Antiprotonic Helium: Measuring the Antiproton Mass and Magnetic Moment

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Outline

- CPT Invariance and its Tests
- The Antiproton Decelerator at CERN
- $\bar{p}$-He Spectroscopy
- The Charge and Mass of the Antiproton
- The Magnetic Moment of the Antiproton
- Outlook


CPT Invariance

Charge conjugation: \( C |p(r, t)\rangle = |\bar{p}(r, t)\rangle \)

Space reflection: \( P |p(r, t)\rangle = |p(-r, t)\rangle \)

Time reversal: \( T |p(r, t)\rangle = |p(r, -t)\rangle \)

Basic assumption of field theory:
\( CPT |p(r, t)\rangle = |\bar{p}(-r, -t)\rangle \sim |p(r, t)\rangle \)

meaning free antiparticle \( \sim \) particle

going backwards in space and time.

Giving up CPT one has to give up:

- locality of interactions \( \Rightarrow \) causality, or
- unitarity \( \Rightarrow \) conservation of matter, information, ... or
- Lorentz invariance
CPT Invariance: violation?

Theoreticians in general: \( CPT \) cannot be violated

\( CPT \)-violating theories:
(Alan Kostelecký, F.R. Klinkhamer, N.E. Mavromatos et al)

- **Standard Model** valid up to Planck scale \( (\sim 10^{19} \text{ GeV}) \).
  Above Planck scale new physics \( \Rightarrow \)
  Lorentz violation possible

- **Quantum gravity**: fluctuations \( \Rightarrow \) Lorentz violation
  loss of information in black holes \( \Rightarrow \) unitarity violation

Motivation for testing \( CPT \) at low energy

- **Quantitative expression** of Lorentz and \( CPT \) invariance
  needs violating theory

- **Low-energy tests** can limit possible high energy violation
How to test $CPT$?

Particle $= -$ antiparticle?

- $\frac{m(K^0) - m(\bar{K}^0)}{m(\text{average})} < 10^{-18}$
- proton $\sim$ antiproton? (compare $m, q, \vec{\mu}$)
- hydrogen $\sim$ antihydrogen? ($2S - 1S$, HFS)
Accelerators at CERN

1989–2000

2009–2025??

Dezső Horváth

Antiprotonic Helium

10-14 September 2012, Stara Lesna, Slovakia
The Antiproton Decelerator at CERN has been built to test CPT invariance

Three experiments test CPT:

**ATRAP:** \[ q(\bar{p})/m(\bar{p}) \leftrightarrow q(p)/m(p) \]
\[ \overline{H}(2S - 1S) \leftrightarrow H(2S - 1S) \]

**ALPHA:** \[ \overline{H}(2S - 1S) \leftrightarrow H(2S - 1S) \]

**ASACUSA:** \[ q(\bar{p})^2m(\bar{p}) \leftrightarrow q(p)^2m(p) \]
\[ \mu_\ell(\bar{p}) \leftrightarrow \mu_\ell(p) \]
\[ \overline{H} \leftrightarrow H \text{ HF structure} \]

**RED:** done, \hspace{1cm} **GREEN:** planned

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The Antiproton Decelerator: cooling

- pbar injection
- Bunch rotation
- Stochastic cooling 6.6 s.
- Electron cooling 8 s.
- Rebunching
- Fast Extraction

~ $4 \times 10^7$ 100 MeV/c antiprotons every 85 s

Mass and Charge of Antiproton

Proton’s well (?) known:

\[ m(p)/m(e) = 1836.15267245(75) \]
\[ q(e) = 1.602176565(35) \times 10^{-19} \text{ C} \]

Precision: \( 4 \cdot 10^{-10} \) and \( 2 \cdot 10^{-8} \)

Relative measurements: proton vs. antiproton

Cyclotron frequency in trap \( \rightarrow q/m \)

\[ \text{TRAP} \Rightarrow \text{ATRAP} \text{ collaboration} \]

Harvard, Bonn, München, Seoul

\( \bar{p} \) and \( H^- \) together \( \Rightarrow 10^{-10} \) precision

Atomic transitions:

\[ E_n \approx -m_{\text{red}} c^2 (Z\alpha)^2/(2n) \rightarrow m \cdot q^2 \]

\[ \text{PS-205} \Rightarrow \text{ASACUSA} \text{ collaboration} \]

Tokyo, Brescia, Budapest, Debrecen, Munich, Vienna
Metastable hadronic atoms

In matter (gas, liquid, solid) $\tau(\text{hadron}) \sim 1 \text{ ps}$ except $\sim 3\%$ of $X^{-}\text{He}$: $K^{-}, \pi^{-}$: decay lifetime; $\bar{p}$: $3–4 \mu s$

Metastable 3-body system
Auger suppressed, slow radiative transitions only

Electron cloud protects $\bar{p}$ against collisions
Electron tightly bound: $1S$; $\bar{p}$: $n \sim 40$, $l \sim n - 1$ Rydberg
\( \bar{p}\text{-He}^+ \): spectroscopy motivation

- Vladimir Korobov calculates \( \bar{p} \) transition frequencies in \( \bar{p}\text{-He}^+ \) with the precision of \( \sim 10^{-9} \)

- Determination of antiproton-to-electron mass ratio to \( 1.3 \times 10^{-9} \).
  \( \rightarrow \) Dimensionless fundamental constant of nature.

- Determination of electron mass in a.u. to \( 1.3 \times 10^{-9} \)
  \( \rightarrow \) One of the data points for CODATA2010 average.

- When combined with cyclotron frequency of antiprotons in a Penning trap measured by the TRAP collaboration, comparison of antiproton and proton mass and charge to \( 7 \times 10^{-10} \)
  \( \rightarrow \) CPT consistency test in PDG2012.
Energy levels of $\bar{p}$He$^4$

Level energies in eV, transition wavelengths in nm
Laser spectroscopy of antiprotonic helium

Induce transition between long-lived and short-lived states

Force prompt annihilation
Laser spectroscopy of antiprotonic helium

Laser spectroscopy: LEAR vs AD

LEAR: slow extraction
$10^6$ laser shots, 50 min

AD: fast extraction
1 laser shot, 2 min

Gated phototube: prompt annihilation (97% $\bar{p}$) off
(Hamamatsu)
Transition frequencies in isolated $\overline{p}$He$^+$ atoms

Exp. precision limited by: collisions, Doppler broadening, laser bandwidth

- **1996-2002:** measured density dependence, extrapolated to zero
- **2003-2004:** reduced collisional effects by stopping slow $\overline{p}$ from RFQ post-decelerator in low-pressure ($<1$ mbar), cryogenic target
- **2005-2007:** reduce laser bandwidth using frequency comb
- **2008:** start 2-photon spectroscopy

Last published CPT-violation limit by 1-photon spectroscopy:

2 ppb ($2 \times 10^{-9}$) at CL 90%.

Radiofrequency quadrupole decelerator

Focussing-defocussing in alternate planes

\[ U \sim 170 \, \text{kV}; \quad f \sim 202 \, \text{MHz}; \quad \text{bias} \sim \pm 55 \, \text{kV} \]

5.3 MeV → 65 keV: efficiency \( \sim 30\% \)
Resolution and stability

Dramatic improvement of resolution and stability

Resonance profile of the \((n, \ell) = (37, 35) \rightarrow (38, 34)\) transition at \(\lambda = 726.1\) nm

2010: He at \(T = 1.5K\), Ti:Sapphire pulsed laser
Determination of $m(\bar{p})$, $q(\bar{p})$

Determination of antiproton mass and charge: possible deviation from those of the proton

**TRAP:** $m/Q$; **ASACUSA:** $m \cdot Q^2$
Two-photon spectroscopy

In low density gas main precision limitation: thermal Doppler broadening even at $T < 10$ K

