

Nuclear Charge Radii:

The N=28 Shell Closure and Prospects in the Z=5 Region



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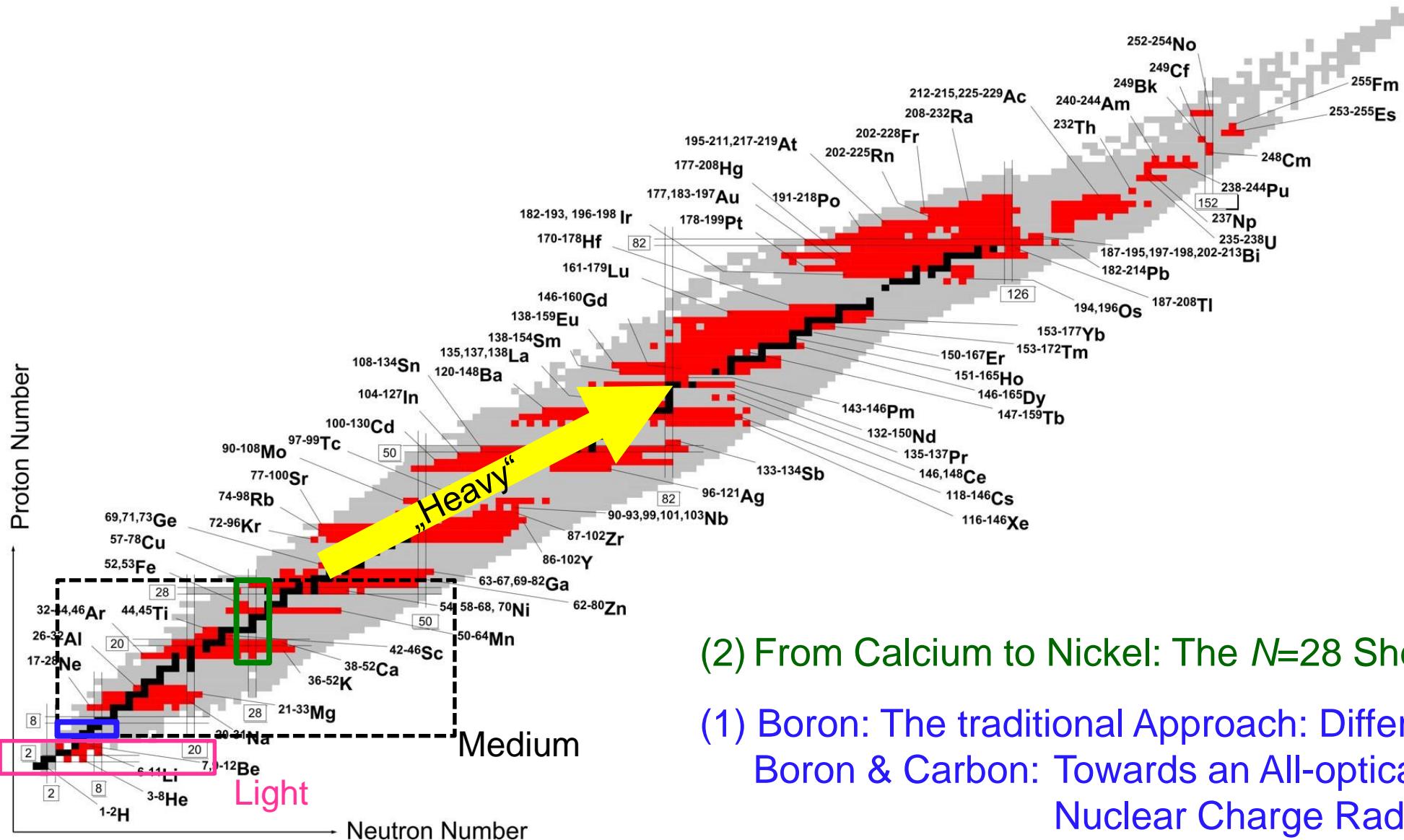


