√Hz drive radial cyclotron quantum transitions.

  • transition rates scale with the cyclotron quantum number.

\[
\frac{dn_{+,-}}{dt} \approx \frac{q^2}{2m_p h v_{+,-}} \Lambda^2 \langle e_n(t), e_n(t - \tau) \rangle
\]
Sub-Thermal Cooling

- Cold particle is prepared by resistive cooling in the PT

- Thermalize particle (6 min.)

- Analyze temperature using the magnetic bottle

- 12 min.

- Particle below threshold -> MEASURE

- Particle above threshold

- NOTE: particles with single spin-flip resolution are in this temperature range

- NOTE: each cyclotron frequency measurement heats the particle to about 300K

- Works (see BASE-Mainz measurements), but sub-thermal cooling is EXTREMELY time consuming
Current Time Budget of a (CERN) Double-Trap Experiment

- spinach analysis
- frequency measurements
- transport
- sub-thermal cooling
- maintenance
**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 useable for measurements
Transport Heating

- 3 months to optimize the transport such that acceptable heating rates were reached (involving details you’re not interested in)

- finally achieved: 17 mK/√cycle

- enables on average about 75 cycles without cooling
### 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><strong>0.44</strong></td>
<td><strong>1.020</strong></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.

Classical trap shifts

Shifts induced by 2 particle approach

This dominant error is not present in double trap measurements.

Has been estimated with the conservative 95% C.L.
The Magnetic Moment of the Antiproton

$g_p/2 = 2.792\,847\,350 \pm 9$

$g_{\bar{p}}/2 = 2.792\,847\,344 \pm 42$

first measurement more precise for antimatter than for matter...

...so how about the proton magnetic moment?

The Magnetic Moment of the Proton

- Compared to the CERN experiment, the Mainz experiment is much advanced.
  - more homogeneous magnetic field
  - more stable magnetic field
  - 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

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

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

methods developed to improve antiproton moment by at least a factor of 5
| Year | Proton \( g_p/2 \) | Antiproton \( g_{\bar{p}}/2 \) | CPT \( |g_p/g_{\bar{p}}| - 1 \) | 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) |

\[
g_p/g_{\bar{p}} - 1 = -0.000 \ 000 \ 000 \ 002 \ (15)\]
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 | $5 \times 10^{-25}$ | $2 \times 10^{-12}$ |

SME:

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

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

Sensitivity (GeV): 

- electron/positron
- muon ($\mu^-$, $\mu^+$)
- proton/antiproton

Spin transition energy and coupling strength $b_3$ (GeV)
Reservoir and Lifetime

• comparably rapid progress is mainly enabled by unique reservoir trap

\[ \tau_{\text{trap}} = 405 \text{ d} \]
\[ \tau_P > 10.2 \text{ a} \]

Imagine we wouldn’t have the reservoir...
2017 – Run -> Prepare to Measure at Higher Precision

!!! STABILIZE !!!

- Measure faster
- Improve absolute stability

Improved cyclotron detector for faster cooling

Improved pressure and flow stabilization system for stronger decoupling from the AD-recovery manifold

Improved magnetic shielding

$S = 100$
BASE is prepared to further improve fractional uncertainties in measurements of the fundamental properties of protons and antiprotons.
Improvements and Future Plans

• New laser-cooling instrument at Mainz available for faster (quasi deterministic) cooling of single protons and antiprotons.

• Some BASE members were involved in the recent proton mass measurement, in this experiment a fractional resolution of 20 p.p.t. was achieved in a novel trap system.

Thanks for your attention!