Electromagnetic Properties of Antihydrogen and the Antiproton: Recent results from ALPHA and BASE

Daniel Maxwell
ALPHA Collaboration
Antiprotons at CERN

The antiproton decelerator (AD) provides $\sim 2 \times 10^7$ antiprotons every 120 s at $\sim 5$ MeV.

Summary of AD physics

- Aim: Tests of CPT invariance and the weak equivalence principle through direct measurements on antimatter.
- Motivation: Search for evidence of physics beyond the standard model, insight into the matter/antimatter asymmetry problem.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Precision Range</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASACUSA</td>
<td>$m_{\bar{p}} / m_e$</td>
<td>M. Hori <em>et al.</em>, Science <strong>354</strong>, 610 (2016)</td>
</tr>
<tr>
<td>BASE</td>
<td>$(q / m)_{\bar{p}} / (q / m)_p$</td>
<td>S. Ulmer <em>et al.</em>, Nature <strong>524</strong>, 196 (2015)</td>
</tr>
<tr>
<td>BASE</td>
<td>$\bar{p} g / 2$</td>
<td>C. Smorra <em>et al.</em>, Nature <strong>550</strong>, 371 (2017)</td>
</tr>
</tbody>
</table>
Recent results from BASE: measurement of antiproton magnetic moment.

Recent results from ALPHA: measurement of antihydrogen 1S-2S lineshape, and antihydrogen ground-state hyperfine splitting.

Outlook for antihydrogen physics at ALPHA.
**BASE overview**

**Observation of spin flips with a single trapped proton**

- S. Ulmer, et al., **PRL** 106, 253001 (2011)

**Proton g-factor measurement**

\[
g/2 = 2.792847350 (7) (6)
\]

First direct high precision measurement of the proton magnetic moment.

**Precise CPT test with baryons**


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

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

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**

H. Nagahama, et al., **Nature Comms.** 8, 14084 (2017)

C. Smorra et al., **Nature** 550, 371 (2017)

\[
g/2 = 2.7928465 (23)
\]

Sixfold improvement compared to previous measurement

\[
g/2 = 2.792 847 344 1 (42)
\]

350-fold improvement compared to previous measurement
**Penning Trap**

Axial

\[ \nu_z = 680 \text{ kHz} \]

Magnetron

\[ \nu_- = 8 \text{ kHz} \]

Modified Cyclotron

\[ \nu_+ = 28.9 \text{ MHz} \]

Invariance relation:

\[ \nu_c = \sqrt{\nu_+^2 + \nu_-^2 + \nu_z^2} \]
Penning Trap

Axial Motion $v_z = 680 \text{ kHz}$

Magnetron Motion $v_- = 8 \text{ kHz}$

Modified Cyclotron Motion $v_+ = 28.9 \text{ MHz}$

Invariance relation: $v_c = \sqrt{v_+^2 + v_-^2 + v_z^2}$

Cyclotron Motion
(Image-current measurements)

$$\omega_c = \frac{q}{m_p} B$$

Larmor Precession
(Continuous Stern Gerlach effect)

$$\omega_L = g \frac{q}{2m_p} B$$

The ratio of these frequencies gives $g$, the magnetic moment in units of $\mu_N$.

$$\frac{\omega_L}{\omega_c} = \frac{g}{2} = \frac{\mu_p}{\mu_N}$$
Magnetic Moment Measurements

Use the continuous Stern Gerlach effect:

- A highly inhomogeneous magnetic field is super-imposed on the Penning Trap (a “magnetic bottle”).
  \[ B_z = B_0 + B_2 (z^2 - \frac{\rho^2}{2}) \]

- Energy of magnetic dipole in magnetic field:
  \[ \Phi_M = - (\vec{\mu}_p \cdot \vec{B}) \]

- Inhomogeneity leads to spin-dependent quadratic axial potential – axial frequency depends on spin state.
  \[ \Delta v_z \sim \frac{\mu_z B_z^2}{m_p} \]

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Magnetic Moment Measurements

Use the continuous Stern Gerlach effect:

- A highly inhomogeneous magnetic field is super-imposed on the Penning Trap (a “magnetic bottle”). \( B_z = B_0 + B_2 (z^2 - \rho^2 / 2) \)

- Energy of magnetic dipole in magnetic field: \( \Phi_M = - (\vec{\mu} \cdot \vec{B}) \)

- Inhomogeneity leads to spin-dependent quadratic axial potential – axial frequency depends on spin state. \( \Delta v_z \sim \mu_p B_2 / m_p \nu_z \)

- Very challenging for proton/antiproton system: \( B_2 \sim 3 \times 10^5 \text{ T/m}^2 \rightarrow \Delta v_z \sim 170 \text{ mHz} \)

- Spin-flips are driven using a RF-field, and the resulting axial frequency shift measured.