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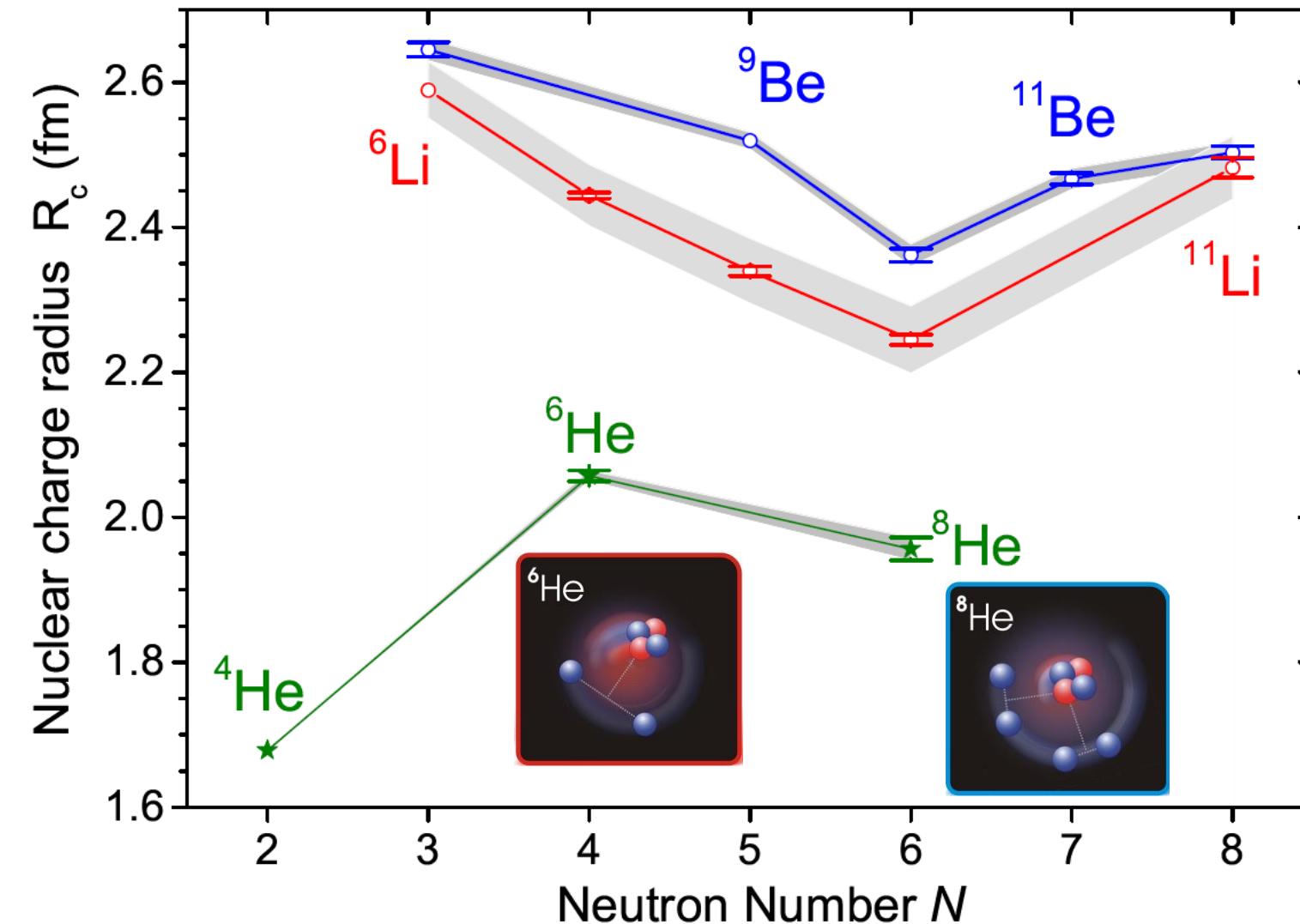


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The Nuclear Chart of Laser Spectroscopy



