Charge radii determined by laser spectroscopy of He-like ions

W. Nörtershäuser, P. Imgram, K. König, B. Maaß, P. Müller, E. Burbach, J. Spahn

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FONDAZIONE BRUNO KESSLER

ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

New perspectives in the charge radii determination for light nuclei

EURO-LABS EUROPEAN LABORATORIES FOR ACCELERATOR BASED SCIENCES

INFN Istituto Nazionale di Fisica Nucleare

FRIB Theory Alliance

SFB 1245

SFB 1245
Atomic Nuclei: From Fundamental Interactions to Structure and Stars

DFG Deutsche Forschungsgemeinschaft

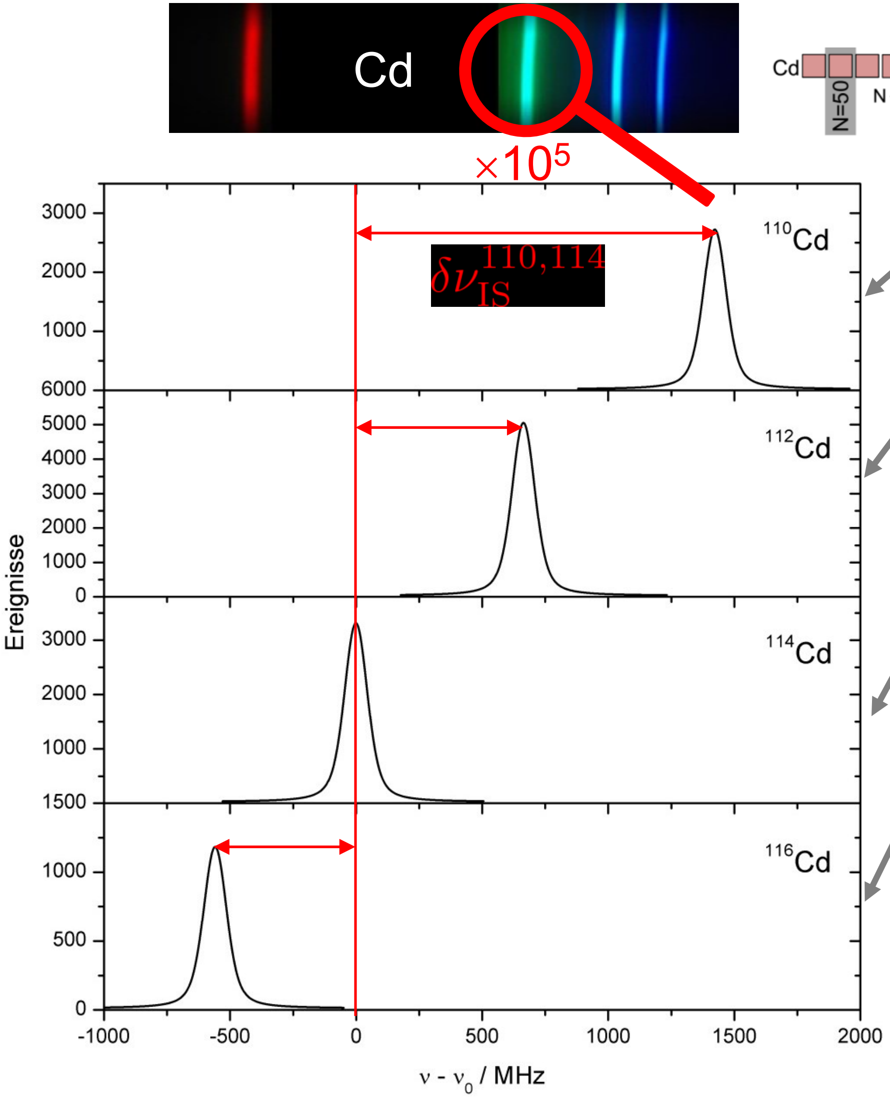
HFHF Helmholtz Forschungsakademie Hessen für FAIR

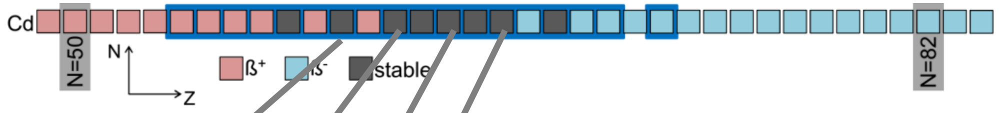
With funding from the: Federal Ministry of Research, Technology and Space

LASER SpHERe

Outline

Isotope Shift





$\delta\nu_{\mathrm{IS}}^{110,114}$

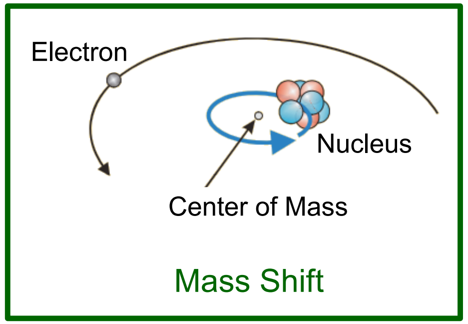
$\delta\nu_{\mathrm{IS}}^{AA'}$

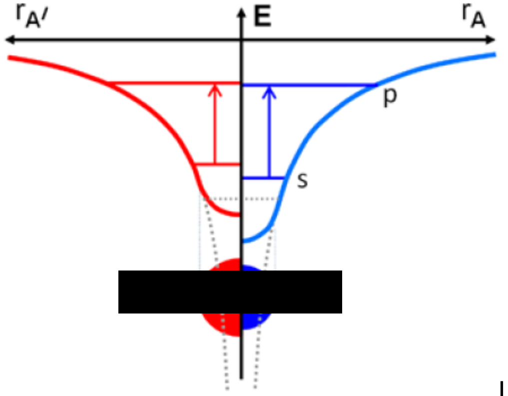
$\delta\nu_{\mathrm{IS}}^{AA'}$ $K_{\mathrm{MS}} \cdot \frac{M_{A'} - M_A}{M_A M_{A'}}$ Mass Shift

$F\ \delta\langle r_c^2\rangle^{AA'}$ Field Shift Volume Shift

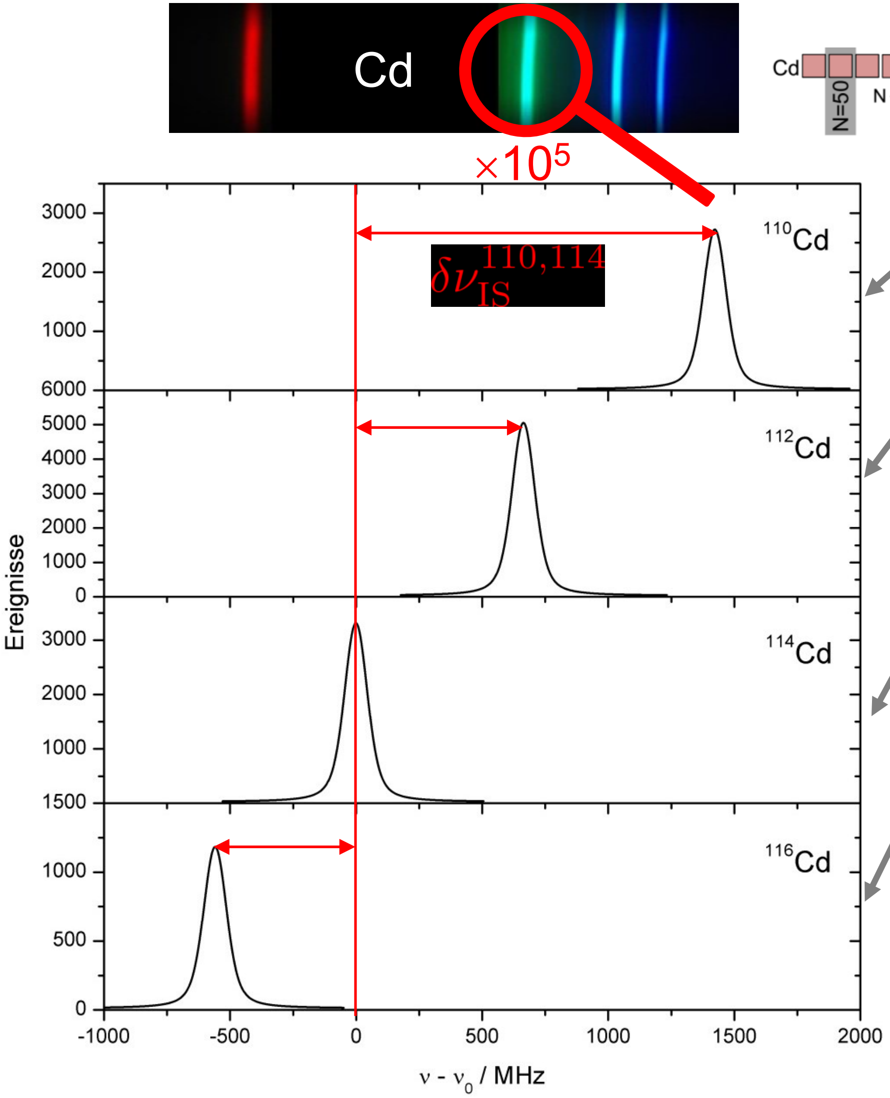
$$\langle r_c^2\rangle = \frac{1}{Z}\int \varrho_c(\vec{r})\, r^2\, \mathrm{d}^3 r$$

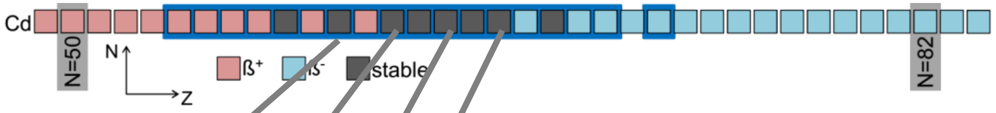
Mean-square charge radius





Isotope Shift





$\delta\nu_{IS}^{AA'}$ [redacted]

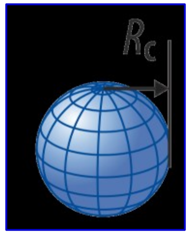
$\delta\nu_{IS}^{AA'}$ [redacted] $K_{MS}\cdot\frac{M_{A'}-M_A}{M_A M_{A'}}$ Mass Shift

[redacted] $F\,\delta\langle r_c^2\rangle^{AA'}$ Field Shift Volume Shift

$$\langle r_c^2\rangle = \frac{1}{Z}\int \varrho_c(\vec{r})\, r^2\, d^3 r$$

Mean-square charge radius

[redacted]



Reference radius required from a different technique → elastic electron scattering muonic atoms

Absolute Radii of Light Isotopes

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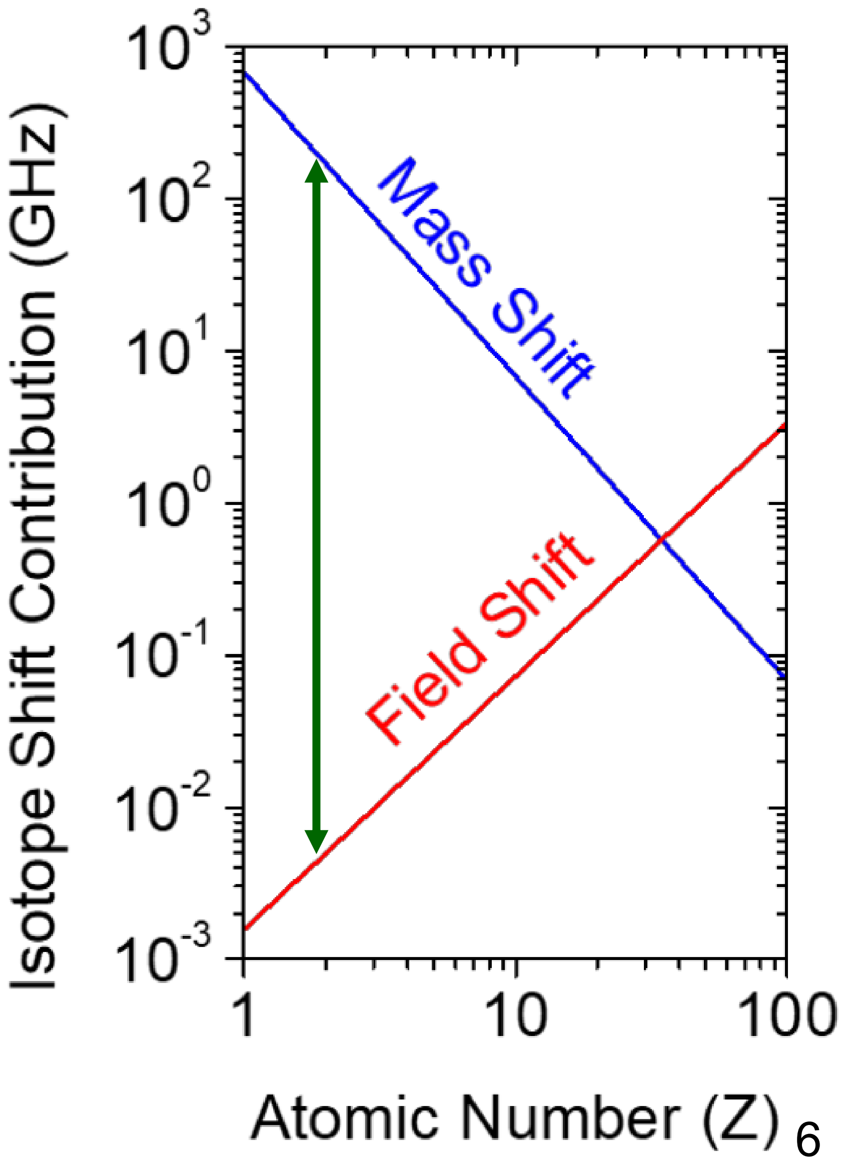
Required Accuracy $< 10^{-5}$

