Probing Nuclear Sizes with Precision Spectroscopy in Bosonic and Fermionic Helium

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LaserLaB VU Amsterdam

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Precision measurements for fundamental physics

**Fundamental Physics**

**Tabletop Experiments**

- High precision measurements
- Bound-state QED (theory collaborators)

\[ \text{He, He}^+, \text{H}_2, \text{HD, HT, HD}^+, \text{H}_2^+, \ldots \]

**Simple, calculable, systems**
Precision measurements for fundamental physics

**Simple, calculable, systems**

- H-atom: $1S \rightarrow 2S$ transition
  - $2S$ metastable level: narrow linewidth
  - $4.5 \cdot 10^{-15}$ precision \[1\]
  - Cornerstone for QED calculation

- Combined with other transitions
  - Proton charge radius $r_p$ and $R_\infty$
  - ‘proton radius puzzle’

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\[1\] Matveev et al. *Phys. Rev. Lett.* 110, no. 23 (June 2013): 230801.
Precision measurements
For fundamental physics

- Next atom, He
- Two electrons:
  - Singlet/Triplet structure
- Two 2S metastable levels:
  - Narrow transition at 1557 nm
  - First measured in 2011 at VU (van Rooij et al.)
Precision measurements
For fundamental physics

- Next atom, He
- Two electrons:
  - Singlet/Triplet structure
- Two 2S metastable levels:
  - Narrow transition at 1557 nm
- \(2^3S_1\) state:
  - Laser cooling and trapping
  - Degree of control
  - Reduce Doppler
Precision measurements
For fundamental physics

- Next atom, He
- Two electrons:
  - Singlet/Triplet structure
- BUT: complicated QED theory from electron-electron terms
- SOLUTION: $^3\text{He}-^4\text{He}$ isotope shift
  - Most difficult terms drop out
  - Nuclear sizes: $\delta r^2 = r_3^2 - r_4^2$
The helium atom

• Measure isotope shift:
  • Electron-electron terms drop out
  • Finite nuclear size remains
  • Scattering data too inaccurate

• Approach:
  • Measure $^3$He-$^4$He isotope shift
  • Extract differential charge radii $r_3^2 - r_4^2$ using QED theory
  • Compare with other measurements:
    Spectroscopic, scattering, $\mu$He$^+$
    Consistency check
Quantum degenerate He

Cooling sequence:
- Magneto-optical trap: 500M @ 0.5 mK
- Doppler cooling in Magnetic Trap: 200M @ 130 μK
- Evaporative cooling: quantum degenerate gas ≤ 1 μK
- Transfer to Optical Dipole Trap (ODT)

Atom detection
- Microchannel plate
- 20 eV internal energy
- Time-of-flight fitting: $N, \mu, T$

[Diagram of He* beam collimation, Magneto-Optical & Magnetic Trap, Zeeman Slower, Optical Dipole Trap, MCP detector]
Precision Spectroscopy

• Magic wavelength Optical Dipole Trap
  • ‘magic wavelength’ @ 320 nm
  • Same trap potential for $2^3S_1$ and $2^1S_0$
  • No ac-Stark shift
  • Homebuilt 2 W cw UV laser

Two ingredients for precision spectroscopy:

- Magic wavelength dipole trap
- Frequency metrology:
  - Cs clock frequency standard
  - Optical frequency comb
  - Ultra stable (< 2 Hz) reference laser
Precision spectroscopy

• Measure *unperturbed* $2^3S_1 \rightarrow 2^1S_0$ transition

• Systematics effects:
  • Spectroscopy Stark shift: extrapolate
  • Dipole trap Stark shift: magic $\lambda$
  • Zeeman shift: spin-stretched states
  • photon recoil: exactly known
  • Interactions: **mean-field shift**
Spectroscopy of a $^4$He BEC

- Dominated by collisions:
  - Penning ionization signal
    \[ \text{He} (2^1S_0) + \text{He} (2^3S_1) \rightarrow \text{He} (1^1S_0) + \text{He}^+ + e^- \]
  - Cold-collision shift:
    \[ \langle \Delta \nu \rangle \propto \frac{a_{ts} - a_{tt}}{a_{tt}} \mu \]

Data Fits:
- BEC
- Thermal
- Total

single shot TOF:
Spectroscopy of a $^4$He BEC

- Systematics analysis:
  - Spectroscopy laser ac-Stark
  - Dipole trap (residual) shift
    - $\lambda_m = 319.81592(15) \text{ nm}$
  - Cold-collision shift: $\langle \Delta \nu \rangle \propto \frac{a_{ts} - a_{tt}}{a_{tt}} \mu$
    - $a_{ts} = 82.5(5.2) \ a_0$
  - $2^3 S_1 \rightarrow 2^1 S_0$ transition:
    - $192\ 510\ 702\ 148.72(0.20) \ \text{kHz}$

Most accurate transition in helium ($10^{-12}$)
Three benchmarks for the $^4$He atom

Bob Rengelink

Working with $^3$He

Production of a Degenerate Fermi Gas of $^3$He$^*$
and investigation of the spectral line shape
Working with $^3\text{He}$

- Low natural abundance
- Recycling system

<table>
<thead>
<tr>
<th></th>
<th>$^3\text{He}$</th>
<th>$^4\text{He}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic mass</td>
<td>3.016 amu</td>
<td>4.0026 amu</td>
</tr>
<tr>
<td>Natural abundance</td>
<td>0.00014 %</td>
<td>99.99986 %</td>
</tr>
<tr>
<td>Nuclear spin</td>
<td>$\frac{1}{2}$</td>
<td>0</td>
</tr>
<tr>
<td>Cost</td>
<td>$2000/L$ [1]</td>
<td>$0.07/L$ [2]</td>
</tr>
</tbody>
</table>

[2] Local party balloon store (2020)
Pauli principle: Ultracold Identical Fermions don’t collide!

- Sympathetic cooling with $^4$He
- Fermi-Dirac distribution: *Doppler broadening*
- No Penning ionisation signal: *Measure trap depletion*
- No collisional shift *
Working with $^3$He

- Sympathetic cooling with $^4$He
- Fermi-Dirac distribution: *Doppler broadening*
- No Penning ionisation signal: *Measure trap depletion*
- No collisional shift *
$2^3S_1 \rightarrow 2^1S_0$ spectroscopy

- Fermion line profile: Doppler broadening

\[ S(\Delta) \propto \int \int \rho_g \delta(\omega - \omega_0) d^3\vec{r} d^3\vec{k} \]

Fermi-Dirac resonance

Juzeliūnas & Mašalas, *PRA* 63, 061602 (2001)

- Expect Doppler broadening: $FWHM \leftrightarrow T_F$

- But wait, reduced linewidth!

![Graph](image)
Understanding the spectral lineshape

\[ S(\Delta) \propto \int \int \left[ \rho_g - \rho_g (1 - \rho_g) \right] \delta(\omega - \omega_0) \, d^3\vec{r} \, d^3\vec{k} \]

Decay $2^1S_0 \to 1^1S_0$: $\tau = 20 \text{ ms}$

Stimulated emission

Excitation Blockade Resonance

Pauli-blocked in dense part of the gas
Testing the lineshape model

\[ \tau = 20 \text{ ms} \]

\[ |2^1S_0\rangle \rightarrow |4^1P_1\rangle \]

\[ |2^3S_1\rangle \]

\[ P_1 \]

\[ \lambda = 396 \text{ nm} \]

\[ r = 4 \text{ ns} \]

\[ V(r) \]

\[ r \]

\[ \text{Nat. Comm. 13, 6479 (2022)} \]
Precision spectroscopy

• Measure *unperturbed* $2^3S_1 \rightarrow 2^1S_0$ energy difference

• Systematic effects:
  • Dipole trap Stark shift
  • Spectroscopy laser Stark shift
  • Zeeman shift
  • photon recoil
  • Lineshape Model ✓
Precision spectroscopy

\[ \hbar \kappa \]

\[ F = \frac{1}{2} \]

\[ |2^1S_0, F = 1/2 \rangle \]

PRELIMINARY RESULT \(^3\)He \(2^3S_1 \rightarrow 2^1S_0 \) (2022):

\[ f_0 = 192 \ 504 \ 914 \ 418.96(17) \text{ kHz} \]

\[ \lambda_m = 319.830 \ 80(15) \text{ nm} \]
Nuclear Charge Radius Difference

Previous result
van Rooij et al.

Zheng et al. (\(^4\text{He}\))
+ Cancio Pastor et al. (\(^3\text{He}\))

Cancio Pastor et al.

Shiner et al.

data: [Phys. Rev. A 95, 062510 (2017)]

\[ r^2(\text{\(^3\text{He}\)}) - r^2(\text{\(^4\text{He}\)}) \text{ (fm}^2\text{)} \]

PRELIMINARY RESULTS

\(2^3\text{S} \rightarrow 2^1\text{S}\)

\(1557 \text{ nm}\)

\(3^\text{He}\) DFG

\(4^\text{He}\) BEC

Trapped quantum gases

\(2^3\text{S} \rightarrow 2^3\text{P}\)

\(1083 \text{ nm}\)

Atomic beam

This work

\(^4\text{He} \text{ Nat Phys 14 (2018)}\)

+ 

\(^3\text{He} \text{ 2022 PRELIMINARY}\)
Nuclear Charge Radius Difference

**Previous Amsterdam result**
(2011)

**This work**

4.4σ

4He Nat Phys 14 (2018)
+ 3He 2022 PRELIMINARY

**Data:** [Phys. Rev. A 95, 062510 (2017)]

Zheng et al. (4He)
+ Cancio Pastor et al. (3He)

Cancio Pastor et al.

Shiner et al.

**2^3S → 2^1S**

Trapped quantum gases

**2^3S → 2^3P**

Atomic beam

PRELIMINARY RESULTS
Nuclear Charge Radius Difference

Previous Amsterdam result (2011)

4.4σ

Previous result van Rooij et al.

Zheng et al. (4\textsuperscript{He})
+ Cancio Pastor et al. (3\textsuperscript{He})

Prof. Shui-ming Hu talk yesterday!

Cancio Pastor et al.

Shiner et al.

$^{4}\text{He} \text{Nat Phys 14 (2018)}$
+
$^{3}\text{He} \text{2022 PRELIMINARY}$

$2^{3}\text{S} \rightarrow 2^{1}\text{S}$

$2^{3}\text{S} \rightarrow 2^{3}\text{P}$

Trapped quantum gases

PRELIMINARY RESULTS

data: [Phys. Rev. A 95, 062510 (2017)]

$r^2(3\text{He}) - r^2(4\text{He})$ (fm$^2$)

1.02 1.03 1.04 1.05 1.06 1.07 1.08

LaserLab AMSTERDAM
**7 kHz (4.4 $\sigma$) deviation?**

**Previous Result:** non-magic wavelength

- Fermi-Dirac: AC Stark shift asymmetry
- Not resolved within laser bandwidth
- **New setup:**
  - magic wavelength: *no AC Stark from trap*
  - improved laser lock: *resolve quantum effects*

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**Diagram:**

- a) Schematic of energy levels.
- b) Simulated line profile with transition frequency.
- c) Graph showing transition frequency with corrected thermal broadening for large Fermi gases.

- 192 504 914 417.2(2.0) kHz

**Correction based on thermal broadening for large Fermi gases**
Nuclear Charge Radius Difference

\[ \sigma_{\text{exp}} > \Gamma = 8 \text{ Hz} \]

\[ \sigma_{\text{exp}} \ll \Gamma = 1.6 \text{ MHz} \]

\[ 2^3S \rightarrow 2^1S \]

\[ 2^3S \rightarrow 2^3P \]

Trapped quantum gases

\[ \sigma_{\text{exp}} > \Gamma = 8 \text{ Hz} \]

\[ \sigma_{\text{exp}} \ll \Gamma = 1.6 \text{ MHz} \]

This work

van Rooij et al. re-evaluation

Previous result
van Rooij et al.

Zheng et al.\((^4\text{He})\)
+ Cancio Pastor et al. \((^3\text{He})\)

Cancio Pastor et al.

Shiner et al.

data: [Phys. Rev. A 95, 062510 (2017)]
Electrons vs. Muons

- He nuclear charge radii from $\mu\text{He}^+$ spectroscopy
  - $^4\text{He}$: 1.67824(83) fm [Krauth et al. Nature 589, p. 527–531 (2021)]
  - Fresh off the press: $^3\text{He}$ 1.97007(94) fm [https://arxiv.org/abs/2305.11679]
Electrons vs. Muons

- He nuclear charge radii from $\mu\text{He}^+$ spectroscopy
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PRELIMINARY RESULTS

- van Rooij et al. (2011) $^2S \rightarrow ^2P$
- Zheng2017($^4\text{He}$) + CP2021($^4\text{He}$) $^2S \rightarrow ^2P$
- Cancio Pastor et al. (2012) $^2S \rightarrow ^2P$
- Shiner et al. (1995) $^2S \rightarrow ^2P$

$\mu$ He$^+$ (arXiv 2023) $^2S \rightarrow ^2P$

This work (Prel.) $^2S \rightarrow ^2P$

*Also fresh: Preliminary Hefei 2023
Electrons vs. Muons

- 3.6σ from $\mu\text{He}^+$
- $2\sigma - 4\sigma$ from $2^3S \rightarrow 2^3P$
- Hefei $^3\text{He}$?
- 1.9 kHz shift for $1\sigma$ agreement with muonic

Discrepancies:
- *New physics? Well...............*
- Very different systematics
- Theory: triplet vs. singlet
- Muonic: higher-order QED
In conclusion

• Fundamental physics with ultracold helium:
  • Precision spectroscopy: narrow transition
  • Nuclear charge radii → most accurate $r_3^2 - r_4^2$
  • QED benchmark
  • Comparison with other works, exciting times:
    \textit{Other spectroscopy, scattering, muonic systems}

• More than just the transition frequency:
  • magic wavelengths: benchmarks for QED
  • $^4$He BEC: insight into collisions, mean-field shift, scattering length $\alpha_{ts}$
  • $^3$He Fermi gas: Observation of unexpected Pauli Blockade effects

• Higher precision? $\Gamma = 8$ Hz (experimentally challenging)
• Other measurements in helium?
Thanks for your attention!

He* team:
- Raphael Jannin
- Kees Steinebach
- Yuri van der Werf
- Rick Bethlehem
- Kjeld Eikema
- Bob Rengelink

Technical support:
- Rob Kortekaas
- Lex van der Gracht

Funding & facilities:
Thanks for your attention!

Questions?

Email: y.vander.werf@vu.nl
• **Systematics analysis: Zeeman shift**

\[ |2^1S_0, F = 1/2\rangle \quad \text{and} \quad |2^3S_1, F = 3/2\rangle \]
Systematic analysis

- 2\textsuperscript{nd} order Zeeman shift:

Using the Breit-Rabi formula with $J \leftrightarrow I$

No coupling to $F = 1/2$ from spin-stretched $m_F = \pm 3/2$

2\textsuperscript{nd} order Zeeman from coupling to $2^3P_J$, same as $^4\text{He}$: $< 4 \text{ mHz/G}^2$
Reduced linewidth

Tails of spectrum: reduced loss

Fermi-Dirac state occupation

Center of spectrum: high loss

We measure the remaining He*
Systematic analysis

- Cold collision shift?

**IDENTICAL** cold* fermions don’t collide

\[
|g_1\rangle \rightarrow \alpha_1 |g_1\rangle + \beta_1 |e_1\rangle \\
|g_2\rangle \rightarrow \alpha_2 |g_2\rangle + \beta_2 |e_2\rangle
\]

\[
|S\rangle = \frac{(\alpha_1 \beta_2 - \alpha_2 \beta_1)}{\sqrt{2}} \cdot (|ge\rangle - |eg\rangle)
\]

\[
\langle S|S\rangle \equiv G_{ge}^{(2)}
\]

\[
\Delta_{mfs} = \frac{\hbar a_{ge}}{m} \rho_g (r) \cdot G_{ge}^{(2)} < 2\pi \times 1 \text{ Hz}
\]

*p-wave frozen out \( T < 500 \text{ mK} \)
Frequency metrology

Hz laser drift

Centralized building HVAC control!

Correction to the real SI second: local Cs clock deviation from GPS

$$\Delta f = 55 \text{ Hz}$$
Finding the magic wavelength

• Measurements at different wavelengths
• Measure strength of the a.c. Stark shift
Thermodynamic shift: @320nm

\[ \langle I_{320} \rangle = \Delta f_{\text{Stark}}/\alpha \approx 5.5 \times 10^7 \text{ Wm}^{-2} \]

\[ I_{\text{peak}} \approx 10^8 \text{ Wm}^{-2} \]

\[ |2^1S_0\rangle \]

Error in a.c. Stark extrapolation?

Average trap intensity

* @ 1W UV power
Electrons vs Muons?

Amsterdam 2022
PRELIMINARY

Cancio Pastor et al.

• Vastly different systems
• Vastly different theory
• Consistency check
• Probe nuclear sizes
• QED test

Shiner et al.

\[ \sigma_{exp} > \Gamma = 8 \text{ Hz} \]

\[ \sigma_{exp} \ll \Gamma = 1.6 \text{ MHz} \]

\[ r^2(3\text{He}) - r^2(4\text{He}) (\text{fm}^2) \]

PRELIMINARY RESULTS
4.4 $\sigma$ deviation?

**2011 result:**
1557 nm dipole trap + direct frequency comb lock
- Fermi-Dirac: AC Stark shift asymmetry
- Not resolved within laser bandwidth
- Verified now with new spectroscopy laser

**2022 result:**
magic wavelength trap + ultrastable reference laser
- Fermi-Dirac: Doppler + Pauli blocking
- No trap AC Stark $\rightarrow$ Fully symmetric
- Quantum effects resolved (2018: $^4$He meanfield)
Testing the model

• Enhanced ground state decay through $4^1P_1$ state

  Eliminate the stimulated emission channel

  Lift Pauli Blockade effect
Testing the model

- Enhanced ground state decay through $4^1P_1$ state

$\tau \approx 20 \text{ ms}$

$\tau \sim 26 \text{ ns}$

$T \approx 95 \text{ nK}$

$T/T_F \approx 0.35 \sim 0.55$
Understanding the spectral lineshape

- Trapped fermionic $^3$He: Fermi-Dirac distribution
  - Distribution over motional states in the trap
  - Laser absorption Doppler broadened ($T_F \sim 1 \, \mu K$)
Before PhD

• Master thesis work at Eindhoven University of Technology

• $^{85}$Rb MOT
• Rydberg excitation ($780 + 480$)
• SLM: shaped excitation volume
Before PhD

• Rydberg spectra:
  • Lineshape mediated by interactions
  • Rydberg facilitation
  • Spatial resolution obscured by ion repulsion