Testing CPT with antiprotonic helium and Antihydrogen

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PANIC Conference
MIT, July 25, 2011

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Matter-antimatter symmetry

- **Cosmological scale:**
  - asymmetry

- **CPT violation**
  - Microscopic:
    - symmetry?
Ways to violate CPT

• SME Kostelecky

\[ (i \gamma^\mu D_\mu - m_e - a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu - \frac{1}{2} H^e_{\mu \nu} \sigma^{\mu \nu} + ic^e_{\mu \nu} \gamma^\mu D^\nu + id^e_{\mu \nu} \gamma_5 \gamma^\mu D^\nu) \psi = 0. \]

CPT & Lorentz violation

• Foam and unitarity violation

SPACE–TIME FOAMY SITUATIONS
NON UNITARY (CPT VIOLATING) EVOLUTION
OF PURE STATES TO MIXED ONES

Montag, 25. Juli 2011

E. Widmann
Current source: AD @ CERN
ASACUSA collaboration @ CERN-AD

Atomic Spectroscopy And Collisions Using Slow Antiprotons

Spokesperson: R.S. Hayano, University of Tokyo

- University of Tokyo, Japan
  - College of Arts and Sciences, Institute of Physics
  - Faculty of Science, Department of Physics
- RIKEN, Saitama, Japan
- SMI, Austria
- Aarhus University, Denmark
- Max-Planck-Institut für Quantenoptik, Munich, Germany
- KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
- ATOMKI Debrecen, Hungary
- Brescia University & INFN, Italy
- University of Wales, Swansea, UK
- The Queen’s University of Belfast, Ireland

~ 44 members
Spectroscopy for tests of CPT and QED

• Antiprotonic helium
  • laser and microwave spectroscopy CPT
test antiproton properties
  • mass, charge: $2 \times 10^{-9}$
  • magnetic moment: $2.9 \times 10^{-3}$
  • most precisely calculated 3-body system
Spectroscopy for tests of CPT and QED

- **Antiprotonic helium**
  - laser and microwave spectroscopy CPT test antiproton properties
  - mass, charge: $2 \times 10^{-9}$
  - magnetic moment: $2.9 \times 10^{-3}$
  - most precisely calculated 3-body system

- **Antihydrogen**
  - hydrogen measured to the highest precision
  - 1S-2S: $10^{-14}$
  - ground-state HFS: $10^{-12}$
Antiprotonic helium „atomcule“

Energy (a.u.)

$I_0 = 0.90$ a.u. (24.6 eV)

$0^+ = 0.90$ a.u. (24.6 eV)

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

Auger decay

Stark mixing

Radiative transitions

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

Nuclear absorption & Annihilation

$\sqrt{\frac{M^*}{m_0}} \sim 38$

$n_0 = 38$

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Antiprotonic helium „atomcule“

Energy (a.u.)

$|\tilde{\rho}^4\text{He}^+\rangle$

$|\tilde{\rho}^4\text{He}^{++}\rangle$

Ionized $\tilde{\rho}\text{He}^{++}$

Auger decay

Stark mixing

Radiative transitions

Neutral $\tilde{\rho}\text{He}^+$

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Nuclear absorption 
& Annihilation

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Neutral $\tilde{\rho}\text{He}^+$

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Nuclear absorption 
& Annihilation
Antiprotonic helium „atomcule“

\[ \text{Neutral } p\text{He}^0 \rightarrow \text{ Ionized } p\text{He}^{++} \]

Energy (a.u.)

\( l_0 = 0.90 \text{ a.u. (24.6 eV)} \)

\( n_0 = \sqrt{\frac{M^+}{m_e}} \approx 38 \)

Nuclear absorption & Annihilation

Stark mixing

Auger decay

Radiative transitions

Neutral pHe

\[ n(s) \rightarrow 30 \]

\[ n(s) \rightarrow 31 \]

\[ n(s) \rightarrow 32 \]

\[ n(s) \rightarrow 33 \]

\[ n(s) \rightarrow 34 \]

\[ n(s) \rightarrow 35 \]

\[ n(s) \rightarrow 36 \]

\[ n(s) \rightarrow 37 \]

\[ n(s) \rightarrow 38 \]

theory vs. experiment

\( \nu_{\text{th}} - \nu_{\text{exp}} \)

\( \nu_{\text{exp}} \) (ppb)

laser spectroscopy:

\( m_p/m_e = 1836.152674(5) \)

M. Hori et al. PRL 96 (2006) 243401

listed in PDG

included in CODATA as proton value

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Magnetic moment of the antiproton

\[ (\nu_{HF^-} - \nu_{HF^+}) \sim \mu \]

Target pressure (mbar)

MW frequency (MHz)

Theory

Hyperfine structure

\( F' = L + 1/2 \)

\( F = L - 1/2 \)

\( J' = L \)

\( J = L - 1 \)

\( \nu_{HF} \)

\( \nu_{HF^-} \)

\( \nu_{HF^+} \)

\( \nu_{SHF^-} \)

\( \nu_{SHF^+} \)

\( J'^+ = L + 1 \)

\( J^- = L \)

\( \sum_{i} \)

The points represented by the data can be averaged to obtain a final value.

The absolute values for the magnetic moments of the proton and antiproton have reached less than 150 mbar in (a).

