’Extreme’ spectroscopy on helium and helium ions

Kjeld Eikema
LaserLaB, Vrije Universiteit Amsterdam,
Quantum Metrology and Laser Applications group

PSI 23 May 2024
Outline

- Introduction - precision measurements for fundamental tests
  - Isotope shift measurement in ultra-cold $^3$He and $^4$He: nuclear size difference
    - quantum differences: cooling, trapping and spectroscopy of $^3$He and $^4$He
    - results and consequence for charge radius difference
    - developments: new $^4$He measurements in progress

- $\text{He}^+$ 1S-2S precision measurement project: charge radius, Ry constant & QED
  - First excitation of the $\text{He}^+$ 1S-2S transition in the extreme ultraviolet @ 30 nm
  - Challenges and solutions to reach 1 kHz ($10^{-13}$ on the transition)

- Summary and outlook
Precision spectroscopy on bound systems

H, µH, µHe⁺, H₂, D₂, HD, HT, H₂⁺, HD⁺, He, He⁺...

CODATA
Fundamental constants

(Trapped) particle measurements
mₚ/mₑ, mₐ/mₚ, α, ...

EDM (e & n) measurements, and other methods

New Physics?

Theory
Spectroscopy targets: He and He$^+$

**Goal:** nuclear charge radius$^2$ difference between $^3$He and $^4$He

**Goal:** absolute nuclear charge radius$^2$ of $^4$He$^+$, test of QED & Rydberg constant

$^4$He \quad $^3$He \quad $^4$He$^+$
Spectroscopy targets: He and He⁺

**Goal:** nuclear charge radius\(^2\) difference between \(^3\)He and \(^4\)He

**Isotope measurement** on the **doubly-forbidden** \(2 \, ^3S \rightarrow 2 \, ^1S\) transition at 1557 nm, acc. <200 Hz (10\(^{-12}\))

Required: ultra-cold \(^3\)He and \(^4\)He & trapping in magic wavelength trap

**Goal:** absolute nuclear charge radius\(^2\) of \(^4\)He\(^+\), test of QED & Rydberg constant

**Two-photon transition involving 30 nm** on \(1S-2S\) transition, acc. target < 1 kHz (10\(^{-13}\))

Required: single trapped & cooled He\(^+\), enough power at 30 nm, and a whole lot more!
The alpha and helion particle charge radius difference from spectroscopy of quantum-degenerate helium

Y. van der Werf, K. Steinebach, R. Jannin, H.L. Bethlem, and K.S.E. Eikema

LaserLab, Vrije Universiteit Amsterdam.
(Dated: June 6, 2023)

The helion charge radius from laser spectroscopy of muonic helium-3 ions

Karsten Schuhmann,1 Luis M. P. Fernandes,2 François Nez,3 Marwan Abdou Ahmed,4 Fernando D. Amaro,2 Pedro Amaro,5 François Biraben,3 Tzu-Ling Chen,6 Daniel S. Covita,7 Andreas J. Dax,8 Marc Diepold,9 Beatrice Franke,9 Sandrine Galtier,3 Andrea L. Gouveia,2 Johannes Götzfried,9 Thomas Graf,4 Theodor W. Hänsch,9 Malte Hildebrandt,8 Paul Índelicato,3 Lucile Julien,3 Klaus Kirch,1,8 Andreas Knecht,8 Franz Kottmann,1,8 Julian J. Krauth,9,10 Yi-Wei Liu,6 Jorge Machado,5 Cristina M. B. Monteiro,2 Françoise Mulhauser,9 Boris Naar,1 Tobias Nebel,9 Joaquim M. F. dos Santos,2 José Paulo Santos,5 Csilla I. Szabo,3 David Taquy,1,8 João F. C. A. Veloso,7 Andreas Voss,4 Birgit Weichelt,4 Aldo Antognini,1,8,* and Randolf Pohl9,10,†

(The CREMA Collaboration)
Introduction He*

Metastable helium (He*)