Excite $\Delta \ell = 2$ transition with 2 photons

Two counterpropagating photons with $\nu_1 \sim \nu_2$ eliminate 1st order Doppler effect

Laser linewidth should not overlap with resonance
1-photon vs 2-photon spectroscopy

\[ \Delta E \]

Virtual state

\( \text{(36,34)} \)

\( \text{(35,33)} \)

\( \text{(34,32)} \)
Near-resonant two-photon spectroscopy

\[(n, \ell) = (36, 34) \rightarrow (34, 32)\]

Doppler suppression:

\[
\Delta \nu_{\gamma_1 \gamma_2} = \left| \frac{\nu_1 - \nu_2}{\nu_1 + \nu_2} \right| \Delta \nu_{\text{Doppler}}
\]

Gain: \(~ 20 \times\)

Limitation: residual Doppler, frequency chirp systematics

Expected \(\Delta f \sim \text{few MHz}\)
Two-photon spectroscopy: setup

M. Hori et al., *Nature* 475 (2011) 484-488
Two-photon spectroscopy: parameters

- Precision of lasers: \(< 1.4 \times 10^{-9}\).
- \(7 \times 10^6 \ \text{p/pulse}, \ E \approx 70 \text{ keV}, 200 \text{ ns long, } \varnothing 20 \text{ mm.}\)
- Target: He gas, \(T \approx 15 \text{ K}, \ p = 0.8 - 3 \text{ mbar}\)
- Laser beams: \(\lambda_1 = 417 \text{ nm}, \ \lambda_2 = 372 \text{ nm, } P \approx 1 \text{ mJ/cm}^2\)
- Transition: \((n=36, \ l=34) \rightarrow (n=34, \ l=32); \ \Delta \nu = 6 \text{ GHz}\)
- Measured linewidth: \(\approx 200 \text{ MHz}\)
- Width: Residual Doppler broadening, hyperfine structure, Auger lifetime, power broadening.

**Nature** 475 (2011) 484-488
Two-photon spectroscopy: spectra

M. Hori et al., Nature 475 (2011) 484-488

Arrows: hyperfine transitions
# Two-photon spectroscopy: uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>error (MHz)</th>
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</thead>
<tbody>
<tr>
<td>Statistics</td>
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<tr>
<td>Collisional shift</td>
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<tr>
<td>A.c. Stark shift</td>
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<tr>
<td>Zeeman shift</td>
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<td>Frequency chirp</td>
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<td>Laser freq. cal.</td>
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<tr>
<td>Hyperfine structure</td>
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<tr>
<td>Line profile sim.</td>
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<tr>
<td>Total systematic</td>
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<tr>
<td>Total experimental</td>
<td>3.5</td>
</tr>
<tr>
<td>Theory</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Experiment-theory (Korobov) comparison of spin-averaged transition frequency

For $p^4\text{He}^+$:
- $(36,34) \rightarrow (34,32)$

For $p^3\text{He}^+$:
- $(33,32) \rightarrow (31,30)$
- $(35,33) \rightarrow (33,31)$

The graph shows the comparison of experimental and theoretical frequencies with the difference in units of parts per billion (ppb).
Two-photon spectroscopy: results

\[ \frac{M_p}{m_e} = 1836.1526736(23) \]

Uncertainties:

\[ 1.8 \times 10^{-6} \text{(stat)}, \ 1.2 \times 10^{-6} \text{(syst)}, \ 1.0 \times 10^{-6} \text{(theor)} \]

Good agreement with proton results, similar (slightly higher) uncertainty.

Assuming CPT invariance our result can be included in the determination of \( M_p \) and \( m_e \).

Using the TRAP limit for difference of \( Q/M \) for the proton and the antiproton and averaging our three values we can establish an upper limit for the charge and mass difference (i.e. possible CPT violation) at

\[ 7 \times 10^{-10} \]

on a 90% confidence level.

