Antihydrogen Spectroscopy
Part 1: Trapping, Cooling, and Lyman-alpha

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International School of Physics “Enrico Fermi”
“Physics with many Positrons”
Course CLXXIV
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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.

hydrogen 1S–2S spectroscopy:

M. Fischer
N. Kolachevsky
M. Niering

frequency-measurement:

Th. Udem
R. Holzwarth
M. Zimmermann

T. W. Hänsch

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.
Antiproton sources

The “Antiproton Decelerator” (AD) at CERN: the only existing source of low-energy antiprotons. Up to $3.5 \times 10^7$ antiprotons at 100 MeV/$c$ every 86 s to:

- ATHENA ($\bar{\Lambda}$) → ALPHA & AEGIS
- ATRAP ($\bar{\Lambda}$)
- ASACUSA ($\bar{p}$-He, $\bar{\Lambda}$-HFS)
- pbarmedical

Facility for Low-Energy Antiproton and Ion Research (FLAIR) at Darmstadt:
- might become the most intense source of cooled antiproton beams
- slow & fast extraction
Antihydrogen physics – recent progress of ATRAP

1995 in-beam production of fast antihydrogen
antiproton Penning-trap mass measurement
ultrahigh-resolution hydrogen laser-spectroscopy

1997 cold antihydrogen proposals: production / trapping / spectroscopy

2000 CERN’s Antiproton Decelerator starts

2002 cold antihydrogen production in three-body collisions
by mixing cold positron and antiproton plasmas

2003 measurement of antihydrogen
Rydberg states, recombination rates, velocities

2004 laser-controlled antihydrogen production

2005 CERN: no beam

2006 antiproton and positron plasmas are stable
in the combined charged-particle & neutral atom trap

2007 antihydrogen production
in the combined charged-particle & neutral atom trap

next: magnetic trapping \[\rightarrow\] spectroscopy

ATRAP collaboration: Harvard, FZ Jülich, MPQ Garching, York (Toronto), Mainz
"State-of-the-Art" spectroscopy of atomic hydrogen: $10^{15} - 10^{17}$ atoms / s at < 8 K

Antihydrogen: 10⁷ antiprotons at 5 MeV every 2 minutes

many, many orders of magnitude...

1S-2S spectroscopy of antihydrogen at 0.2 K (Zeeman-broadening 20 kHz)
0.8 W power at 243 nm on 1 mm diameter
-> excitation rate 0.3 / s

Residual Zeeman-shift for 1 S–2 S transition ($F = 1, m_F = 1$) $\rightarrow$ ($F = 1, m_F = 1$):

186 kHz/T $/\div$ 0.67 K/T $=\Rightarrow$ 278 kHz/K

⇒ laser cooling to mK-temperatures necessary for precise 1 S–2 S spectroscopy

Radiation at Lyman-α will be essential for experiments with antihydrogen.

Laser-cooling of antihydrogen at 1 K down to ~ mK using radiation at Lyman-α: velocity change per photon: 3.3 m/s
-> need to scatter ~ 50 photons.
20 nW at 122 nm on 1 mm diameter
-> excitation rate 100/s

Shelving spectroscopy

Single 1S-2S excitation events in a single atom are detected using the strong Lyman-α transition.
Outline: “Antihydrogen Spectroscopy”

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
Magnetic trapping of (anti-)hydrogen atoms

Atoms in the upper two states are repelled from regions with increasing magnetic field → can be trapped

traps are extremely shallow:
1 Tesla ↔ 670 mK

Laser-cooling and laser-spectroscopy of antihydrogen

"State-of-the-Art" spectroscopy of atomic hydrogen:
\(10^{15} - 10^{17}\) atoms / s at < 8 K

antihydrogen:
10\(^7\) antiprotons at 5 MeV every 2 minutes
many, many orders of magnitude...

\[ \text{velocity change per photon: } 3.3 \text{ m/s} \]
\[ \rightarrow \text{need to scatter } \sim 50 \text{ photons.} \]
20 nW at 122 nm on 1 mm diameter
\[ \rightarrow \text{excitation rate } 100/\text{s} \]

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(Zeeman-broadening 20 kHz)
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Radiation at Lyman-\(\alpha\) will be essential for experiments with antihydrogen.

\(\text{Residual Zeeman-shift for 1 S–2 S transition} \quad (F = 1, m_F = 1) \rightarrow (F = 1, m_F = 1):\)
\[ 186 \text{ kHz/T} \bigg/ 0.67 \text{ K/T} = 278 \text{ kHz/K} \]
\[ \Rightarrow \text{laser cooling to mK-temperatures necessary for precise 1 S–2 S spectroscopy} \]
Cooling of neutral antihydrogen atoms in a magnetic trap

- **evaporative cooling**
  needs high densities

- **sympathetic cooling**
  has a problem with annihilation

- **laser cooling**
  possible, but requires laser radiation at Lyman-alpha

  (Anti-)hydrogen laser cooling limits:
  - Doppler limit: 2.4 mK (Rb: 140 µK)
  - recoil limit: 1.3 mK (Rb: 0.37 µK)
Generating radiation in the vacuum ultraviolet

four-wave mixing

\[
P_4 = \frac{9}{4} \frac{\omega_1 \omega_2 \omega_3 \omega_4}{\pi^2 c_0^2 c_0^2 b^2} \left( \frac{N}{\Delta k} \right)^2 \left| \chi^3 \right|^2 \left| \mathcal{P}_1 \mathcal{P}_2 \mathcal{P}_3 \right| \left| G(b\Delta k) \right|^2
\]