$2^3S_1$ state

Accessible narrow transition
Precision spectroscopy

Laser cooling & trapping
High experimental control

$ab$ $initio$ calculations
Fundamental physics tests
Metastable helium (He*)

Metastable $2^3S_1$ state:
- $20 \text{ eV}$ internal energy
- $\tau \approx 8000 \text{ s}$
- Single-particle detection

Accessible narrow transition:
- Doubly forbidden $2^3S_1 \rightarrow 2^3S_0$ ($1557 \text{ nm}$)
- $8 \text{ Hz}$ natural linewidth
- Einstein A coefficient $\sim 9.8 \times 10^{-8} \text{ s}^{-1}$

Laser cooling
- Cycling $2^1S_0 \rightarrow 2^1P$ transition ($1083 \text{ nm}$)

ab initio calculations
- Two-electron correlations
- Measure $^4\text{He} - ^3\text{He}$ isotope shift
- Fundamental constants:
  - (differential) nuclear charge radius
- $^4\text{He}$ measured, $10^{-12}$ level [Nat Phys 14, 2018]
Making quantum degenerate He*
Making quantum degenerate He* 

**Populating the $2^3S_1$ state**
- DC discharge source
- Liquid nitrogen cooling
- $^3$He recycling

\[ 1^1S_0 \rightarrow 2^3S_1 \rightarrow 2^3P_2 \]

- 1083 nm
- 20 eV
Initial trapping of He* and cooling to degeneracy

**Laser cooling**
- 1083 nm laser red detuned
- Zeeman slower: detuning from velocity change compensated with tapered magnetic field
- Magneto-optical trap: 0.5 mK
- Magnetic trapping
- Suppression Penning ionization by spin polarization: max $m_J$

$^4\text{He} \ ^3\text{S}_1 \ J=1$

$B$ magnetic field

$4He \ ^3S_1 \ J=1$

$m_J=+1$

$m_J=0$

$m_J=-1$

$\text{Penning ionization: } He^* + He^* \rightarrow He + He^+ + e^-$
Fermions and Bosons: very different!

Evaporative cooling to quantum degeneracy

- $^4$He collides, re-thermalizes and forms a Bose condensate
- $^3$He does not collide at $\mu$K temperatures; only S-wave collisions, which is forbidden for fermions. Solution mix $^3$He and $^4$He!

$^4$He $^3S_1$ \[ J=1 \]

$^3$He and $^4$He in a trapping potential
Spectroscopy also very different!

- Trapped bosonic $^4$He: all atoms in ground state
  No Doppler, but 'mean field' shift & broadening

- Trapped fermionic $^3$He: Fermi-Dirac distribution

- Many motional states in the trap occupied

- Doppler broadening ($T \sim 1 \mu K$)

$^4$He in a trapping potential

Spectroscopy $2\ ^1S - 2\ ^3S \ @ \ 1557\ nm$
Fermions and Bosons: very different!

• Trapped bosonic $^4$He: all atoms in ground state
  No Doppler, but 'mean field' shift & broadening
• Trapped fermionic $^3$He: Fermi-Dirac distribution
  • Many motional states in the trap occupied
  • Doppler broadening ($T_F \sim 1 \, \mu K$)

$^3$He and $^4$He in a trapping potential

Spectroscopy $^1S - 2^3S @ 1557 \, \text{nm}$
Trapping in a focused laser beam: “ODT”

**Cancel magnetic field influence:**
switch between opposite m states

**Required:** magnetic state
independent trapping

**Solution:** “optical dipole trap”
Based on a focused laser beam

320 nm ‘magic wavelength’
- Same trap for $2^3S_1$ and $2^1S_0$
- No AC Stark shift on transition

- Homebuilt 1 W cw UV laser
Atom detection (loss of atoms)

- Microchannel plate
- 20 eV internal energy
- Time-of-flight fitting: $N, \mu, T$
- Spectroscopy: $N_{\text{atom}}(f_{\text{laser}})$
Detection and measuring spectrum ($^3$He)