$\delta\nu_{\mathrm{IS}}^{AA'}$ $K \cdot M$ F

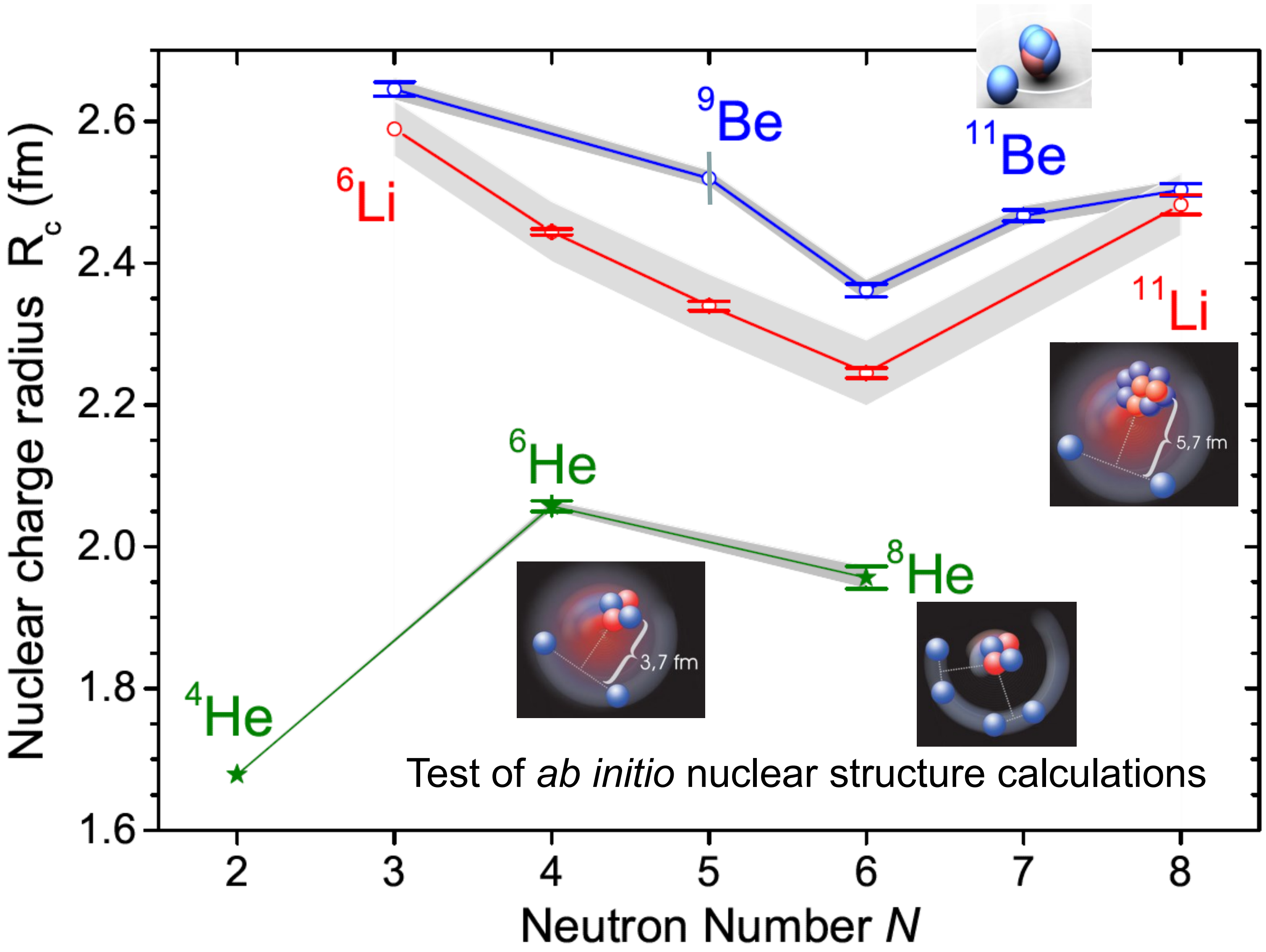
Theory

Mass Shift Calculations:

He (2 e⁻) : F. Marin et al., Z. Phys. D **32**, 285 (1995).
Li (3 e⁻) : Z.C. Yan and G.W.F. Drake, PRA **61**, 022504 (2000).
Be (4 e⁻) : M. Puchalski et al., PRA **89**, 012506 (2014).
B (5 e⁻) : B. Maaß et al, PRL **122**, 182501 (2019).



Nuclear Radii of the Lightest Isotopes



Error Bars: $\sigma(\delta\nu_{IS})$

A. Krieger *et al.*, PRL **108**, 142501 (2012)

R. Sanchez *et al.*, PRL **96**, 033002 (2006)

P. Müller *et al.*, PRL **99**, 252501 (2008)

Grey Regions: $\sigma(R_c)$

$R_c(^9\mathrm{Be}) = 2.519\,(12)(39)^a$ fm

J.A. Jansen *et al.*, Nucl. Phys. A **188**, 337 (1972)

[a] B. Ohayon *et al.*, Physics 2024, **6**, 206

$R_c(^6\mathrm{Li}) = 2.589\,(39)$ fm

W. Nörtershäuser *et al.*, Phys. Rev. C **84**, 024307 (2011)

$\mathbf{R_c(\alpha) = 1.678\,24(83)}$ **fm**

J.J. Krauth *et al.*, Nature **589**, 527 (2021)

Motivation: The Proton-Halo Nucleus ^{8}B

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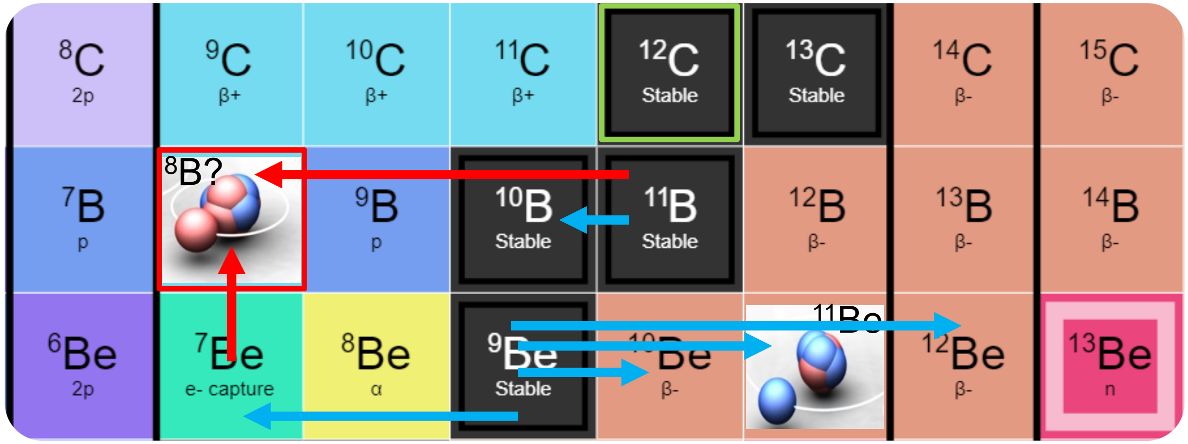


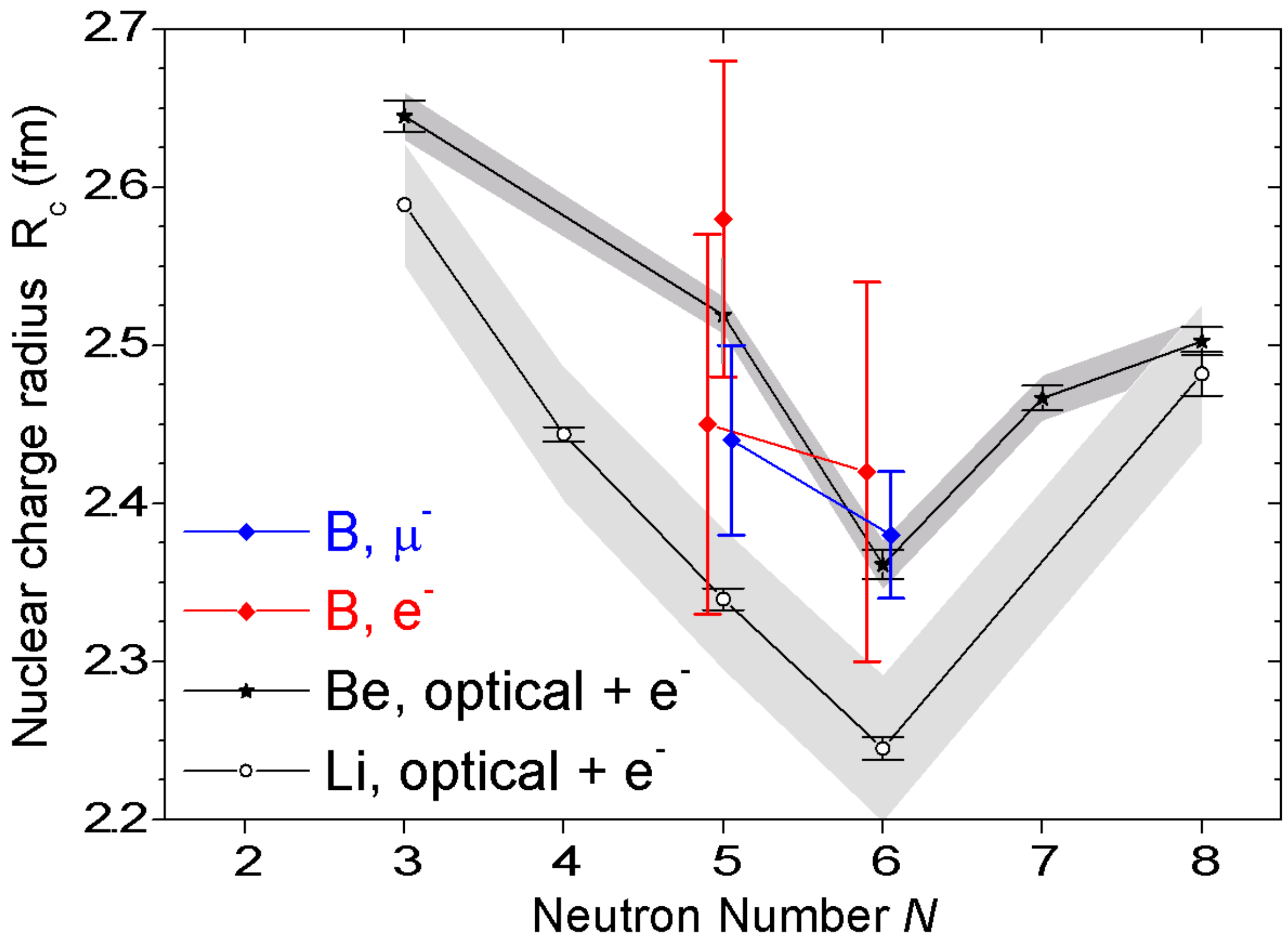
$$\delta\nu_{\mathrm{IS}} - \delta\nu_{\mathrm{MS}}^{\mathrm{Theory}} \propto \delta\langle r_c^2\rangle \longrightarrow R_c(A) = \sqrt{R_c^2(A_{\mathrm{ref}}) + \delta\langle r_c^2\rangle^{A_{\mathrm{ref}},A}}$$

Reference Radii required

„Proton-halo size“: $R_c(\mathrm{p_{halo}}) = R_c(^{8}\mathrm{B}) - R_c(^{7}\mathrm{Be})$

Conclusion: To gain information about the proton halo of ^{8}B, we need reliable reference radii for Be and B **on equal footing** !

The „Tragedy of Boron“: Reference Radii



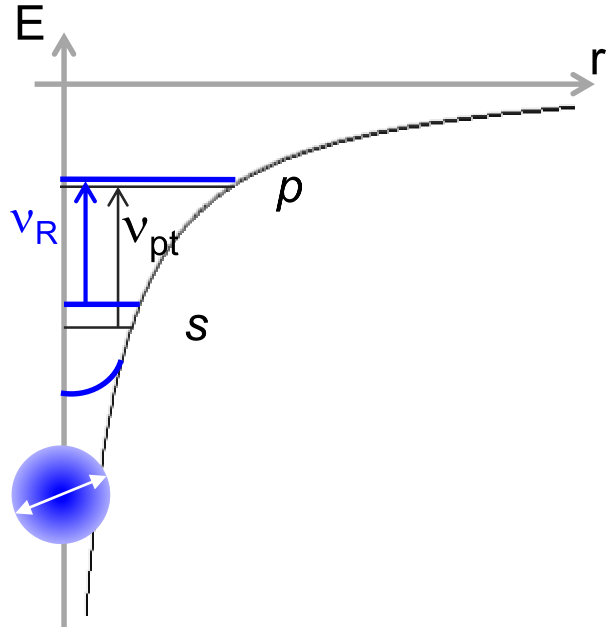
[1] Stovall, Nucl. Phys. 86, 225 (1966)
[2] Cichocki et al., PRC 51, 2406 (1995)
[3] Schaller *et al.*, Nucl. Phys. A 343, 333 (1980)
[4] Olin *et al.*, Nucl Phys A 360, 426 (1981)

Problem 1:
No reliable reference radii for boron !