The authors would like to acknowledge V. Korobov (Joint Institute for Nuclear Research) for the support of the experiment.

The individual transition frequencies have a negligible dependence on reduced chi-squared number of antiprotons captured.

Despite these considerations, the magnetic moment of the antiproton is directly proportional to this frequency source, shot-to-shot microwave power fluctuations and uncontrollable fluctuations of the AD pressure.

The limit of experimental precision has been reached for the magnetic moment of the antiproton, but yields no further information.

The predicted density shift for the point between experiment and the closest theory is more thorough test of the theory but yields no further information.

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Magnetic moment of the antiproton

\[(V_{HF}^- - V_{HF}^+) \sim \mu\]

Hyperfine structure

Comparison theory-experiment

\[\mu_s^p = -2.7862(83) \mu_N\]

\[\frac{\mu_s^p - |\mu_s^p|}{\mu_s^p} = (2.4 \pm 2.9) \times 10^{-3}\]


listed in PDG
Magnetic moment of the antiproton

\[(V_{HF}^− - V_{HF}^+) \sim \mu\]

Hyperfine structure

Comparison theory-experiment

\[\mu_S = -2.7862(83) \mu_N\]

\[\frac{\mu_p^+}{|\mu_S^p|} = (2.4 \pm 2.9) \times 10^{-3}\]


listed in PDG

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Hydrogen and Antihydrogen

HYDROGEN

Bohr  Dirac  Lamb  HFS

HFS  Lamb  Dirac  Bohr

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Hydrogen and Antihydrogen

1s-2s
2 photon
λ=243 nm
Δf/f=10^{-14}
Hydrogen and Antihydrogen

**HYDROGEN**

- Ground state hyperfine splitting \( f = 1.4 \text{ GHz} \)
- \( \Delta f/f = 10^{-12} \)

1s-2s
2 photon
\( \lambda = 243 \text{ nm} \)
\( \Delta f/f = 10^{-14} \)

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Precision Spectroscopy of Hydrogen and CPT

- Sensitivities
- 1S-2S
  - Electron mass
  - Proton mass
  - Proton charge

\[ \nu_{1S-2S} \]

\[ \Delta_{\text{CPT}}(m_e) \]

\[ \Delta_{\text{CPT}}(m_p) \]

\[ \Delta_{\text{CPT}}(r_p) \]

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Precision Spectroscopy of Hydrogen and CPT

- Sensitivities
- 1S-2S
  - Electron mass $\Delta_{\text{CPT}}(m_e)$
  - Proton mass $\Delta_{\text{CPT}}(m_p)$
  - Proton charge $\Delta_{\text{CPT}}(R_p)$
- 2S-2P (Lamb shift)
  - $R_p$

![Graph showing transition frequencies and sensitivities with indicative values and uncertainties.](image-url)
Precision Spectroscopy of Hydrogen and CPT

• Sensitivities
• $1S-2S$
  • Electron mass $\Delta_{\text{CPT}}(m_e)$?
  • Proton mass $\Delta_{\text{CPT}}(m_p)$
  • Proton charge $\Delta_{\text{CPT}}(R_p)$
• $2S-2P$ (Lamb shift)
  • $R_p$
• GS-HFS
  • Proton magnetic moment $\mu_p$
  • $\mu_e$
  • Proton magnetic radius $R_M$
• Theory
  • $R_p$ and $R_M$
Precision Spectroscopy of Hydrogen and CPT

- Sensitivities
- \(1S-2S\)
  - Electron mass \(\Delta_{\text{CPT}}(m_e)\)
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Energy scale (GeV):

- \(10^{-18}\)
- \(10^{-21}\)
- \(10^{-24}\)
- \(10^{-27}\)

K0 limit

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New idea: \( \overline{\text{H}} \) Formation in a “cusp” trap

- First antihydrogen production in 2010
- expectation: polarized beam

Y. Yamazaki, A. Mohri
RIKEN/Japan

Y. Enomoto et al.

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Experiments

• **Ongoing: Rabi method**

  ![Diagram of Rabi method](image)

  Linewidth reduced by $D/L$

  $Δv/v ~ 10^{-7}$

• **Phase 2: Ramsey separated oscillatory fields**

  ![Diagram of Ramsey method](image)

  Linewidth reduced by $D/L$
Future experiments

- Phase 3: trapped Hbar
- Hyperfine spectroscopy in an atomic fountain of antihydrogen

M. Kasevich, E. Riis, S. Chu, R. DeVoe,
PRL 63, 612–615 (1989)
Future experiments

- **Phase 3: trapped Hbar**
- Hyperfine spectroscopy in an atomic fountain of antihydrogen

Confinement of antihydrogen for 1,000 seconds

M. Kasevich, E. Riis, S. Chu, R. DeVoe,
PRL 63, 612–615 (1989)

ALPHA collaboration
G. B. Andresen et al.
Nature Physics, 7, 1–7 (2011)
Summary and Outlook
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  • Fundamental symmetries, gravitation, nuclear & atomic physics
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    • Long-term high-precision experiments need
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• CERN-AD is unique in the world
• More low-energy antiprotons needed
  • ELENA upgrade at CERN (recently approved, start 2014?)
  • FLAIR at FAIR (next decade)