S. Ulmer, A. Mooser et al. PRL 106, 253001 (2011)
0.8 p.p.m Measurement

Resolve these frequencies to determine $g_p$
0.8 p.p.m Measurement

- 6-fold improvement on previous best measurement.
- The sharpness of slope of the onset of the resonances is limited by a random walk in the magnetron mode, changing the magnetic field sampled.

\[ g \bar{p} / 2 = 2.7928465 \ (23) \]

H. Nagahama et al., Nat. Commun. 8, 14084 (2017)
Double-Penning Trap, Two-Particle Method

Measure spin flip probability as a function of drive frequency in the homogeneous magnetic field of the precision trap.

1) Measure cyclotron $v_c$  
2) Drive spin transition at $v_{rf}$

no spin-flip in PT

spin-flip in PT
Spin-state resolution

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

The cyclotron energy of the Lamor particle must be < 0.2 K, otherwise axial frequency fluctuations in the analysis trap are too large to resolve SSF.
The magnetic moment of the antiproton

\[ \frac{g_p}{2} = 2.7928473441 (42) \]


\[ \frac{g_p}{2} = 2.79284734462 (82) \]

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

- 1.5 p.p.b measurement of the antiproton g-factor.
- In agreement with the proton g–factor, measured to 0.3 p.p.b.
BASE collaboration

Slides provided by BASE spokesperson, Stefan Ulmer.
ALPHA Overview

The goal of the ALPHA experiment is to perform precision comparisons of the properties of antihydrogen with those of hydrogen.

Milestones:

- **2010**: Trapped antihydrogen.
- **2010**: Antihydrogen confinement for 1000s.
- **2011**: Observation of microwave driven spin-flips.
- **2016**: Observation of the 1S-2S transition.
- **2016**: Measurement of the ground-state hyperfine splitting.
- **2017**: Characterisation of the 1S-2S transition lineshape.


ALPHA-1 apparatus
ALPHA-2 apparatus
ALPHA-2 Apparatus

Antiproton “catching trap”  Antihydrogen “atom trap”
Antihydrogen synthesis

- Slowly merge the particles (in 1s) by lowering the barrier between them.
- We typically mix 3 million positrons (at ~20K) with 90,000 antiprotons (at ~50K) forming around 50,000 antihydrogen atoms.

Trap positrons and antiprotons in adjacent potential wells of a Penning-Malmberg trap.
Antihydrogen synthesis

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Trap positrons and antiprotons in adjacent potential wells of a Penning-Malmberg trap.
Antihydrogen trapping

The magnetic field at the trap center is \( \sim 1 \text{T} \), and the trap depth corresponds to \( \sim 0.5 \text{K} \).

Before mixing the particles, a magnetic minimum trap is energised consisting of an octupole and five mirror coils.

The magnetic field at the trap center is \( \sim 1 \text{T} \), and the trap depth corresponds to \( \sim 0.5 \text{K} \).
Antihydrogen detection

- We detect antihydrogen by ramping down the trap magnets to release the atoms.
- Image the annihilation products with a silicon vertex detector.
- Event topology allows us to distinguish antiproton annihilations from cosmic rays.
- Reconstruction efficiency: 0.69
- Background: 40mHz.
Antihydrogen accumulation

We can accumulate trapped antihydrogen through multiple mixing cycles, and have demonstrated trapping of $>1000$ atoms in this way.

\[
\text{Number of } \bar{\text{H}} \text{ detected}
\]

\[
\text{Number of mixing cycles}
\]

\[0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5
\]

\[0 \quad 10 \quad 20 \quad 30 \quad 40 \quad 50 \quad 60 \quad 70
\]

\[0 \quad 2 \quad 2 \quad 1
\]

\[26 \quad 5
\]

\[\text{ALPHA Collaboration, Nat. Comms. 8, 681 (2017).}\]
1S-2S experiment

Measure the resonant frequency of the $1S_d-2S_d$ transition, and compare with the expected value in hydrogen (in the same trap environment).

We require:
- Knowledge of the magnetic field at the trap center.
- Sufficient laser intensity to excite the two-photon transition (at ~243nm).
- The 243nm laser is frequency stabilized to a ULE cavity and referenced to a frequency comb.
- The enhancement cavity is locked to the 243nm laser giving 1W of power inside the atom trap.
1S-2S experiment procedure

- Exposing atoms to light for 300s, at a fixed frequency.
- Remove atoms in the $1S_c$ state by driving positron spin-flip transition to the $1S_b$ (non-trappable) state.
- Turn off the trapping field, and measure how many atoms are still in the trap (disappearance measurement).

Measure the resonant frequency of the $1S_d-2S_d$ transition, by:

- Exposing atoms to light for 300s, at a fixed frequency.
- Look for atoms leaving the trap during laser excitation period (appearance measurement).
1S-2S lineshape

![Graph showing normalized signal vs. detuning (D) with data points for disappearance and appearance, and a 1000 mW simulation curve.]

Disappearance, $r_s(D)$
Appearance, $r_l(D)$

1000 mW Simulation

1S-2S lineshape

Fit: \[ f_{d-d} = 2,466,061,103,079.4 \ (5.4) \ kHz \]

Calculated: \[ f_{d-d} = 2,466,061,103,080.3 \ (0.6) \ kHz \]

Measured resonance frequency is consistent with the expected resonance frequency in hydrogen, and therefore consistent with CPT invariance, to a precision of $2 \times 10^{-12}$. 
Measurement of hyperfine splitting

- We inject microwaves at around 28GHz to drive positron spin-flip transitions $|c\rangle$ to $|b\rangle$, and $|d\rangle$ to $|a\rangle$.
- Frequency difference between the transitions is the ground-state hyperfine splitting, independent of B-field.

- Due to the highly inhomogeneous magnetic field, the transition lineshapes are strongly broadened.
Ground-State Hyperfine Splitting

- Scan microwave frequency over each transition in 300kHz increments (4s pulses).

- Determine the ground-state hyperfine splitting from the separation of the onsets of the two transitions to be: $1420.4 \pm 0.5$ MHz.

Outlook

• Laser cooling of antihydrogen.
• Improved precision measurement of the 1S-2S resonance frequency.
• Gravitational measurements on antihydrogen: the ALPHA collaboration is currently constructing a new experiment (ALPHA-g) where we will study the free-fall of antihydrogen in a vertical trap.
Matter-antimatter comparisons