Problem 2:
The absolute Be radii are also not very precise.

Question: Can we get reference radii purely based on optical data?

All-Optical Absolute Charge Radii



[redacted]

Electronic Factor
($\rightarrow$ Wavefunction)

$$= F_{i\rightarrow f}\,\langle r_c^2\rangle$$

- Measure **transition frequency** ν_R
- Compare with high precision atomic calculation for a point-like nucleus ν_{pt}
- Difference ν_R - ν_{pt} is finite-size effect and **proportional to the ms charge radius**
- So far applied **only for H-like systems**, i.e., H, μH and μHe
- Two-electron system requires elaborate QED calculations, which have been improved considerably

  V.A. Yerokhin, V. Patkóš & K. Pachucki, PRA **98**, 032503 (2018)
  V. Patkóš, V.A. Yerokhin &K. Pachucki, PRA **103**, 042809 (2021)
  V.A. Yerokhin, V. Patkóš & K. Pachucki, PRA **106**, 022815 (2022)

Theory Results

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Here we address a more ambitious task of **determining the absolute value of the nuclear charge radius, specifically that of the helium atom.** [….] We achieve this by performing the complete calculation of the α^7m QED effects. [V. Patkóš, V.A. Yerokhin & K. Pachucki, PRA **103**, 042809 (2021)]

TABLE VII. Comparison of experimental results for various transitions with the

Transition	Theory	Experiment	Difference
$2\,^3S$–$3\,^3D_1$	786 823 849.540 (52)[a]	786 823 850.002 (56)	−0.462 (76)
$2\,^3P_0$–$3\,^3D_1$	510 059 754.863 (16)[a,b]	510 059 755.352 (28)	−0.489 (32)
$2\,^3P$–$2\,^3S$	276 736 495.620 (54)	276 736 495.600 0 (14)	0.020 (54)

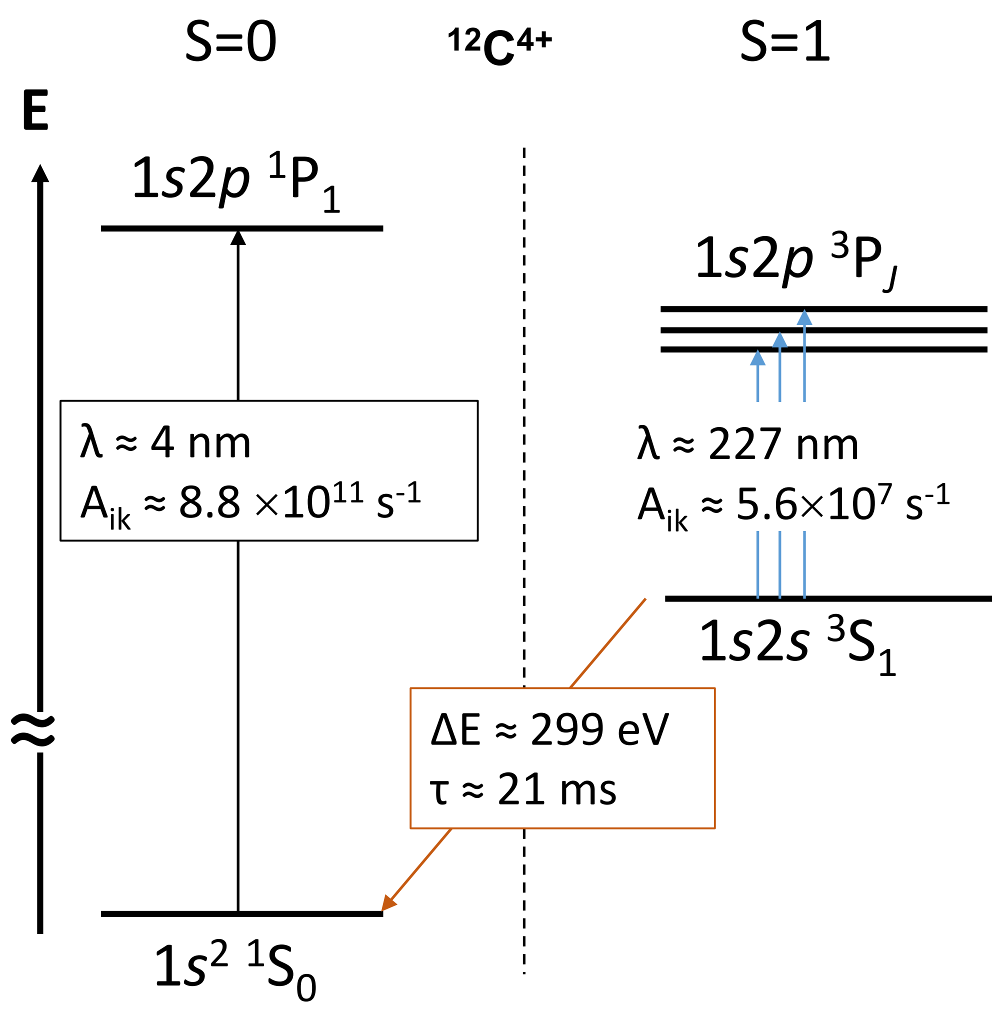
[a]Using theoretical energy $E(3\,^3D_1) = 366\,018\,892.691\,(23)$ from Ref. [37].

[b]Using theoretical results for the $2\,^3P$ fine structure from Ref. [38].

Finite nuclear size contribution: 3.415 (4) MHz

Our naive expectation: In He-like ions, the FNS effect will further grow and we will be even more sensitive to it

The Case of $^{12}C^{4+}$

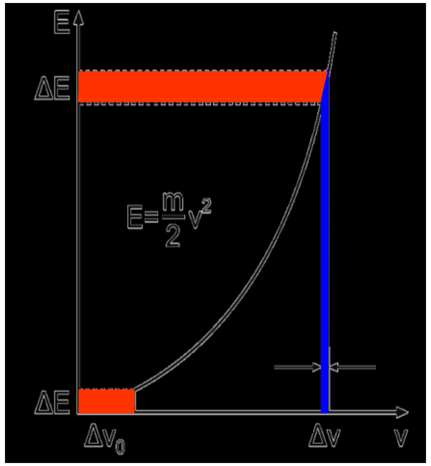


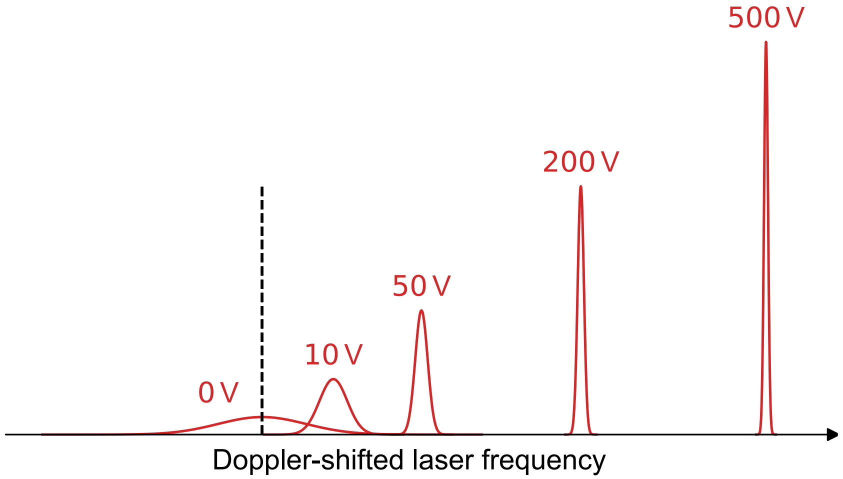
e⁻ scattering: $R_c(^{12}C) = 2.471(6)$ fm
I. Sick, PLB **116**, 212 (1982)

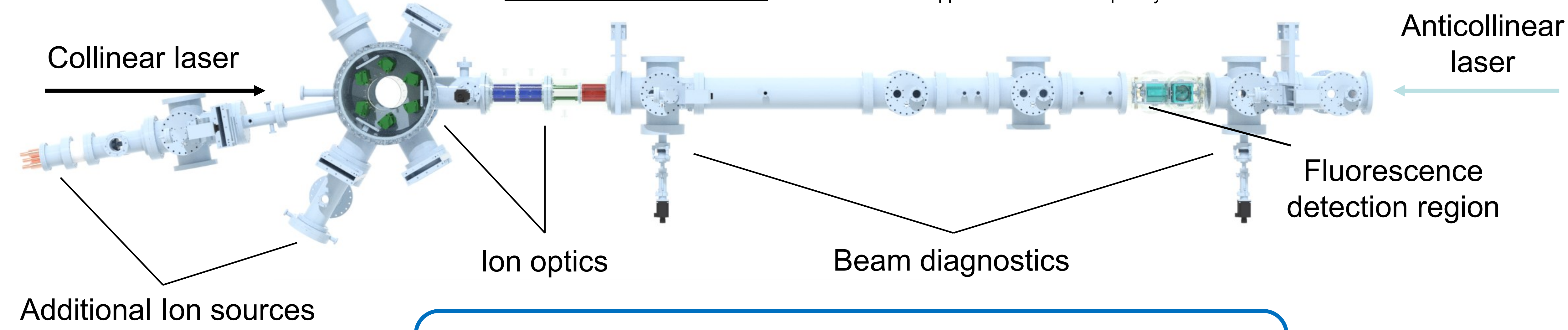
Muonic atoms: $R_c(^{12}C) = 2.4829(19)$ fm
W. Ruckstuhl *et al.*, NPA **430**, 685 (1984)

- Nuclear Charge Radius of ^{12}C well known
  → Test of Theory
- Easy to produce in an EBIS
- $\lambda \approx 227$ nm → Ti:Sa × 4 stabilized to frequency comb
- $I = 0$ → no hyperfine-structure induced level mixing

Experimental Setup: COALA Beamline

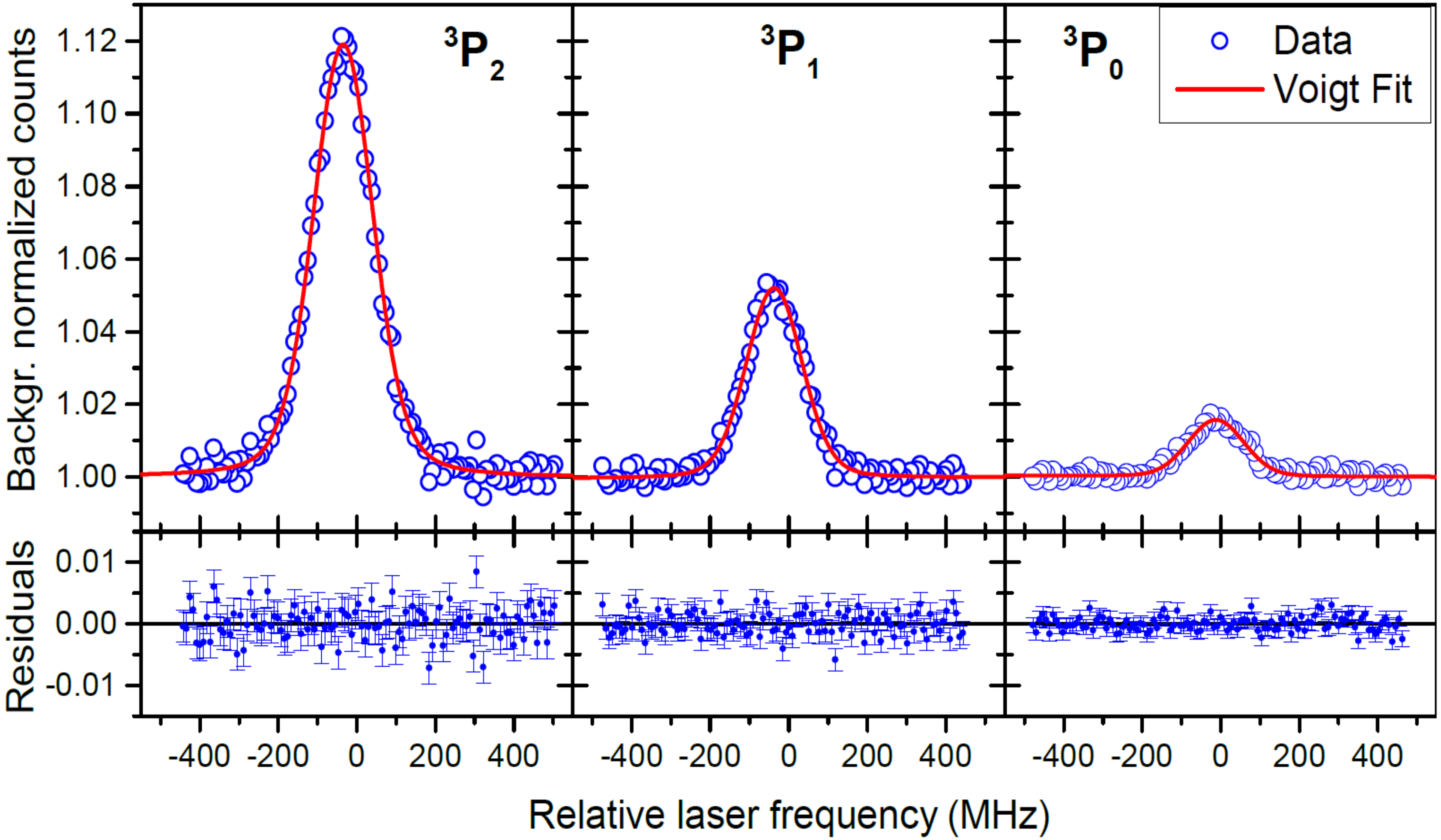


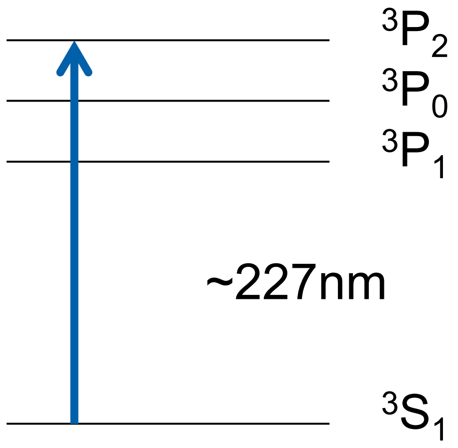




$$\left.\begin{aligned} \nu_a &= \nu_0\gamma(1-\beta) \\ \nu_c &= \nu_0\gamma(1+\beta) \end{aligned}\right\} \nu_c \cdot \nu_a = \nu_0^2\gamma^2 \cdot (1+\beta)(1-\beta) = \nu_0^2$$

Results on ^{12}C





- Measured all three fine structure transitions several times
- Estimation of systematic uncertainties
- Determined the center-of-gravity transition frequency $^3S_1 \rightarrow {}^3P_J$

Transition Frequencies: Comparison to Literature

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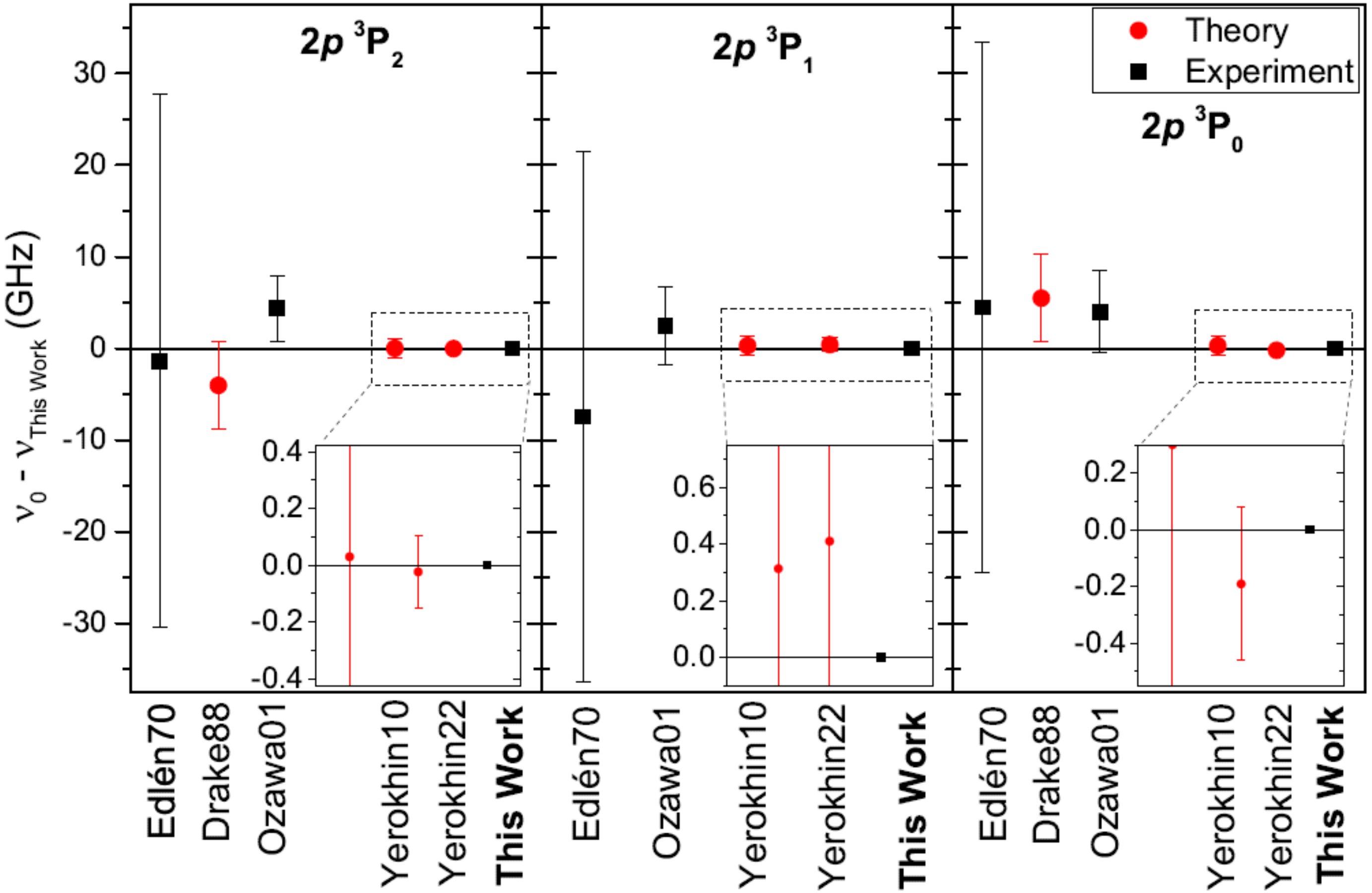
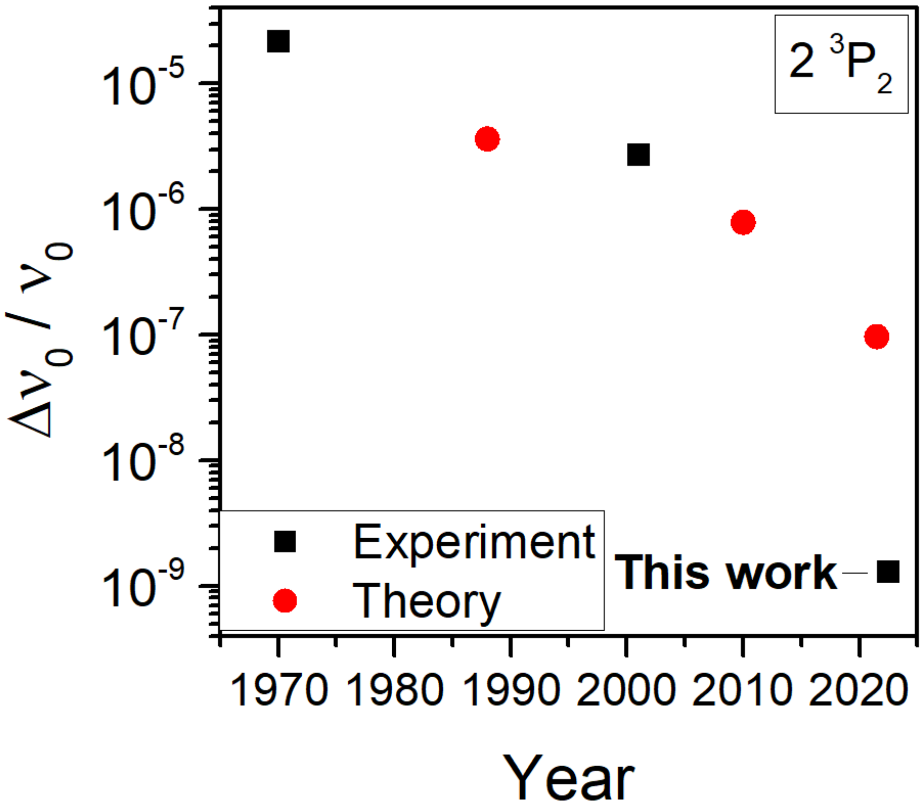
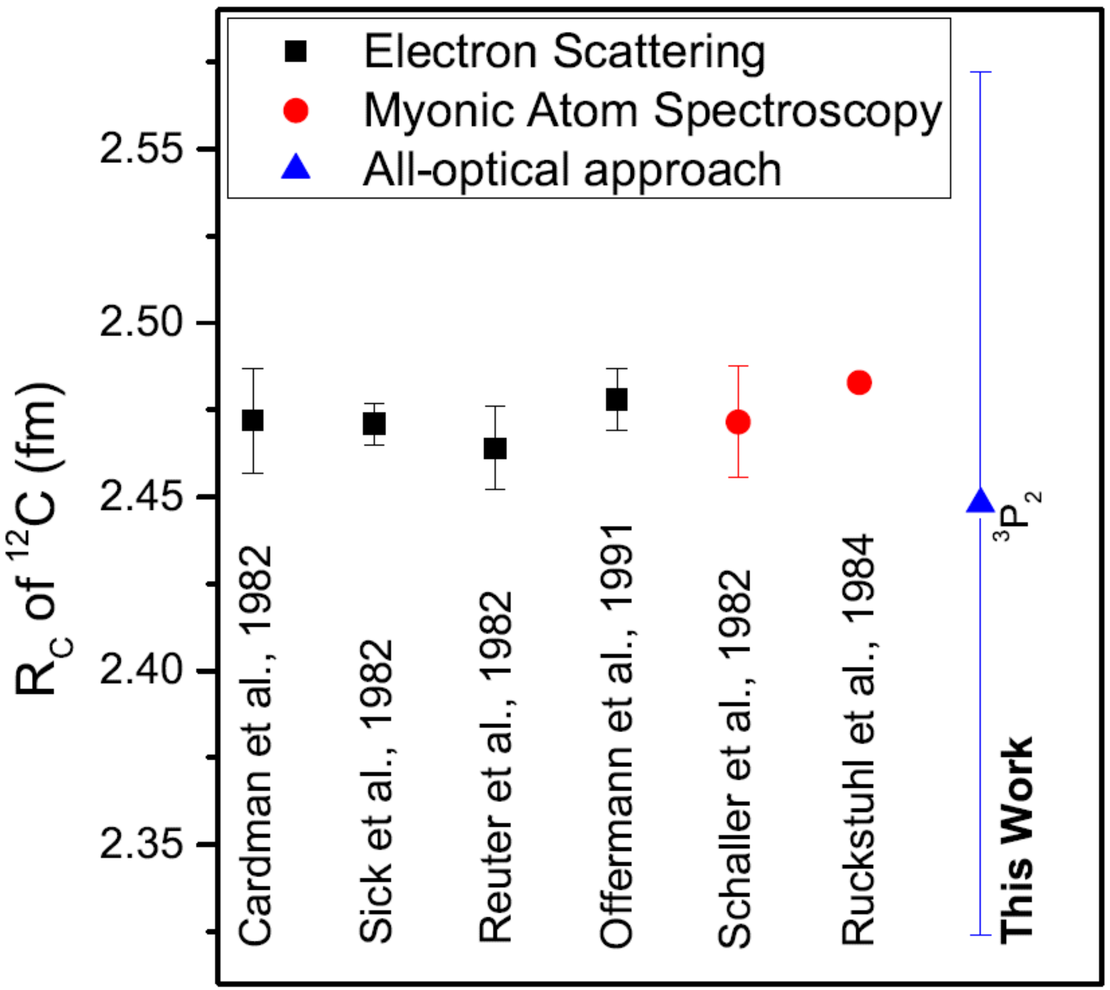




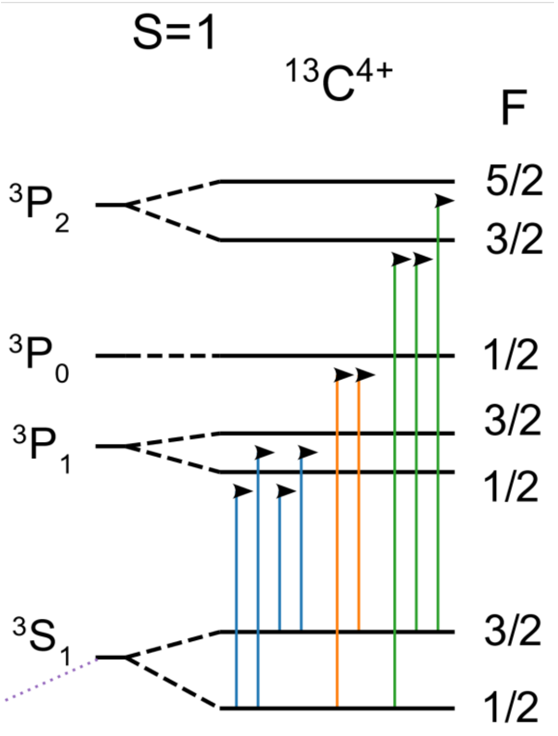
First All-Optical Nuclear Charge Radius of ^{12}C



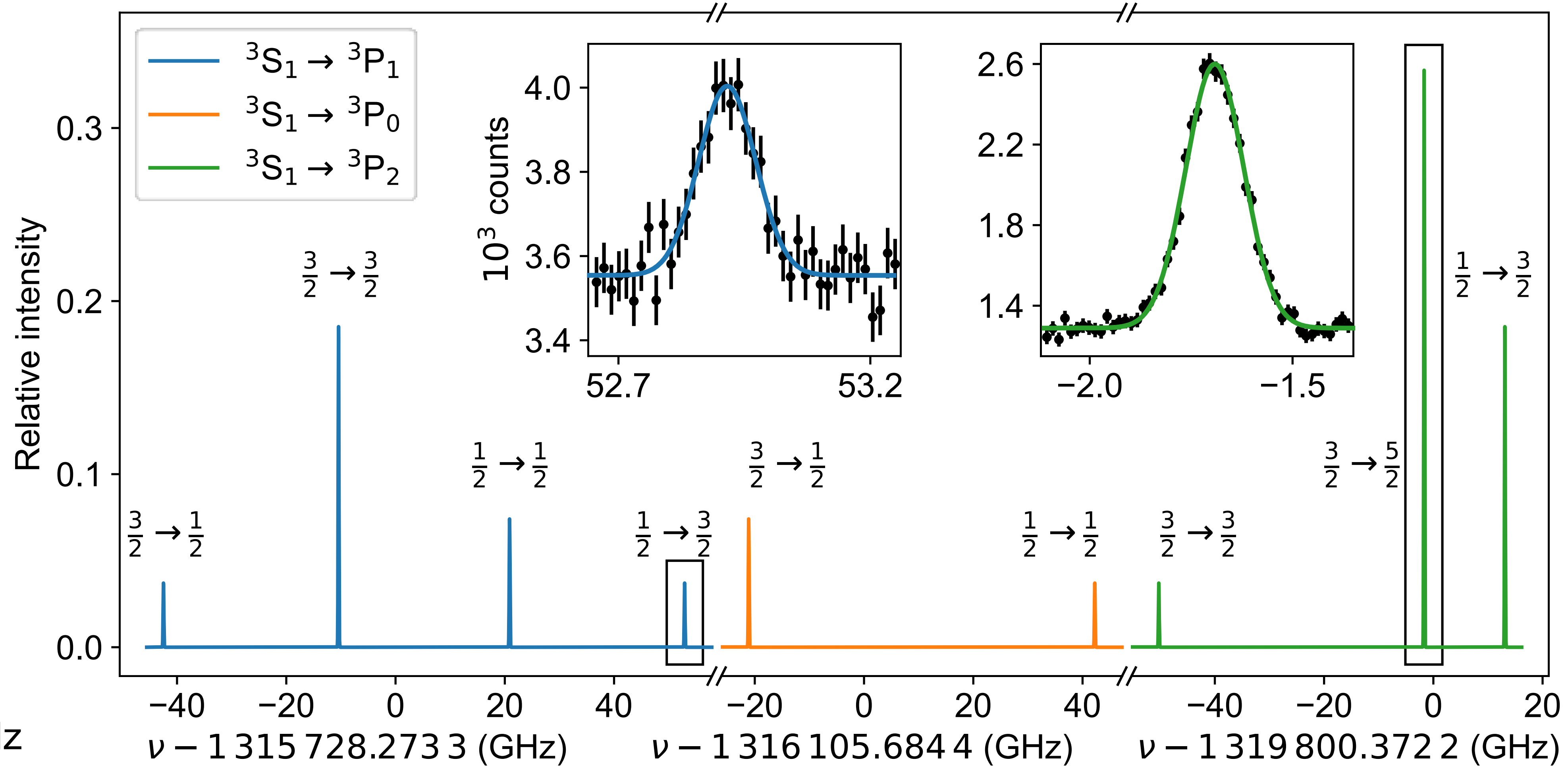
- **Improved** previous experiments by **>3 orders** of magnitude
- Theory also **improved by one order** and has good agreement with Exp.
  → more work needed for competitive all-optical R_C
- **First** high-precision laser spectroscopy in C isotope chain
  → starting position for regular isotope shift measurements to extract $\delta\langle r^2\rangle$ **of ^{13}C and ^{14}C**

P. Imgram *et al.*, PRL **131**, 243001 (2023)

Measurements on $^{13}C^{4+}$

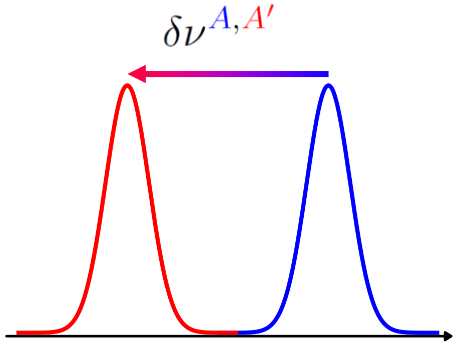


Hyperfine Mixing shifts transitions by up to 2 GHz



→ Every HFS transition in all fine-structure transitions must be measured

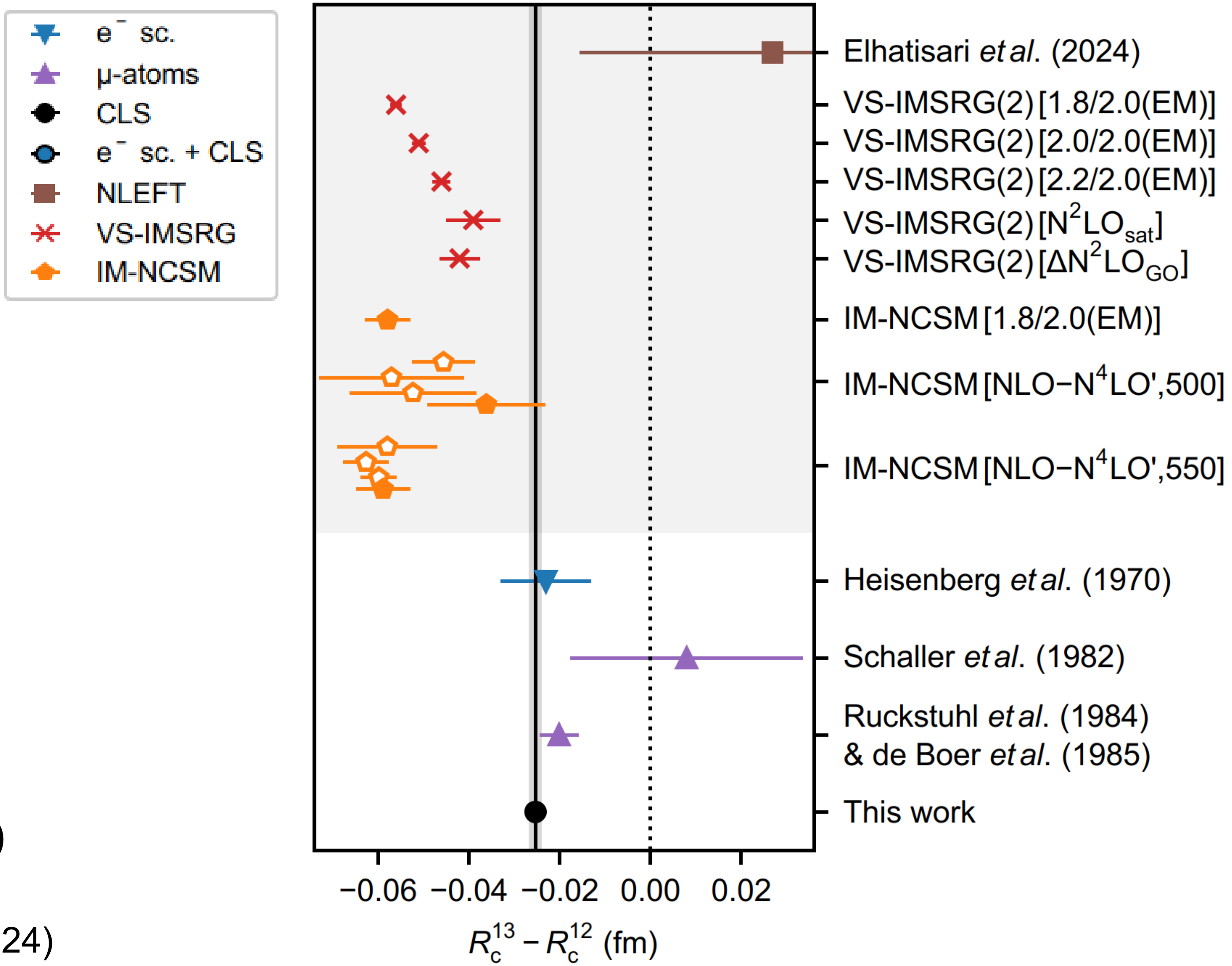
Nuclear Charge Radius of ^{13}C



$$\delta\nu^{A,A'} := \nu^{A'} - \nu^{A} = \delta\nu_M + F\delta\langle r^2\rangle^{A,A'}$$

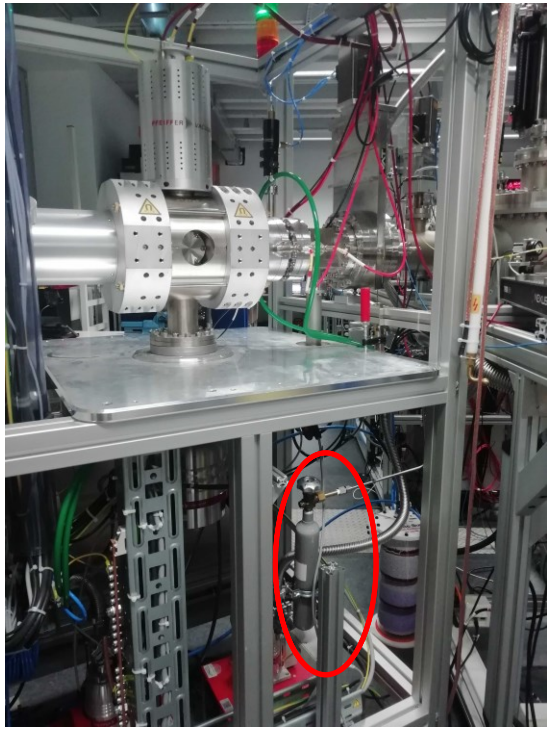
$$\iff \quad \delta\langle r^2\rangle^{A,A'} = \frac{\delta\nu^{A,A'} - \delta\nu_M}{F}$$

- Improved R_{ch}(^{13}C) determined with electrons by factor of 6
- Similar precision as muonic result
- 3σ deviation for R_{ch}
- Larger discrepancy than in ^{12}C (2σ)

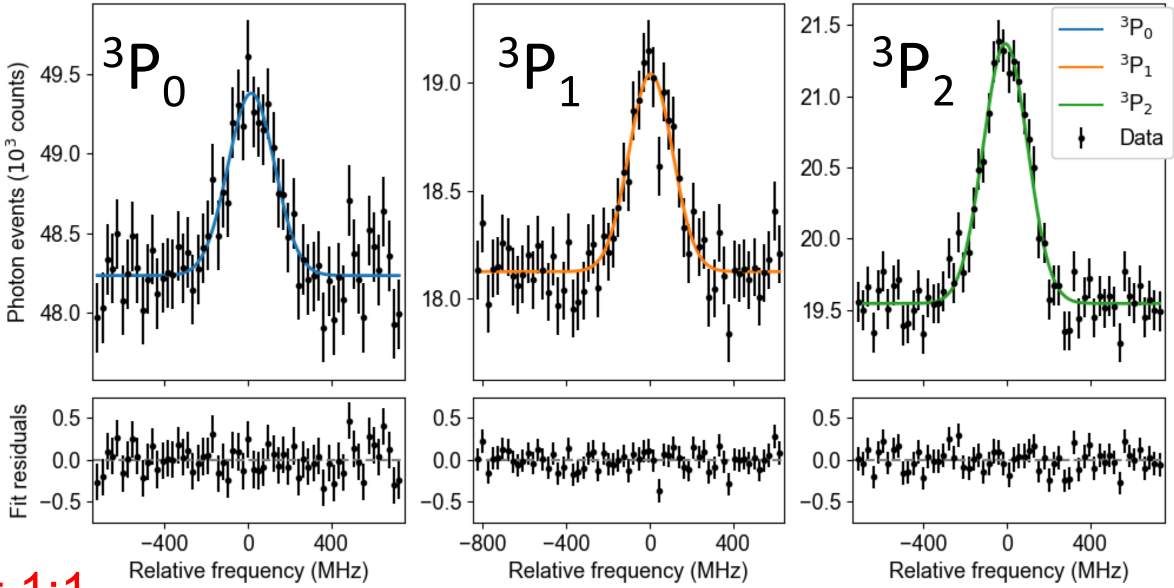


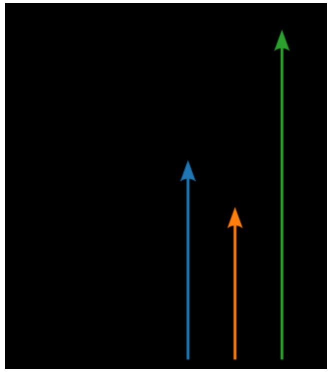
P. Müller, et al., Nature Comm. **16**, 6234 (2024)

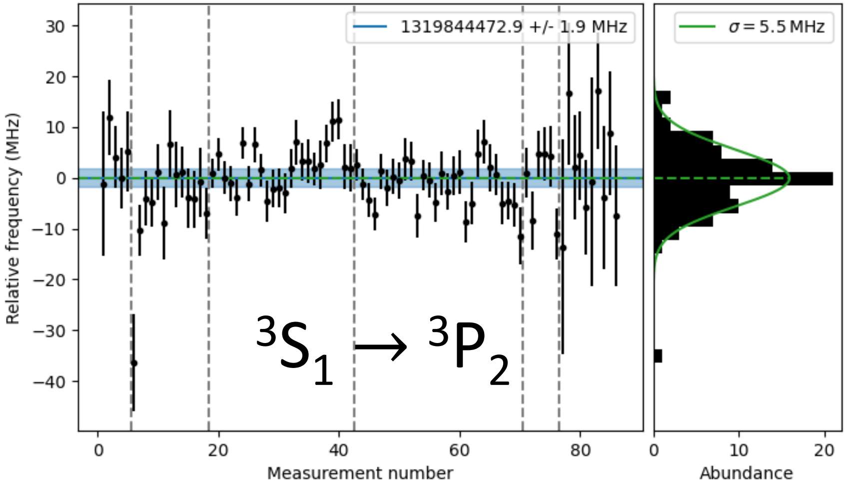
Measurements of ^{14}C



$^{14}CO_2$:$^{12}CO_2$ = 1:1
1.4 l, 50 mbar,
2 mmol ^{14}C, 50 mCi







- Determination of the $^3S_1 \rightarrow {}^3P_J$ transition frequencies in $^{14}C^{4+}$ on a 2-MHz precision level
- Extraction of the differential nuclear charge radius $\delta\langle r^2\rangle^{12,14}$ from the isotope shifts
- Additional check of theory: Splitting Isotope Shift

K. König et al., to be published (2025)

Measurements of Boron

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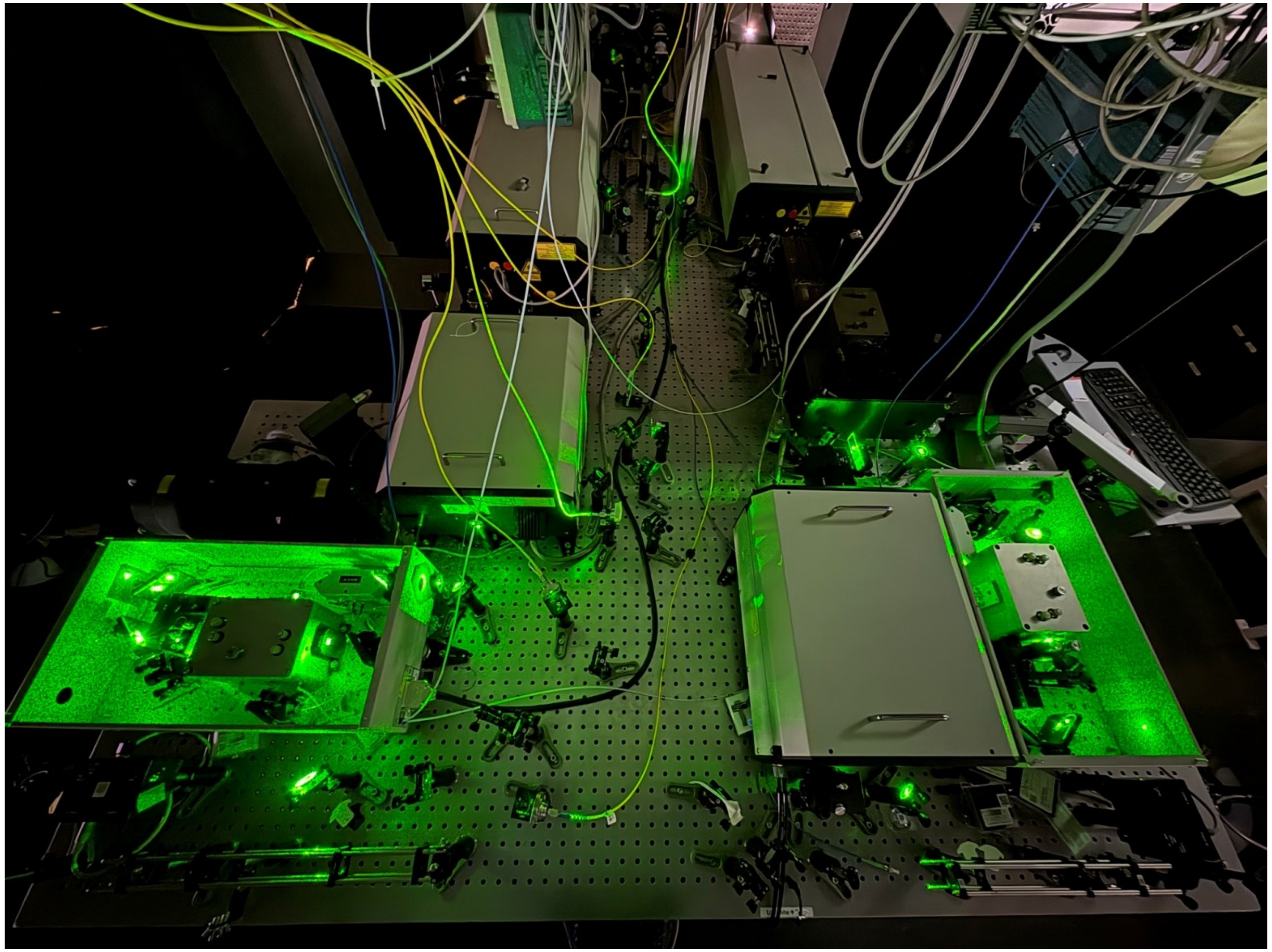
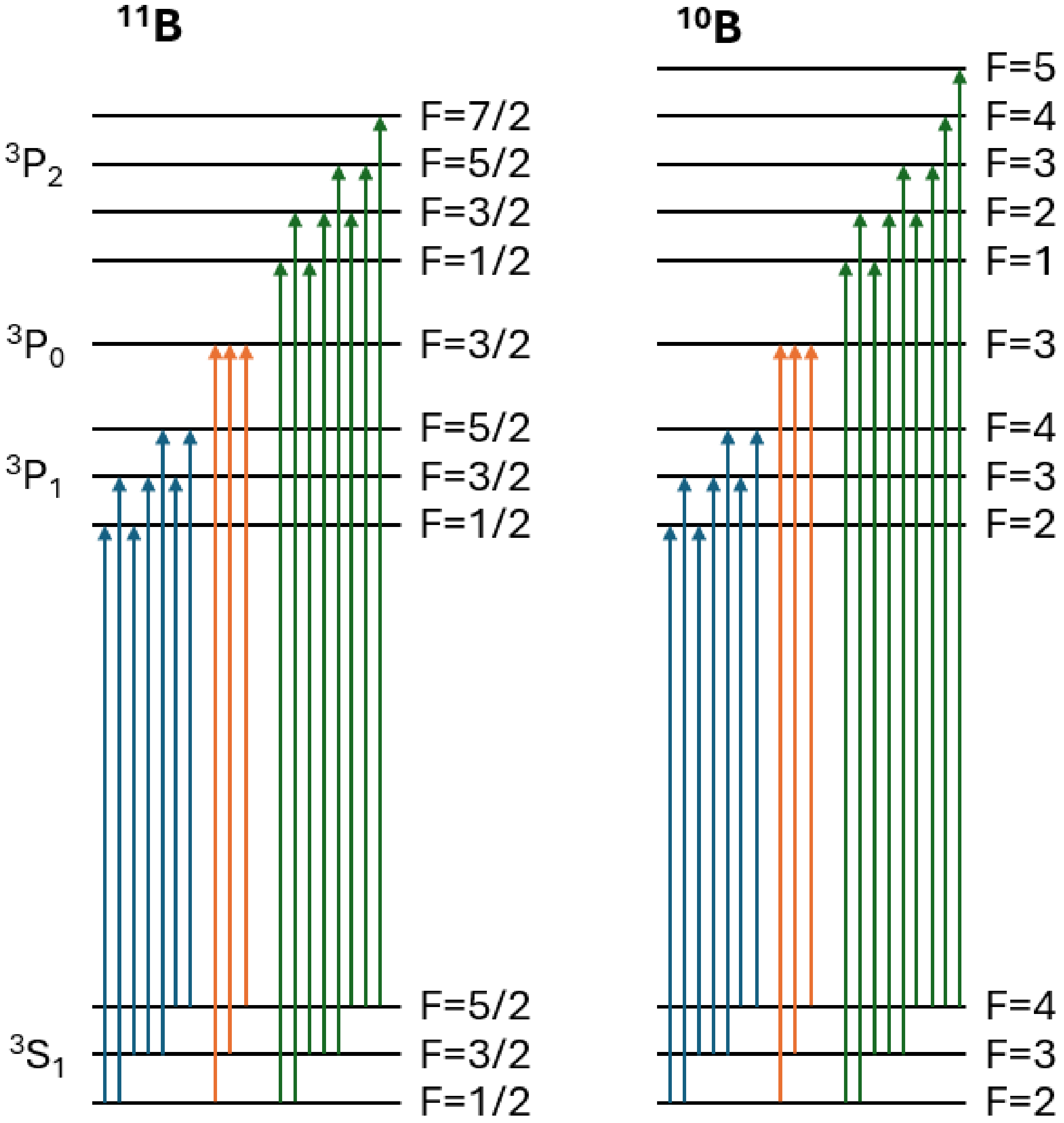
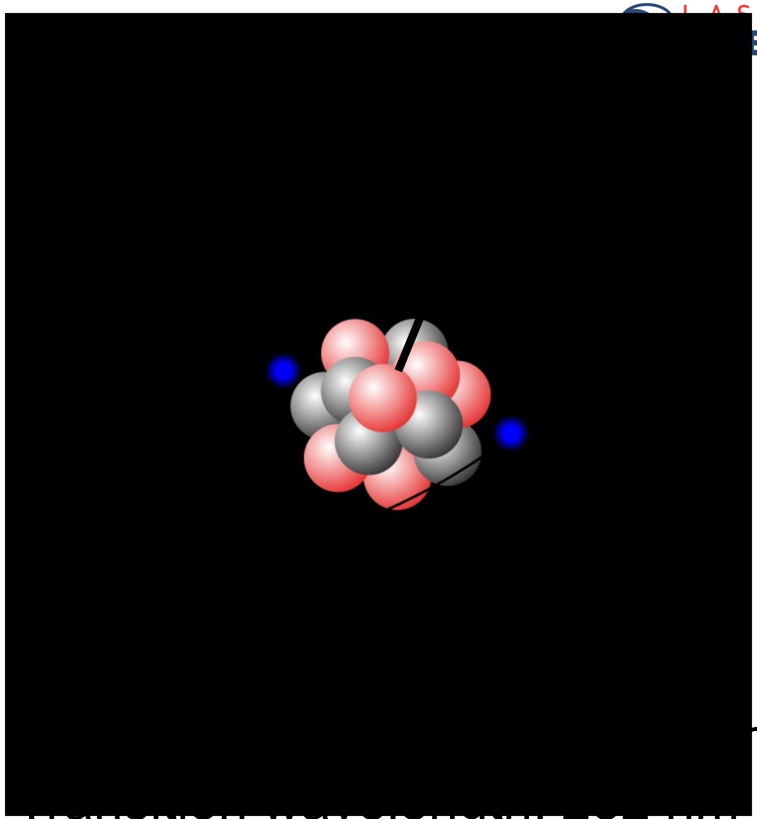
B	250 nm, neutral beam
B^{+}	No laser transition
B^{2+}	206 nm, very deep UV
B^{3+}	282 nm, from metastable state
B^{4+}	No laser transition

So far laser spectroscopy was never done for 3 charge states



Challenge in Boron

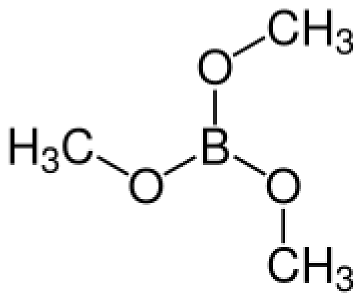




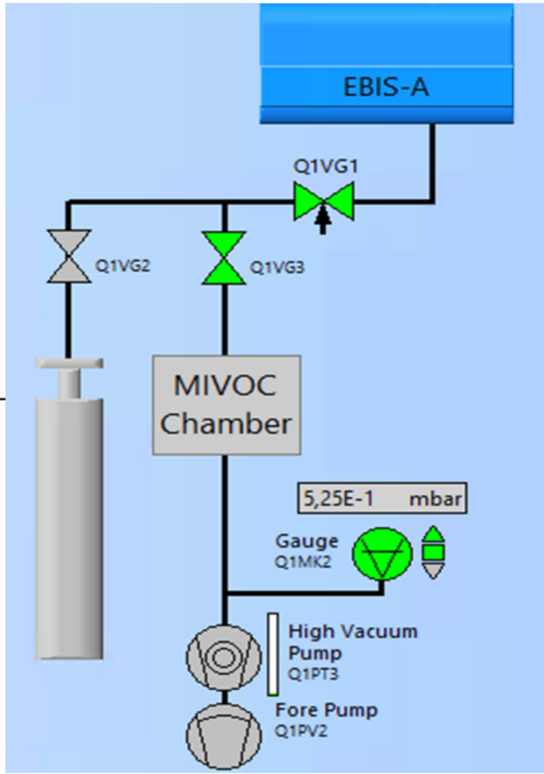
[redacted]