Atom detection (loss of atoms)
- Microchannel plate
- 20 eV internal energy
- Time-of-flight fitting: $N, \mu, T$
- Spectroscopy: $N_{\text{atom}}(f_{\text{laser}})$

Measuring the $2 \, ^3S_1 – 2 \, ^1S_0$ at 1557 nm
- Sample preparation
- Set laser, 3s exposure
- Alternate background shots
- Measure remaining atoms
Pauli-blocking of stimulated emission
R. Jannin et al., Nat. Comm. 13, 6479 (2022)
$^3\text{He}$ spectroscopy result (under review)

$^3\text{He}$ transition frequency: 192 504 914 418.96(17) kHz
\(^3\text{He spectroscopy result: radius}\)

\(^3\text{He Transition Frequency: 192 504 914 418.96(17)kHz}\)

Then with:

- previous measurement of \(^4\text{He}\) in 2018

we determine a new improved value for the charge radius\(^2\) difference:

\[
\text{Our result: } r_h^2 - r_\alpha^2 = 1.0757(12)_{\exp(9)}^{\text{theo}} \text{ fm}^2
\]

\[
\text{Theory: } r_h^2 - r_\alpha^2 = 1.084(40) \text{ fm}^2
\]

Agrees, but experiment 27x better, therefore compare different experiments

Theory value based on the values/publications below; common mode error cancellation in the difference is not considered

\[
r_{\alpha, \text{theory}} = 1.663(11) \text{ fm}
\]


\[
r_{h, \text{theory}} = 1.962(4) \text{ fm}
\]

Helion-alpha particle charge radius$^2$ difference

Our He* result on arXiv: 2305.02333v1
CREMA $\mu$He* result on arXiv: 2305.11679v2

$3.6 \sigma$ difference
Recent improvements for $^4$He new measurement:

1. **Reduced linewidth**
   -> Increased stability of the ODT, removed AC-magnetic field sources

2. **Speed up measurement**
   -> Reduced measure time by factor 5

3. **Stabilization of magnetic field**
   -> Observed random jumps magnetic field of 2-3mG; now stabilized to 100 $\mu$G
Magnetic field jumps...
$^4\text{He}$ ion signal + TDC = much more information

Measurement via ion production

$\text{He}^*( 2^3S_1) + \text{He}^*( 2^1S_0) \rightarrow \text{He} ( 1^1S_0) + \text{He}^+ + e^-$

$\tau = 300 \mu s \rightarrow \Delta f = 500 \text{Hz}$

Lifetime $2^1S_0$
BEC is oscillating in the optical dipole trap...

~30Hz -> Axial trap frequency
Early test measurements promising

\[ f_{\text{measured}} = f_0 + A P_{\text{Spectro}} + B P_{\text{ODT}} + C \mu_{\text{chem.pot}}. \]

70Hz ‘uncertainty’ in only 7 days of measuring!
Remarkable what 1 neutron difference can make: $^3\text{He}$ vs. $^4\text{He}$

Most precise transition measurement in helium (1 : $10^{12}$)

$^3\text{He} \ 2 \ 3S_1 \rightarrow 2 \ 1S_0$ transition frequency: 192 504 914 418.96(17)kHz

Resulting charge radius squared difference most precise, but 3.6 $\sigma$ difference with $\mu\text{He}^+$

$$r^2_h - r^2_a = 1.0757(12)_{\text{exp}}(9)_{\text{theo}} \text{ fm}^2$$

**Outlook:**

New $^4\text{He}$ measurement in progress and promising; target $\sim$ 50 Hz

Expected charge radius$^2$ difference (with updated theory) factor of 2 better
Thanks to the He* team

He* team:
• Kees Steinebach
• Yuri van der Werf
• Raphael Jannin
• Rick Bethlem
• Kjeld Eikema

Technical support:
• Rob Kortekaas
• Ronald Buijs
• Lex van der Gracht

Wim Vassen: † 11-2-2019

Funding: