Antihydrogen Spectroscopy
Part 2: Testing CPT, 1S–2S spectroscopy, and optical frequency measurements

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• Stepwise excitation is a competing process to four-wave sum-frequency mixing.

• But it can be useful, nevertheless.

• We use fluorescence at 1014 nm wavelength (out of the $7^1S_0$ state) as a diagnostic for overlapping beams.
Two-photon resonance

- The two-photon resonance of the beams at 253 nm and 408 nm with the $7^1S_0$ state in mercury is an essential part of Lyman-alpha generation.
- Fixed detuning of the UV beam, scan the blue beam.
- Observe the fluorescence out of the $7^1S_0$ state.

- Two-photon peaks, coherent excitation, $\delta_{23} = \delta_{13}$
- Double single-photon peak, successive excitation, $\delta_{23} = 0$
- Velocity-selective double resonance, atoms of one velocity class are resonant with both beams, $\delta_{23}/k_{23} = \delta_{13}/k_{13}$

Thomas Beyer et al., to be published.
Towards enhanced Lyman-alpha generation in a resonator

- Optical enhancement cavity for three wavelengths:

  projected VUV enhancement = \( 0.63 \times 105 \times 0.75 \times 70 \times 0.3 \times 40 = 42000 \)

- Mercury heatpipe:

  mercury evaporation residue on Brewster window
1.) **Today:**

- Trapping of antihydrogen
- Laser-cooling of trapped antihydrogen
- Continuous-wave Lyman-alpha source

2.) **Wednesday:**

- Using antihydrogen spectroscopy to test CPT
- Ultrahigh-resolution Doppler-free two-photon laser spectroscopy
- Optical metrology / frequency combs

3.) **Thursday:**

- Hyperfine spectroscopy
- The magnetic moment of the antiproton
- Beyond Lyman-alpha laser-cooling
1 S–2 S-Spectroscopy test of the CPT symmetry

Doppler-free two-photon laser-spectroscopy of the 1S–2S transition in atomic hydrogen using an ultrastable dye-laser and a cold hydrogen atomic beam.

line center: $2466\,061\,413\,187\,103(46)$ Hz

M. Niering et al., PRL 84 (2000) 5496
M. Fischer et al., PRL 92 (2004) 230802

Goal: Measure antihydrogen transition frequencies.

The CPT theorem: For any process, the mirror image, antiparticle, and time-reversed process will look exactly the same. Identical spectra
Comparing hydrogen and antihydrogen transition frequencies could provide very stringent tests of CPT.
CPT tests: need test model with CPT violation

Local, point-particle quantum field theories:

CPT theorem (Pauli, Lüders, Bell, '54): "Lorentz symmetry implies CPT invariance"

\[
\text{CPT transf.} \begin{cases} 
- \text{rotations} \\
- \text{boosts} 
\end{cases}
\]

\[
\text{CPT transf.} \begin{cases} 
- \text{charge conjugation C} \\
- \text{parity inversion P} \\
- \text{time reversal T} 
\end{cases}
\]

Anti-CPT theorem (Greenberg, PRL '02): "CPT violation implies Lorentz breaking"

- CPT tests are also Lorentz tests
- will discuss CPT and Lorentz violation together
**Pre-Relativity Situation**

- **Galilean symmetry** believed valid for **over 200 years**
- Agreement with observations, incl. planetary motion:
  \[ v \sim 30 \text{ km/s} \sim 10^{-4} \text{ c} \]
- Extrapolation of validity by 3-4 orders of magnitude fails
- Conceptual difficulties with Maxwell’s electrodynamics

**Present Situation**

- **Lorentz symmetry** believed valid for about **100 years**
- Agreement with observations
  \[ E \sim 10^{12} \text{ GeV} \sim 10^{-8} E_{\text{Planck}} \]
- Extrapolate validity of Lorentz symmetry to \( E_{\text{Planck}} \) and far beyond
- Conceptual difficulties with **Quantum Gravity**
Quantum gravity combines

Quantum physics: $h = 6.6 \cdot 10^{-34}$ J$\cdot$s
Special Relativity: $c = 3.0 \cdot 10^8$ m/s
Gravity: $G = 6.7 \cdot 10^{-11}$ N$\cdot$m$^2$/kg$^2$

→ quantum-gravity scale likely to be set by these constants

$E_{\text{Planck}} = \sqrt{\frac{hc}{2\pi G}} = 1.2 \times 10^{19}$ GeV $\sim 10^{15}$ $E_{\text{LHC}}$

$L_{\text{Planck}} = \sqrt{\frac{hG}{2\pi c^3}} = 1.6 \times 10^{-35}$ m $\sim 10^{-20}$ $R_{\text{electron}}$

the corresponding measurements are an enormous challenge
suggests two possibilities for implementation of LV

(1) modification of transfs. between inertial frames
   - relatively simple
   - purely kinematical
   - purely phenomenological
   **Examples:**
   - Robertson's framework
   - its Mansouri-Sexl extension
   - mod. disp. rel. (next slide)

(2) nontrivial vacuum, LT are maintained
   - **motivated** by candidate fundamental theories
     (see Sec C)
   - fully dynamical+microscopic description possible
     (see next section on SME)
   - incorporates some of the kinematical approaches

**deformed “lightcone”**
- no longer Lorentzian spacetime structure
- vacuum remains empty

**lightcone**
- structure of underlying spacetime unchanged
- vacuum contains background with direction
How to obtain low-energy effective theory?

fundamental theory
(noncommutative geometry, strings, varying couplings, ...)?

Issue: presently no complete and realistic fundamental theory

low-energy effective theory (SME)

Idea: - examine manifestations of Lorentz/CPT violating vacuum
- construct all possible modifications to SM (previous sec.)

Advantage: - independent of underlying theory
- describes all low-energy effects of Lorentz violation
Testing the CPT symmetry by antihydrogen spectroscopy


Ralf Lehnert (MPI f. Physik)

modified Dirac equation for an electron in the proton Coulomb potential

\[
\left( i \gamma^\mu \partial_\mu - q \gamma^\mu A_\mu - m_e - a_\mu^e \gamma^\mu - b_\mu^e \gamma 5 \gamma^\mu - \frac{1}{2} H_{\mu\nu}^e \sigma^{\mu\nu} + i c_\mu^e \gamma^\mu D^\nu + i d_\mu^e \gamma 5 \gamma^\mu D^\nu \right) \Psi = 0
\]

\[\text{standard Dirac equation} \otimes \text{CPT violating} \otimes \text{CPT preserving terms}\]

\[\rightarrow \text{leading-order energy shifts:}\]

\[
\Delta E^{(H/\bar{H})}(m_J,m_I) \approx \left( a^e_0 + b^e_0 - c^e_0 m_e - d^e_0 m_p \right) + \left( -b^p_3 - d^p_3 m_e + H^e_{12} \right) m_J/|m_J| + \left( -b^p_3 - d^p_3 m_p + H^p_{12} \right) m_I/|m_I|
\]

1S–2S frequency difference:

\[\Delta^{H-\bar{H}} \nu_{1S-2S} \approx -(b^e_3 - b^p_3)/\pi\]

Ground state HFS frequency difference:

\[\Delta^{H-\bar{H}} \nu_{\text{HFS}} \approx -2b^p_3/\pi\]
Some tests involving antimatter

(i) Antihydrogen spectroscopy

The 1s-2s transition

- allowed 2-photon 1s-2s transitions

\[ |d\rangle_2 \]
\[ |c\rangle_2 \]
\[ |b\rangle_2 \]
\[ |a\rangle_2 \]

\[ |d\rangle_1 \]
\[ |c\rangle_1 \]
\[ |b\rangle_1 \]
\[ |a\rangle_1 \]

only the c, d states are trapped

\[ |d\rangle_n = |\frac{1}{2}, \frac{1}{2}\rangle \]  \textbf{Note: no spin mixing}

\[ |c\rangle_n = \sin \theta_n |\frac{1}{2}, -\frac{1}{2}\rangle + \cos \theta_n |\frac{1}{2}, \frac{1}{2}\rangle \]

with \[ \tan 2\theta_n \approx \frac{51 \text{mT}}{n^3 B} \]

\textbf{Note: } \theta_n, \text{ and thus spin mixing, depends on level } n \text{ and field } B