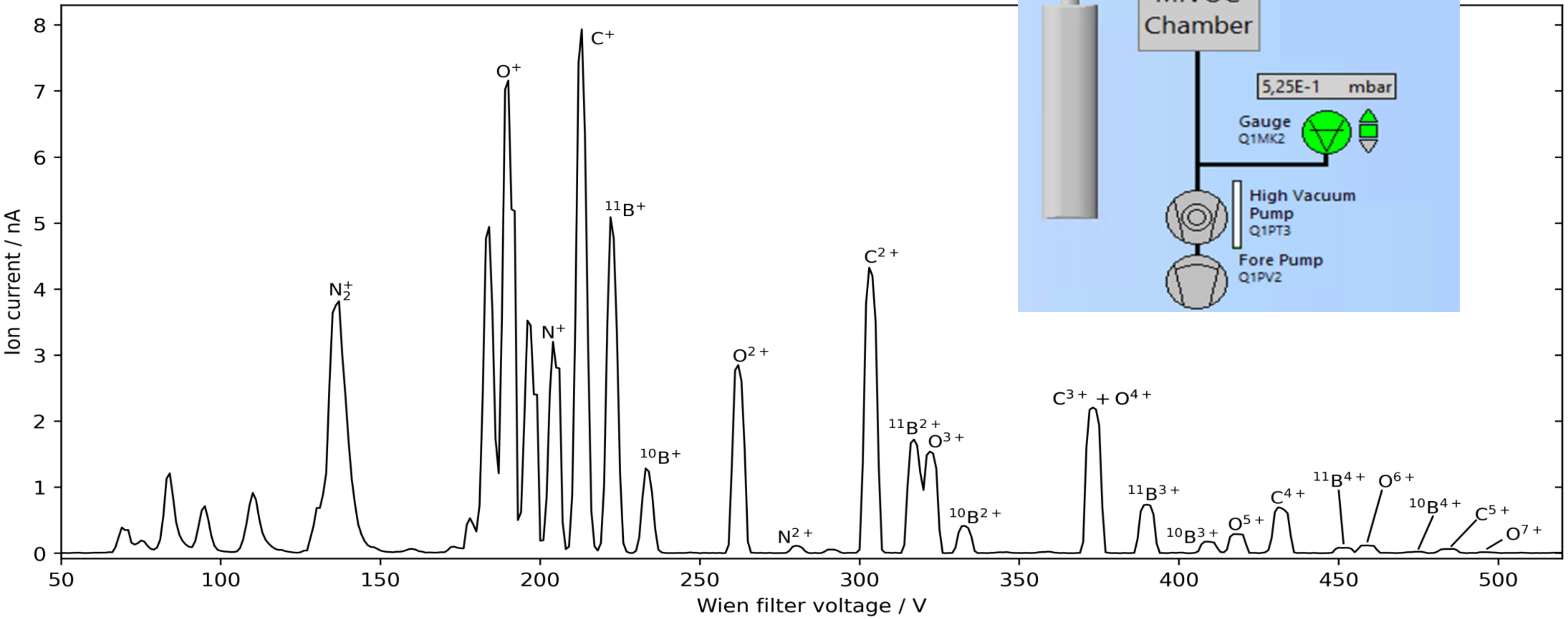
^{11}B (I=3/2): 18 hyperfine transitions
^{10}B (I=3): 19 hyperfine transitions

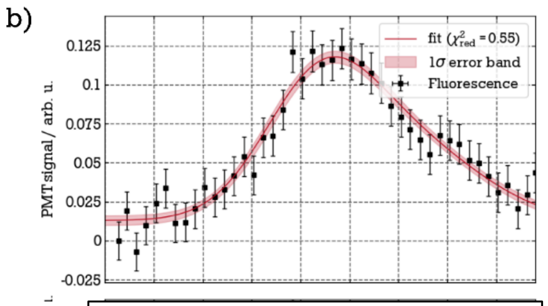
Helium-Like B^{3+}: Production and First Measurements



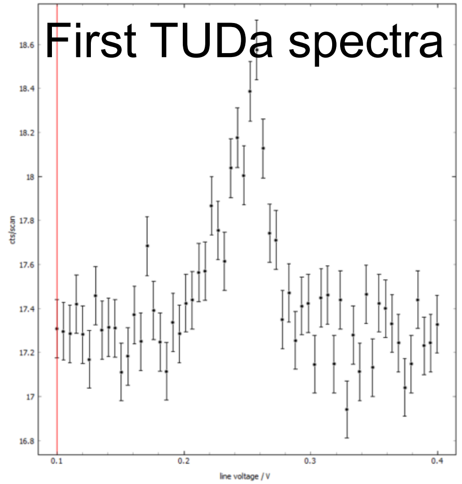
Trimethylborat
- Liquid
- Vapor pressure 150 mbar







K. Mohr, et al., Atoms 11, 11 (2023)



Relative strength of weakest transition 0.5 %

Helium-Like B^{3+}: Production and First Measurements

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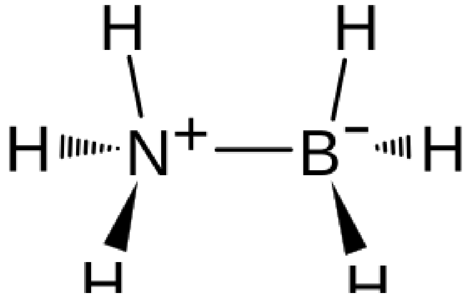
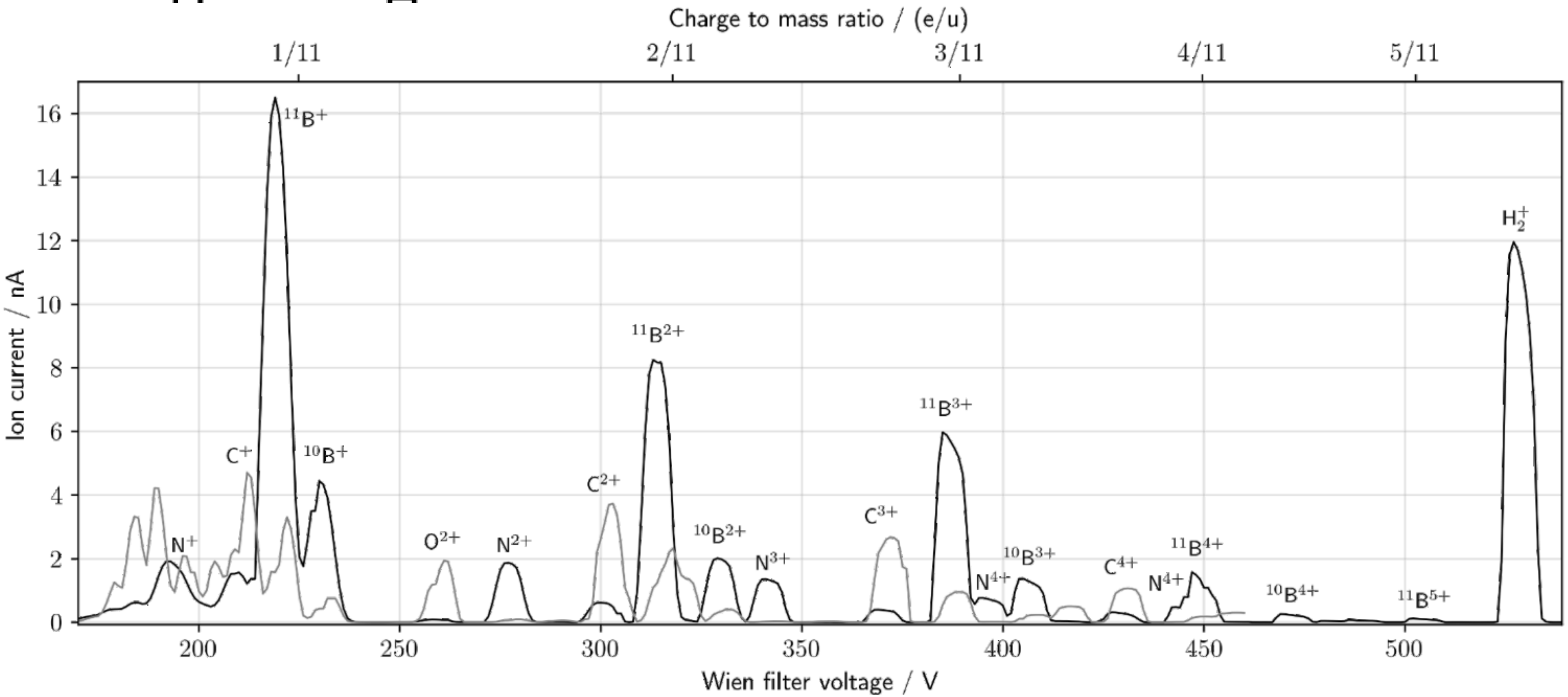
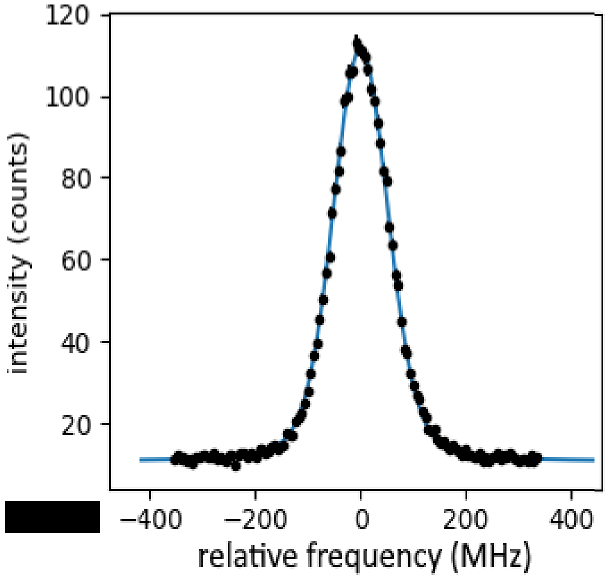
ammonia borane (BH_3NH_3)



Abundance of all boron charge states improved by a factor of 6
→ enables laser spectroscopy of transitions in less abundant ^{10}B ions