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


N. F. Ramsey, Rev. Mod. Phys. 62, 541 (1990)

M. Ahmadi et al., Nature 548, 66 (2017)
Thank you for your attention!
### Additional slides: 1S-2S

<table>
<thead>
<tr>
<th>Laser detuning, $D$ (kHz)</th>
<th>Number of trials</th>
<th>Atoms lost during laser exposure, $L$</th>
<th>Atoms lost during microwave exposure, $M$</th>
<th>Surviving atoms, $S$</th>
<th>Initially trapped atoms, $N_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set 1</td>
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<td></td>
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</tr>
<tr>
<td>-200</td>
<td>21</td>
<td>$7 \pm 7$</td>
<td>$383 \pm 23$</td>
<td>$504 \pm 25$</td>
<td>$894 \pm 35$</td>
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<tr>
<td>-100</td>
<td>21</td>
<td>$22 \pm 9$</td>
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<td>$494 \pm 24$</td>
<td>$931 \pm 35$</td>
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<td>$75 \pm 14$</td>
<td>$411 \pm 23$</td>
<td>$424 \pm 23$</td>
<td>$910 \pm 35$</td>
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<tr>
<td>Set 2</td>
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<td>$26 \pm 9$</td>
<td>$394 \pm 23$</td>
<td>$466 \pm 24$</td>
<td>$886 \pm 34$</td>
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<tr>
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<td>$113 \pm 16$</td>
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<td>$219 \pm 22$</td>
<td>$390 \pm 23$</td>
<td>$269 \pm 18$</td>
<td>$878 \pm 37$</td>
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<td>$173 \pm 20$</td>
<td>$438 \pm 24$</td>
<td>$296 \pm 19$</td>
<td>$907 \pm 37$</td>
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<tr>
<td>Set 3</td>
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<tr>
<td>-200</td>
<td>23</td>
<td>$8 \pm 7$</td>
<td>$354 \pm 22$</td>
<td>$479 \pm 24$</td>
<td>$841 \pm 33$</td>
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<td>0</td>
<td>23</td>
<td>$303 \pm 26$</td>
<td>$454 \pm 25$</td>
<td>$248 \pm 17$</td>
<td>$1,005 \pm 40$</td>
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<tr>
<td>+50</td>
<td>23</td>
<td>$176 \pm 20$</td>
<td>$390 \pm 23$</td>
<td>$339 \pm 20$</td>
<td>$905 \pm 37$</td>
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<tr>
<td>+200</td>
<td>23</td>
<td>$36 \pm 11$</td>
<td>$446 \pm 24$</td>
<td>$459 \pm 23$</td>
<td>$941 \pm 35$</td>
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<td>Set 4</td>
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<td>$525 \pm 26$</td>
<td>$541 \pm 25$</td>
<td>$1,073 \pm 37$</td>
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<td>-50</td>
<td>21</td>
<td>$86 \pm 15$</td>
<td>$475 \pm 25$</td>
<td>$495 \pm 24$</td>
<td>$1,056 \pm 38$</td>
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<td>0</td>
<td>21</td>
<td>$274 \pm 25$</td>
<td>$480 \pm 25$</td>
<td>$275 \pm 18$</td>
<td>$1,029 \pm 40$</td>
</tr>
<tr>
<td>+25</td>
<td>21</td>
<td>$202 \pm 21$</td>
<td>$516 \pm 26$</td>
<td>$305 \pm 19$</td>
<td>$1,023 \pm 38$</td>
</tr>
<tr>
<td>Total</td>
<td>344</td>
<td>1,991</td>
<td>6,917</td>
<td>6,137</td>
<td>15,045</td>
</tr>
</tbody>
</table>

\[
r_i(D) = \frac{L(D)}{L(0)} \quad r_s(D) = \frac{S(-200\text{kHz}) - S(D)}{S(-200\text{kHz}) - S(0)}
\]
### Error Budget 1S-2S

<table>
<thead>
<tr>
<th>Type of Uncertainty</th>
<th>Estimated Size (kHz)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical Uncertainties</td>
<td>3.8</td>
<td>Poisson errors and curve fitting to measured data</td>
</tr>
<tr>
<td>Modelling Uncertainties</td>
<td>3</td>
<td>Fitting of simulated data to piecewise-analytic function</td>
</tr>
<tr>
<td>Modelling Uncertainties</td>
<td>1</td>
<td>Waist size of the laser, antihydrogen dynamics</td>
</tr>
<tr>
<td>Magnetic-field Stability</td>
<td>0.03</td>
<td>From microwave removal of 1S\textsubscript{c}-state atoms (see text)</td>
</tr>
<tr>
<td>Absolute Magnetic-field Measurement</td>
<td>0.6</td>
<td>From electron cyclotron resonance</td>
</tr>
<tr>
<td>Laser-frequency Stability</td>
<td>2</td>
<td>Limited by GPS clock</td>
</tr>
<tr>
<td>d.c. Stark Shift</td>
<td>0.15</td>
<td>Not included in simulation</td>
</tr>
<tr>
<td>Second-order Doppler Shift</td>
<td>0.08</td>
<td>Not included in simulation</td>
</tr>
<tr>
<td>Discrete Frequency Choice of Points</td>
<td>0.36</td>
<td>Determined from fitting sets of pseudo-data</td>
</tr>
<tr>
<td>Total</td>
<td>5.4</td>
<td></td>
</tr>
</tbody>
</table>

The estimated statistical and systematic errors (at 121 nm) are tabulated.
Additional slides: power dependence 1S-2S
Additional slides: Relative precision

- antihelium \((m/q)\)
- antideuteron \((m/q)\)
- kaon \(\Delta m\)
- \(e^+ g/2\)
- \(\mu^+ g/2\)
- \(m_{\bar{p}}/m_e\)
- \((q/m)_{\bar{p}}/(q/m)_p\)
- \(\bar{p} g/2\)
- \(\bar{H} 1S-2S\)
- \(\bar{H} GS HFS\)
Additional slides: Energy Sensitivity

- $\text{kaon } \Delta m$
- $\overline{\rho} g / 2$
- $\overline{\text{H } 1S-2S}$
- $\overline{\text{H GS HFS}}$

Energy Sensitivity (GeV)


M. Ahmadi et al., Nature 548, 66 (2017)