How are d→d and c→c transitions affected by Lorentz/CPT violation?
The $d_2 \rightarrow d_1$ transition with Lorentz/CPT violation

Leading-order energy shifts (Bluhm, Kostelecký, Russell, PRL '99)

Hydrogen (electron and proton angular momenta $J$ and $I$):

$$\Delta E_{LV} = \Delta E_{e+p} + \Delta E_e \frac{m_j}{|m_j|} + \Delta E_p \frac{m_I}{|m_I|}$$

level-independent combinations of Lorentz-/CPT-violating SME coefficients

Note: both $d_1$ and $d_2$ have $m_j = 1/2$ and $m_I = 1/2$ → shift is level independent

Result: no leading-order Lorentz/CPT violation in $d_2 \rightarrow d_1$ transition
The $c_2 \rightarrow c_1$ transition with Lorentz/CPT violation

Difference between $H$ and $\bar{H}$ transition frequencies (Bluhm, Kostelecký, Russell, PRL '99):

- level-dependent spin mixing → unsuppressed signal
- $\Delta E_H - \Delta E_{\bar{H}} \approx \kappa \Delta E_{e+p}$
- combination of Lorentz-/CPT-violating SME coefficients

Result:
- leading-order Lorentz/CPT violation in $c_2 \rightarrow c_1$ transition
- experimental issue: effect is $B$-field dependent
Hyperfine Zeeman transitions within the 1s state

Difference between H and $\bar{H}$: $d1 \rightarrow c1$ transition frequencies
(Bluhm, Kostelecký, Russell, PRL '99):

$$\delta E^H_{cd} - \delta E^\bar{H}_{cd} \approx (\text{CPT-}/\text{Lorentz-violating SME coefficient for } p)$$

Instantaneous comparison assuming 1m Hz resolution:
$10^{-26}$ GeV sensitiv. to CPT- / Lorentz-violating SME coefficient for p.
another class of tests: searches for sidereal variations

observables $\sim \vec{b} \cdot \vec{B}$ (e.g., transition frequencies) are time dependent:

$\Delta E \rightarrow \Delta E(t)$

one sidereal day
2003: Hydrogen 1S-2S spectrometer
Hydrogen spectrometer, February 2003
The Hydrogen Cold Atomic Beam

- Hydrogen atoms
- Cold finger
- Lyman-α detector
- 243 nm
- Vacuum system
- Solarblind photomultiplier tube
- Time resolved photon-counting
- LHe
- Graphite-coated net
- 6 Kelvin
- U quench
- Chopper
Hydrogen 1S-2S resonance

$\Delta \nu/\nu = 4.3 \times 10^{-13}$ Hz @ 243 nm

2S signal [cps] vs. detuning [kHz @ 243 nm]
Frequency spectrum in optical frequency synthesis

Log Frequency (Hz)

- $10^{15}$
- $10^{14}$
- $10^{13}$
- $10^{12}$
- $10^{11}$
- $10^{10}$
- $10^7$

Molecular overtones

- H$_2$O
- CH$_4$
- CO$_2$
- CH$_3$OH
- HCOOH
- HCN
- OsO$_4$
- BWO

- Cs
- H, Hg$^+$
- Ca
- I$_2$
- Rb, Cs

FIG. 1. PTB’s frequency chain to the Ca intercombination line (PLL = phase locked loop, details are given in the text).
Optical Frequency Comb Synthesizer
\[ f_m = m \, f_{\text{rep}} + f_{\text{offset}} \]
Self-referencing frequency comb

R. Holzwarth et al.,

D. Jones et al.,
Science 288, 635 (2000)

T.W. Hänsch,
Witnessed disclosure
(March 30, 1997)
measuring the frequency of hydrogen with a laser comb

1. Take an extremely stable laser and divide the light into two beams.
2. Adjust the frequency of the laser so that it exactly matches the energy difference in the hydrogen atom.
3. Measure the frequency of the light in the other laser beam with an optical frequency comb.
Hydrogen 1S-2S Absolute Frequency

\[ f(1S-2S) = 2,466,061,413,187,103 (46) \text{ Hz} \]

(hyperfine centroid)

1S–2S-Spectroscopy with hydrogen in a magnetic trap

1 S–2 S-Spectroscopy with hydrogen in a magnetic trap


$10^{10} - 10^{13}$ atoms at 0.1 mK – 25 mK

cold collision frequency shift
and Bose-Einstein condensation

FIG. 1. Schematic diagram of optical excitation and detection apparatus. The UV beam is aligned along the axis of the magnetic trap. The beam traverses the cloud of trapped atoms (typically 10 cm long, 500 μm diameter), and is retroreflected. After a UV excitation pulse, the (metastable) 2S atoms are detected by applying an electric field across the quench plates which mixes the 2S state with the 2P state (1.6 ns lifetime). The resulting $L_\alpha$ photons are detected with the microchannel plate.

FIG. 5. Determination of the lifetime of 2S atoms in the trap: $T \approx 250 \mu$K, $n \approx 4 \times 10^{12} \text{cm}^{-3}$. The atoms were excited by short UV pulses and quenched after a variable delay. This procedure was repeated $10^4$ times. The straight line is the best fit by an exponential decay. The error bars represent statistical fluctuations only. In this particular trap configuration, the lifetime is 110 ms. Lifetimes between 50 and 100 ms have been observed for other trap configurations. A systematic study of the experimental factors that affect the lifetime measurements has not been carried out.
1S–2S Spectroscopy with hydrogen in a magnetic trap

FIG. 2. 1S–2S excitation spectrum displaying a time of flight profile. The UV detuning (at 243 nm) is \( \delta \). The density is \( 3 \times 10^{12} \text{ cm}^{-3} \), the temperature is 1.7 mK, and the UV power is \( \approx 1.5 \text{ mW} \). The total UV exposure time at each point is 2.7 s. Here the dominant source of broadening is the finite interaction time of an atom moving across the UV beam, which leads to an exponential spectrum: \( \exp(-|\delta|/\delta_0) \). The solid line corresponds to \( \delta_0 = 11 \text{ kHz} \), which yields a full width at half maximum of 15 kHz.

FIG. 4. 1S–2S excitation spectrum in the regime of motional narrowing. Each data point represents a total exposure of 350 ms. The upper solid line is the calculated spectrum including the effects of trap anharmonicity, photoionization, and an estimated laser linewidth. The best fit is for a laser linewidth of 3.0 kHz (full width at half maximum) at 243 nm. From the curve the sample temperature is found to be 150 \( \mu \text{K} \). The lower curve is the line shape calculated for a monochromatic light source. Inset: schematic diagram of trap vibrational states on the 1S and 2S electronic manifolds, indicating allowed transitions from the lowest three 1S trap states.
Shelving spectroscopy with a single ion in a trap


FIG. 2. Recording of the Ba$^+$ resonance fluorescence at 493 nm (upper trace) vs scanned frequency of red laser light (full scan $\approx$ 10 min). Background pressure $10^{-8}$ mbar. Three ions are present in the trap. Downward steps mark transitions to $^2D_{\frac{5}{2}}$ accompanied by quenching of the interaction with the laser light. The feature 300 MHz below line center marks the two-photon (or Raman) resonance $^1S_{\frac{1}{2}}$-$^2D_{\frac{5}{2}}$. The formation of Raman coherence considerably reduces light scattering and optical cooling. The lower trace is the optogalvanic signal from a hollow-cathode discharge.

FIG. 3. Resonance fluorescence, at 493 nm, of single Ba$^+$ vs time. Green laser 300 MHz down from line center, red laser at center frequency. The signal corresponds to 4000 counts/s.
Shelving spectroscopy with a single (anti-)hydrogen atom in a trap?

- Set the 243 nm laser to a fixed frequency.
- Detect single two-photon excitation events with 100 % quantum efficiency utilizing the resonance fluorescence at Lyman-\(\alpha\).
- Measure for a while → determine the excitation probability
- Set the 243 nm laser to the next frequency.
- ⇒ excitation probability as a function of 243 nm laser frequency
- ⇒ high-resolution spectroscopy with just a single atom
- not demonstrated for neutral atoms, yet
Outline: “Antihydrogen Spectroscopy”

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