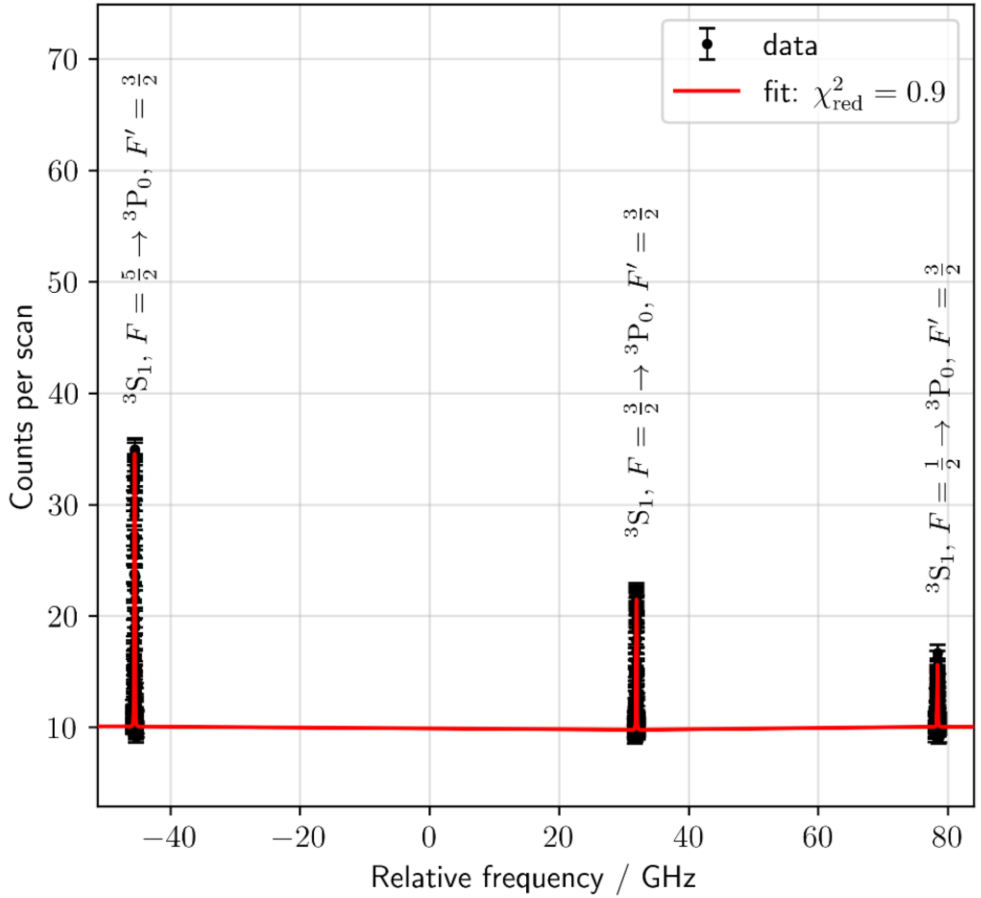
improved production



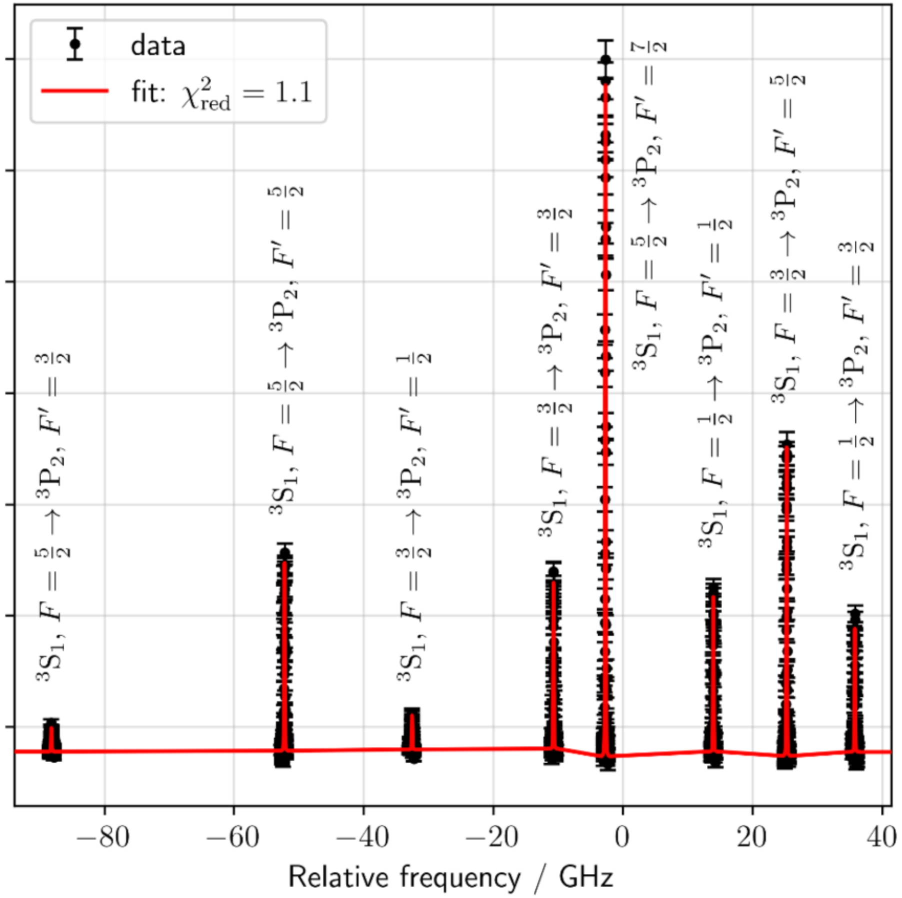
Analysis on B^{3+} Started

≈ 20,000 spectra recorded
Systematics studied
Two fine-structure transition in ^{11}B analyzed

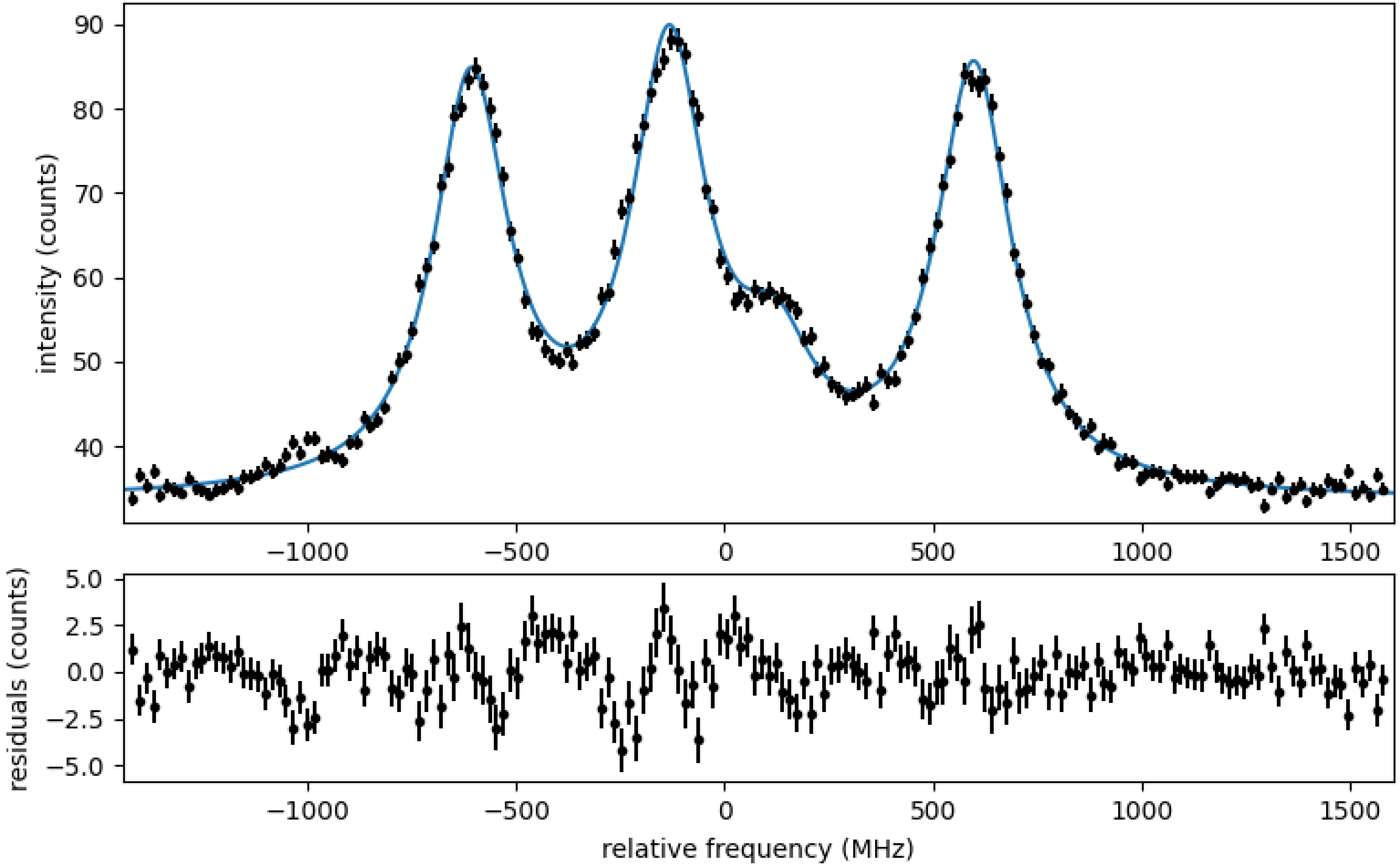
$^3S_1 \rightarrow {}^3P_0$



$^3S_1 \rightarrow {}^3P_2$



Measurements on Neutral Boron

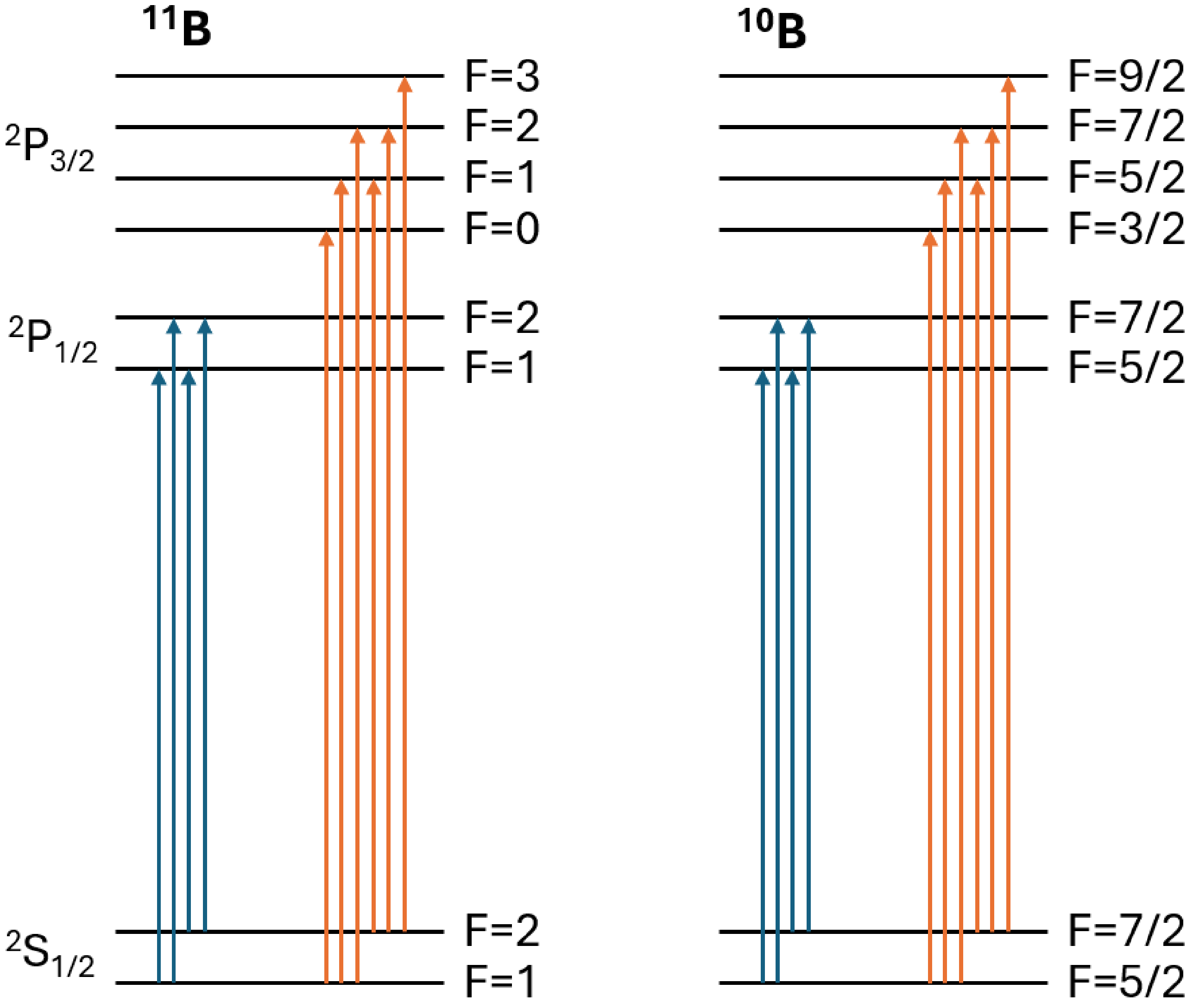


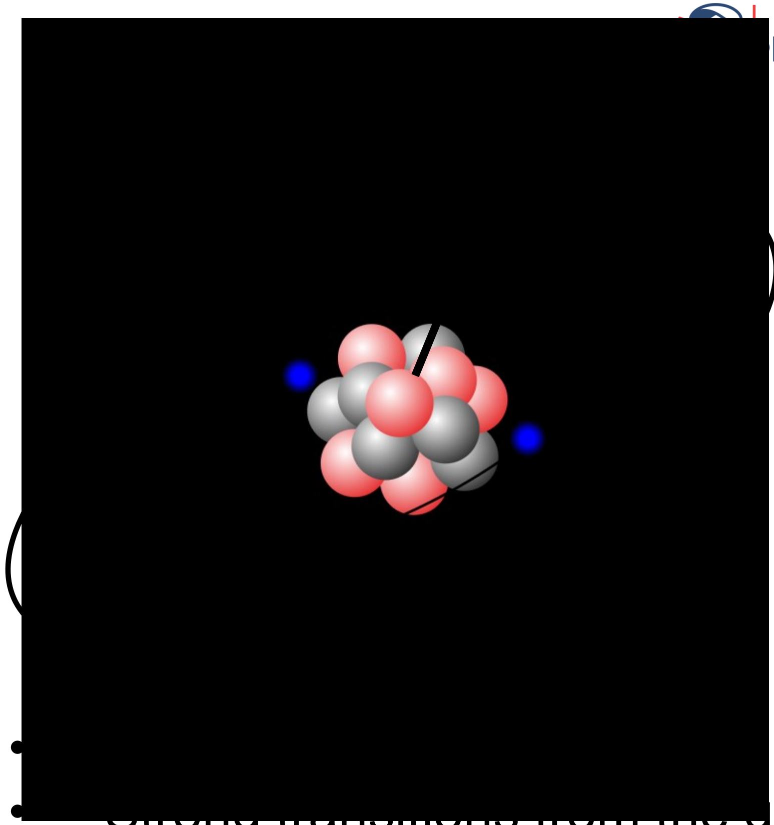
Determined rest-frame frequencies and $^{10,11}B$ isotope shift

Weaker signal than expected:

- Ground state not efficiently populated in the CEC
- Test with cooled beam in the ionic ground state when RFQ is installed
- Test with other reaction partners for higher efficiency for ^{8}B

Last Charge State: Li-like B^{2+}





- Strong transitions from the ground state
- Deep UV transitions at 207 nm

Summary

- Laser spectroscopy of He-like systems is able to provide absolute charge radii but for better precision theory has to be improved
- The charge radii of $^{13,14}C$ could be improved by measurements of the isotope shift.
- Ab initio calculations have considerable issues calculating these charge radii
- The splitting isotope shift of these isotopes provides a consistency check for the atomic structure calculations within an isoelectronic system
- Charge Radii of $^{10,11}B$ isotopes will be determined in three different charge states with 2,3 and 5 electrons. This will test the consistency of the mass shift calculations for different electronic systems.
- Precise charge radii differences provide systematic tests for muonic atom spectroscopy
- Charge radii from muonic spectroscopy are anker points for planned isotope shifts measurements of short-lived isotopes in this region

Thank you!

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