M. Hori et al., Nature 475 (2011) 484-488
Measuring the magnetic moment of $\bar{p}$
Level splitting in $\bar{p}$He$^+$ atoms

Step 1: depopulation of $F^+$ doublet with $f_+$ laser pulse

Step 2: equalization of populations of $F^+$ and $F^-$ by microwave

Step 3: probing of population of $F^+$ doublet with 2nd $f_+$ laser pulse

Magnetic moments

$\mu(p) \sim \mu(\bar{p}) \Rightarrow CPT$ invariance OK


Microwave frequency scan
$^{4}\bar{p}He$ HF structure: expt vs. theory

$\bar{p}^3\text{He}$ HF structure: laser scan

Auger decaying daughter state

Radiatively decaying parent state

Interaction:
- $S_{\pm}$
- $S_h$
- $S_p$

Laser: 723 nm

MW: 16 GHz, 11 GHz

$\Delta f = 1.72\pm0.03$ GHz

$\triangleright$ verify splitting of laser transition lines
$\triangleright$ determine laser resonance frequency

$\triangleright$ fit with 4 Voigt functions plus constant for signal background
$^3$He HF structure: microwave scan

![Microwave frequency scans](image)

$V_{HF} = 11.12548 \text{GHz}$

<table>
<thead>
<tr>
<th>$\nu_{HF}^- (\text{GHz})$</th>
<th>$\delta_{HF}^- (\text{ppm})$</th>
<th>$\Gamma (\text{MHz})$</th>
<th>Korobov [37,70]</th>
<th>$\Delta \nu_{\text{mb-exp}} (\text{ppm})$</th>
<th>Kino [41]</th>
<th>$\Delta \nu_{\text{HF-exp}} (\text{ppm})$</th>
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<tbody>
<tr>
<td>11.125 48(09)</td>
<td>7.2</td>
<td>1.69(0.11)</td>
<td>11.125 00(55)</td>
<td>43</td>
<td>11.125 15(55)</td>
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<td>11.157 93(13)</td>
<td>11.7</td>
<td>2.20(0.15)</td>
<td>11.157 73(55)</td>
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<td>11.157 56(55)</td>
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<tr>
<td>$\Delta \nu_{HF}$ (GHz)</td>
<td>0.03245(15)</td>
<td>523.9</td>
<td>0.0327219(16)</td>
<td>48.9</td>
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</tr>
</tbody>
</table>

Comparison of Theory & Experiment

Results published in Physics Letters B
→ Publication on final results is in progress

Theory
Y. Kino et al., Hyperfine Interactions 146 331 (2003).
Conclusion

- The first sub-Doppler two-photon spectroscopy of antiprotonic helium: two transitions in $^4\text{He}$ and one in $^3\text{He}$. Results agree with 3-body QED calculations.

- Determined $M_\overline{p}/m_e$ ratio to 1.3 ppb. Result agrees with CODATA proton value (0.4 ppb).

- Further improvement partially hindered by theoretical uncertainty (QED terms $< \alpha^6$, radiative recoil corrections)

Future prospects

- Colder atoms, better lasers, better detectors

- ELENA (colder antiproton beams at 100 keV of higher luminosity)

- Use more transitions, collect more statistics
Thanks for your attention
MUSASHI: slow antiproton beam

Monoenergetic
Ultra
Slow
Antiproton
Source for
High-precision
Investigations

Musashi Miyamoto self-portrait ~ 1640

5.8 MeV $\bar{p}$ injected into RFQ
100 keV $\bar{p}$ injected into trap
$10^6 \bar{p}$ trapped and cooled (2002)
$\sim 350000$ slow $\bar{p}$ extracted (2004)
Cold $\bar{p}$ compressed in trap (2008)
$(5 \times 10^5 \bar{p}, E = 0.3 \text{ eV}, R = 0.25 \text{ mm})$