- \( \mathcal{P}_1 \mathcal{P}_2 \mathcal{P}_3 \): power product of the fundamental beams
- \( \left| \chi^3 \right|^2 \): nonlinear susceptibility (– resonance denominators!)
- \( b\Delta k \): phase-mismatch integral

phase-matching integral:

Gouy phase-shift in the focus:

plane waves: \( P_4 \) maximum for \( \Delta k = 0 \)

strongly focused beams:

\[
\left| G(b\Delta k) \right|^2 = \text{max.} = 46.3 \text{ for } (b\Delta k) = -4
\]

desirable: strong fundamental beams, resonances, and optimal phase-mismatch.
Pulsed laser cooling of hydrogen atoms in a magnetic trap

- cw dye laser
- pulse amplifier
- frequency doubler
- frequency tripler

Continuous four-wave mixing in mercury vapour

- Lyman-\(\alpha\) is at 121.6 nm in the vacuum-ultraviolet (VUV).
  - lenses & windows: \(T=50\%\)
  - mirrors: \(R=85\%\) max.
  - beams in vacuum or He

- in this wavelength region:
  - no tunable direct lasers
  - no frequency doubling crystals
  ➤ use higher-order nonlinear optical processes

- first generation Lyman-\(\alpha\) source:
  K. S. E. Eikema, J. W., and T. W. Hänsch

- 2nd generation Lyman-\(\alpha\) source:
  solid-state laser systems
Four-wave mixing in mercury vapour

- CW Ti:Sapph.
- Laser system
- Lyman-α generation
- Laser system
- Lyman-α generation
Frequency doubling cavities

in: 2.2 W @ 514 nm

out: 900 mW @ 257 nm

in: 1.5 W @ 798 nm

out: 600 mW @ 399 nm
VUV yield as function of wavelength

Improving the Lyman-alpha source

Better yield:
Output is sufficient for antihydrogen cooling times of minutes.
Shorter cooling times need higher power levels.

- “Recycle” the fundamental beams in an enhancement cavity
- Stretch the focus in a hollow fiber (filled with mercury vapor)
- Go closer to the one-photon resonance at 253.7 nm

Use reliable solid-state laser systems:

<table>
<thead>
<tr>
<th>λ</th>
<th>Garching</th>
<th>Mainz</th>
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<tbody>
<tr>
<td>257 nm</td>
<td>single-mode Ar⁺-laser &amp; SHG</td>
<td>→ disk-laser &amp; SHG &amp; SHG</td>
</tr>
<tr>
<td>399 nm</td>
<td>Ar⁺-laser / Ti:Sa-laser &amp; SHG</td>
<td>→ semiconductor MOPA &amp; SHG</td>
</tr>
<tr>
<td>545 nm</td>
<td>Ar⁺-laser / dye-laser</td>
<td>→ fibre MOPA &amp; SHG</td>
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Generation of continuous coherent radiation at Lyman-alpha

a laser-beam at 122 nm wavelength (Lyman-alpha) in the vacuum-ultraviolet \( \lambda_{\text{Lyman-alpha}} \approx \frac{1}{4} \lambda_{\text{visible}} \)
New cw Lyman-\(\alpha\) source at Mainz

- based on solid-state lasers:
  - **545 nm**
    - Yb-fibre laser at 1091 nm
    - + frequency-doubling in LBO
  - **408 nm**
    - diode-laser MOPA at 816 nm
    - + frequency-doubling in LBO
  - **253.7 nm**
    - Yb:YAG disc-laser at 1014 nm
    - + frequency-doubling in LBO
    - + frequency-doubling in BBO
Solid-state laser system in the UV at 253 nm

Yb:YAG disc laser \((g_{\text{max}} \text{ at } \sim 1030 \text{ nm})\)
- tuned from down to 1014 nm
frequency doubling in LBO to 507 nm
frequency doubling in BBO to 253 nm

yield:
up to 0.9 W
in the UV

Solid-state laser system in the blue at 408 nm

- Diode-pumped green pump-laser, 10.5 W at 533 nm

- Ti:Sapphire laser (Coherent 899), 1.3 W at 816 nm

- Frequency-doubling in Brewster-cut LBO crystal in an external enhancement cavity, 430 mW at 408 nm
Solid-state laser system in the yellow-green at 545 nm

Yb fibre laser at 1091 nm
frequency doubling in LBO to 545 nm
10 W → 3.5 W

iodine spectroscopy

F. Markert et al., Optics Express 15 (2007) 14476
Overlapping the fundamental beams

Beam shaping and alignment:
  - astigmatism compensation
  - large beams on the focussing lens
  → high focal intensity
  - divergence adjustment
  - beam alignment
  → foci at the same spot

After the mercury vapor cell:
- MgF₂ lens used as a dispersion monochromator
- Lyman-alpha interference filters
- solar-blind photomultiplier
Solid-state continuous coherent Lyman-alpha generation

yield at Lyman-alpha ≃ (two-photon resonance)$^2$

first “new” Lyman-alpha photons at Mainz

- optimal phasematching expected at $b\Delta k \simeq -4$
- $\Delta k$ depends on the dispersion in the mercury vapour
- scan the mercury temperature (→ density)

M. Scheid et al., Optics Express (2009) in press
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