ASACUSA: Measuring the Antiproton Mass and Magnetic Moment

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Outline

- CPT Invariance and its Tests
- The Antiproton Decelerator at CERN
- The Charge and Mass of the Antiproton
- The Magnetic Moment of the Antiproton
- Outlook: ELENA


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?

Field theorists 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?

\[ \frac{m(K^0) - m(\overline{K}^0)}{m(\text{average})} < 10^{-18} \]

- proton \sim\text{ anti}proton? (compare \( m, q, \vec{\mu} \))
- hydrogen \sim\text{ anti}hydrogen? (\( 2S - 1S \), HFS)
Accelerators at CERN

1989–2000

2009–2025??

Dezső Horváth
ASACUSA
9 October 2013, St. Petersburg, Russia
The Antiproton Decelerator at CERN has been built to test CPT invariance.

Three experiments test CPT:

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

**ALPHA:** \( \bar{H}(2S' - 1S') \leftrightarrow H(2S' - 1S') \)

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

**RED:** done,  **GREEN:** planned
The Antiproton Decelerator: cooling

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

Proton’s well (?) known:

\[ \frac{m(p)}{m(e)} = 1836.15267245(75) \]

\[ q(e) = 1.602176565(35) \times 10^{-19} \text{ C} \]

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

Relative measurements: proton vs. antiproton

Cyclotron frequency in trap \( \rightarrow \frac{q}{m} \)

TRAP \( \Rightarrow \) ATRAP collaboration

Harvard, Bonn, München, Seoul

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

Atomic transitions:

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

PS-205 \( \Rightarrow \) ASACUSA collaboration

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

In matter (gas, liquid, solid) $\tau$(hadron) $\sim 1$ ps
except $\sim 3\%$ of $X^{-}$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: $1S$

$\bar{p}$He: $n \sim 40$, $l \sim n - 1$, Rydberg state
\( \overline{p} \text{-He}^+ \): spectroscopy motivation

- Vladimir Korobov calculates \( \overline{p} \) transition frequencies in \( \overline{p} \text{-He}^+ \) 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 $\bar{p}\text{He}^4$

Level energies in eV, transition wavelengths in nm

Metastable $\bar{p}\text{He}^+$

Auger-Dominated $\bar{p}\text{He}^+$

$\bar{p}\text{He}^{2+}$ Ion
Induce transition between long-lived and short-lived states

Force prompt annihilation
ASACUSA: Spectroscopy setup

AD beam 100 MeV/c

Ti window 20 μm

vacuum window 50 μm Kapton

PMT with light guide

Cerenkov counter

He gas

cryostat

entrance window Ti 20 μm

beam profile monitor

quartz windows

laser beam
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 $\bar{p}$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 $\bar{p}$ 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 \(T = 1.5 K\), Ti:Sapphire pulsed laser
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


Few Body Syst. 54 (2013) 917-922.
1-photon vs 2-photon spectroscopy

Virtual state

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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: \(\sim 20 \times\)

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: \( < 1.4 \times 10^{-9} \).
- \( 7 \times 10^6 \ \overline{\text{p}}/\text{pulse}, \ E \approx 70 \ \text{keV}, \ 200 \ \text{ns long}, \ \varnothing 20 \ \text{mm} \).
- 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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<tbody>
<tr>
<td>Statistics</td>
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<td>Collisional shift</td>
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<td>A.c. Stark shift</td>
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<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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<td>Line profile sim.</td>
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<tr>
<td>Total systematic</td>
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<tr>
<td>Total experimental</td>
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<tr>
<td>Theory</td>
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</tbody>
</table>

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

- $p \quad ^4\text{He}^+$
  - $(36,34) \rightarrow (34,32)$
  - $(33,32) \rightarrow (31,30)$

- $p \quad ^3\text{He}^+$
  - $(35,33) \rightarrow (33,31)$

$\frac{(\nu - \nu_{\text{exp}})}{\nu_{\text{exp}}}$ (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


$^\Lambda^4\text{He} \text{ HF structure: expt vs. theory}

\begin{align*}
\text{MW Freq (MHz)}
\end{align*}

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

$\textbf{p}^3\text{He HF structure: microwave scan}$

Comparison of Theory & Experiment

Results published in Physics Letters B
$\rightarrow$ Publication on final results is in progress

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

S. Friedreich et al.
Plans, future prospects

- Colder atoms \((T = 1.6 \, \text{K})\), better lasers, better detectors (segmented scints)
- Use more transitions, collect more statistics
- ELENA (colder antiproton beams at 100 keV of higher luminosity)
- Spectroscopy on \(\overline{\text{H}}\) beam
MUSASHI: slow $\bar{p}$ and $\bar{H}$ beam

Monoenergetic
Ultra
Slow
Antiproton
Source for
High–precision
Investigations

Musashi Miyamoto self-portrait $\sim$ 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 $\times$ $10^5$ $\bar{p}$, $E = 0.3$ eV, $R = 0.25$ mm)

$\bar{H}$-beam formed for in-flight spectroscopy: 2010-2012
Spectroscopy with $\bar{\text{H}}$ beam

$\bar{\text{H}}$ spectr in flight: polariser, resonator, analyser

Analogy: polarised light


E. Widmann et al., progress reports in conf. papers
Extra Low ENergy Antiprotons

Success of RFQ post-decelerator of ASACUSA ⇒ CERN decided to build storage ring ELENA.


AD:
5.8 MeV $\bar{p}$, $3 \times 10^7$/shot
ELENA:
100 keV $\bar{p}$,
1.8 $\times 10^7$/shot
4 bunches to 4 expts every 120 sec

Dániel Barna:
Design of beam line
Segmented detectors for Paul trap

A. Sótér, K. Todoroki, T. Kobayashi, D. Barna, D. Horváth, M. Hori:

Submitted to Nucl. Instr. Meth

Trap design: D. Barna, M. Hori
Conclusion

- The first sub-Doppler two-photon spectroscopy of antiprotonic helium: two transitions in \(^4\)He and one in \(^3\)He. Results agree with 3-body QED calculations.
- Determined \(M_p/m_e\) 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)
- Big improvement expected from ELENA in 2016.
Thanks for your attention