Paving the way for bound-state QED tests in singly ionized helium

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Testing bound-state QED

Simple systems are the ideal probe:

- **Atomic hydrogen**
- Other hydrogenlike systems
  - Positronium, Muonium,
  - D, He⁺, ...
- Other light atoms:
  - He
- Simple molecules
  - H₂, HD, HD⁺, ...

Limitations due to the nuclear charge radius? → Use **muonic** atoms!

**Situation for He⁺:**
- Narrow 1S-2S transition
- Better sensitivity to higher-order QED terms (compared to H)
- Can be trapped
- Charge radius has been measured
Helium ion spectroscopy

**muonic He**

- Large mass of bound lepton!
- Sensitive to nuclear properties
- Determine polarizability or charge radius

**electronic He**

- Can be measured with high precision!
- Determine polarizability or charge radius
- Test (Z\(\alpha\))\(^6\ldots7\) QED terms

\[ \mu^- \quad \text{muonic He}^+ \]

\[ e^- \quad \text{electronic He}^+ \]

\[ \Delta E_{\text{exp}}(1S-2S) \]

Alpha charge radius + \[ R_\infty \]

Insert

QED

Probe
# Situation in Hydrogen-like Helium

Uncertainties which enter the theory determination of the 1S-2S transition frequency

<table>
<thead>
<tr>
<th>Bohr term (Rydberg constant $R_\infty$)</th>
<th>QED (higher order 2- and 3-loop)</th>
<th>Nuclear Size (alpha charge radius)</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_\infty$ from CODATA14/18</td>
<td>current status</td>
<td>$r_\alpha$ from scattering</td>
<td>Current status</td>
</tr>
<tr>
<td>57 kHz / 19 kHz (PRP: 320 kHz)</td>
<td>110 kHz</td>
<td>295 kHz</td>
<td></td>
</tr>
<tr>
<td>$R_\infty[\mu p+\text{H}(1S-2S)]$</td>
<td>future</td>
<td>$r_\alpha$ from $\mu^4\text{He}^+$</td>
<td>projected</td>
</tr>
<tr>
<td>9 kHz</td>
<td>~10 kHz</td>
<td>~60 kHz</td>
<td>~1 kHz</td>
</tr>
</tbody>
</table>

[Theory numbers from He$^+$ Workshop at MPQ, May 2018]

~10kHz if pol. could be calculated to higher precision

13.06.19  J.J. Krauth
High-precision spectroscopy at XUV wavelengths

Laser source in the XUV range

Upconvert a frequency comb (FC)
High-precision spectroscopy at XUV wavelengths

Laser source in the XUV range

Upconvert a frequency comb (FC)

Need high peak intensities for upconversion

Pure direct FC spectroscopy

Ramsey-comb spectroscopy

Amplify **full repetition rate** FC and upconvert via intra-cavity HHG

→ Very challenging to reach required Peak-intensities
→ Comb-structure is maintained
→ 2x 60nm

Select, amplify and upconvert **only 2 pulses** of a FC and perform a Ramsey type measurement

→ High peak intensities achievable
→ Narrow-band comb-structure restored by measuring at different delays.
→ 790nm + 32nm

MPQ, Garching
VU, Amsterdam
Ramsey-Comb Spectroscopy

\[ \text{signal} \propto \cos \left( 2\pi f_{tr} T_{\text{delay}} - \Delta \phi \right) \]

Measure relative phase evolution:
\[ \rightarrow \text{Constant systematic phase shifts cancel as e.g. AC Stark shift} \]

Ramsey-Comb Laser

Pump-backend
Nd:YVO$_4$

synchronized
($f_{rep} = 126$ MHz)

Frequency comb
Ti:Sa

$\times n T_{rep}$

Post-amplifier
Nd:YAG

28 mJ

SHG

NOPCPA

1 nJ

Phase measurement

3 mJ
NOPA
Noncollinear Optical Parametric Amplification

3 passes though BBO crystals pumped by 532 nm 50 ps @ 5 GW/cm²
• Tuning over 700-1000nm with little effort
• Output ~3mJ
• Bandwidth adjustable from 300nm to 0.2nm
• No memory effect (no inversion)
• Phase of pump beam does not influence the phase of the signal, but the amplitude does
Ramsey-Comb Laser

Pump-backend
Nd:YVO₄

synchronized
\(f_{\text{rep}} = 126 \text{ MHz}\)

Frequency comb
Ti:Sa

\(n \times T_{\text{rep}}\)

Post-amplifier
Nd:YAG

SHG

28 mJ

NOPCPA

1 nJ

Phase measurement

3 mJ

HHG

\(n \times T_{\text{rep}}\)
High-harmonic generation

Required Intensity: $10^{14}$ W/cm$^2$
A comb in the XUV

Fundamental: \[ f_n = f_{ceo} + n f_{rep} \]

q\textsuperscript{th} harmonic: \[ f_m = q f_{ceo} + m f_{rep} \]

Coherent process

Efficiency \(<10^{-6}\)
Plasma creation in argon jet

Plasma formation might introduce delay-dependent phase shifts!

Allison et al., PRL 107, 183903 (2011)
Measurement in xenon

First Ramsey-comb measurement using a high-harmonic generation source

Laura Dreissen

13.06.19

J.J. Krauth
Plasma induced phase shift

The effects on the phase are negligible: e.g. 7(9)mrad between $\Delta N=2$ and $\Delta N=4$
Systematics

Zeeman shift:

- For $\Delta B = 2.0$ Gauss
- $\Delta \omega = 475 MHz$ MHz

DC-Stark shift:

- $V = 0$ V/cm
- $V = 29$ V/cm

AC-Stark shift:

- $N=2$
- $N=3$

Mode determination:

- Fitted frequency [MHz]
- Yohiro et al. 1985
- V = 125.4 MHz
- V = 125.4 MHz
- V = 126.6 MHz
Absolute frequency calibration

Preliminary results:

\[ f = 2\,726\,086\,012\,473\ (630) \text{ kHz} \]
\[ \frac{df}{f} = 2.3 \times 10^{-10} \]

- The most accurate frequency measurement with a HHG source!
- Improvement of $10^4$ with respect to previous measurement [1]

Conclusions from xenon measurements:

- HHG and RCS go well together, HHG shifts can be avoided
- We have performed the most accurate frequency measurement with a HHG source
- The accuracy is limited by the limited interaction time with the xenon atoms
- Future experiments in the helium ion are feasible
Setup for the He\textsuperscript{+} measurement
Measurement principle

1) Sympathetic ground-state cooling
2) Ion separation and Ramsey-comb excitation
3) When He$^+$ is excited it gains momentum due to the high recoil of the XUV photon
4) Motional quanta from He$^+$ are coupled to Be$^+$, which is read out by state-dependent fluorescence
Conclusions from xenon measurements:

- HHG and RCS go well together, HHG shifts can be avoided
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Roadmap towards the He$^+$ measurement:

- Set up cooling laser for ground state cooling
- Build new improved RCS laser setup to reduce phase-noise
- Install the trap provided by PTB
Thank you for your attention!

The He\(^+\) group

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Elmer Gründeman
Mathieu Collombon
Julian Krauth
Kjeld Eikema

Collaborators on the ion trap:
Piet Schmidt and Tanja Mehlstäubler (PTB)