Nuclear Radii of the Lightest Isotopes



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

Grey Regions: $\sigma(R_c)$

$$R_c(^9\text{Be}) = 2.519 (12) \text{ fm}$$

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

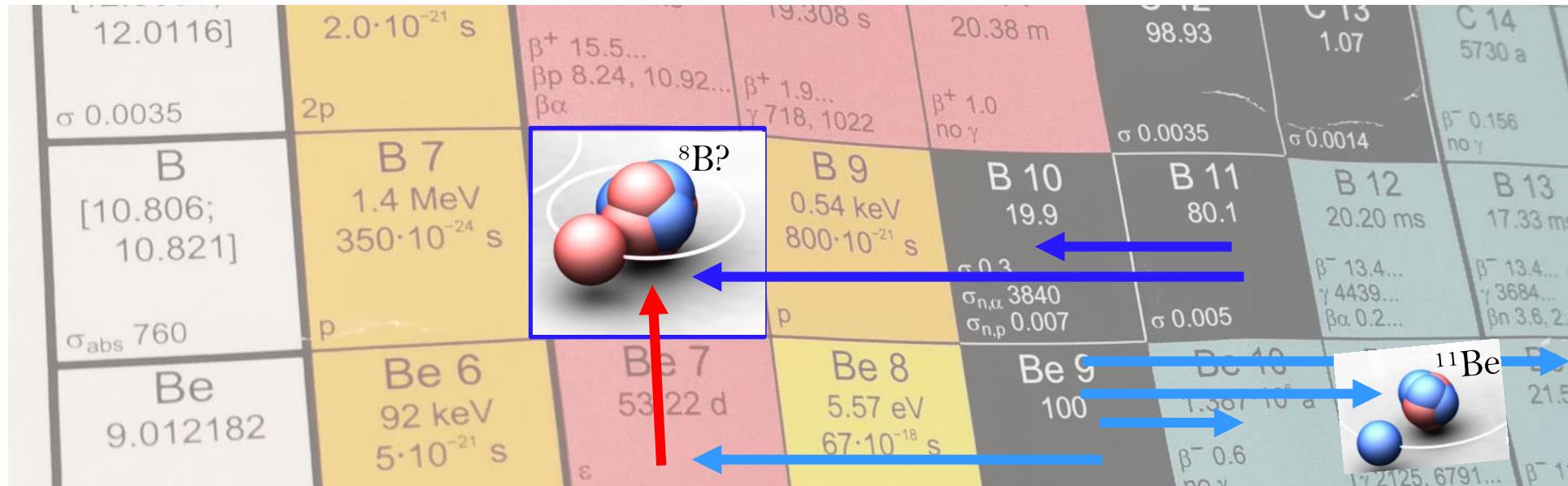
$$R_c(^6\text{Li}) = 2.589 (39) \text{ fm}$$

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

$$r_\alpha = 1.678\,24(83) \text{ fm}$$

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

The Proton-Halo Nucleus ${}^8\text{B}$



$$\delta\nu_{\text{IS}} - \delta\nu_{\text{MS}}^{\text{Theory}} \propto \delta\langle r_c^2 \rangle$$

$$R_c(A) = R_c(A_{\text{ref}}) + \delta\langle r_c^2 \rangle^{A_{\text{ref}}, A}$$

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

Reference Radius required

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

Approach for $^{10,11}\text{B}$ Isotope Shift Measurements



Using Resonance Ionization (Mass) Spectrometry:

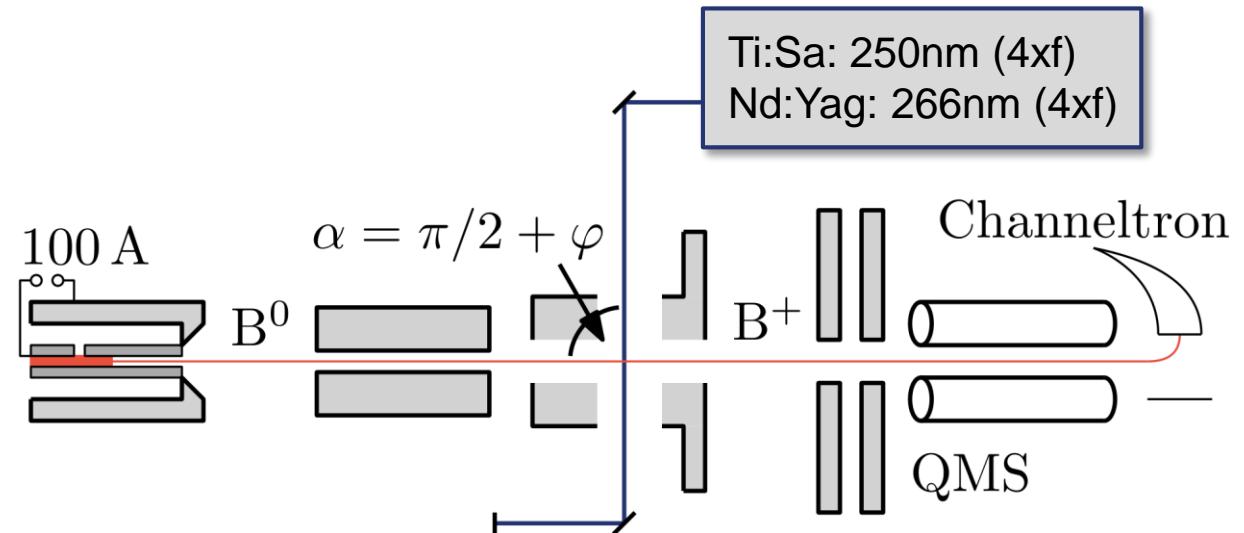
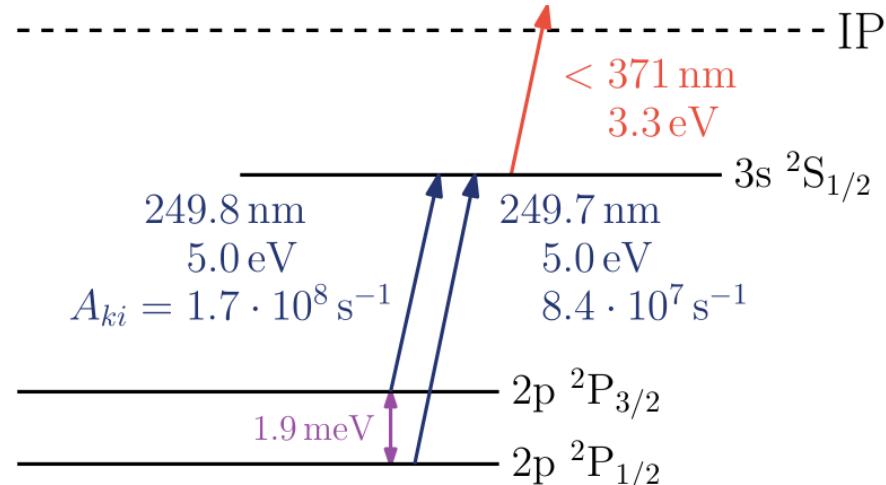
Detecting resonantly ionized ions/atoms

Doppler shift:

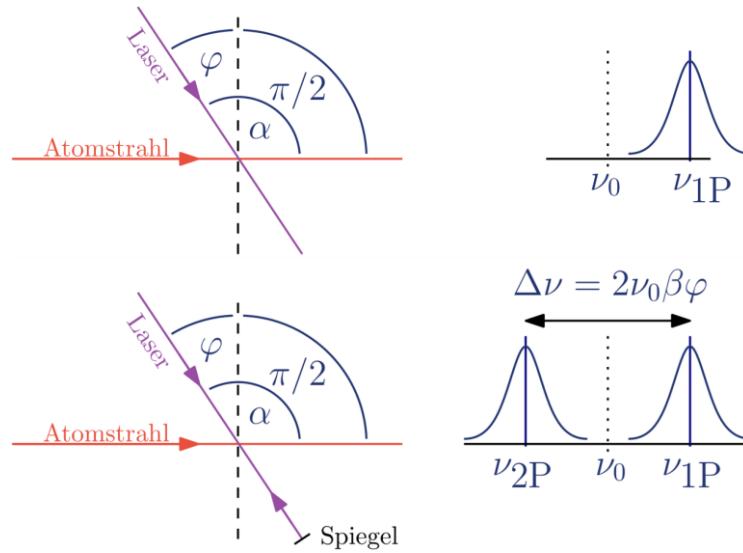
$$\nu_{\text{observed}} = \nu_0 \frac{\sqrt{1 - \frac{v^2}{c^2}}}{1 - \frac{v}{c} \cos \alpha} \sim \frac{30 \text{ kHz}}{8 \text{ MHz/mrad}}$$



$\sim 2600\text{K}$, $\sim 2100 \text{ m/s}$



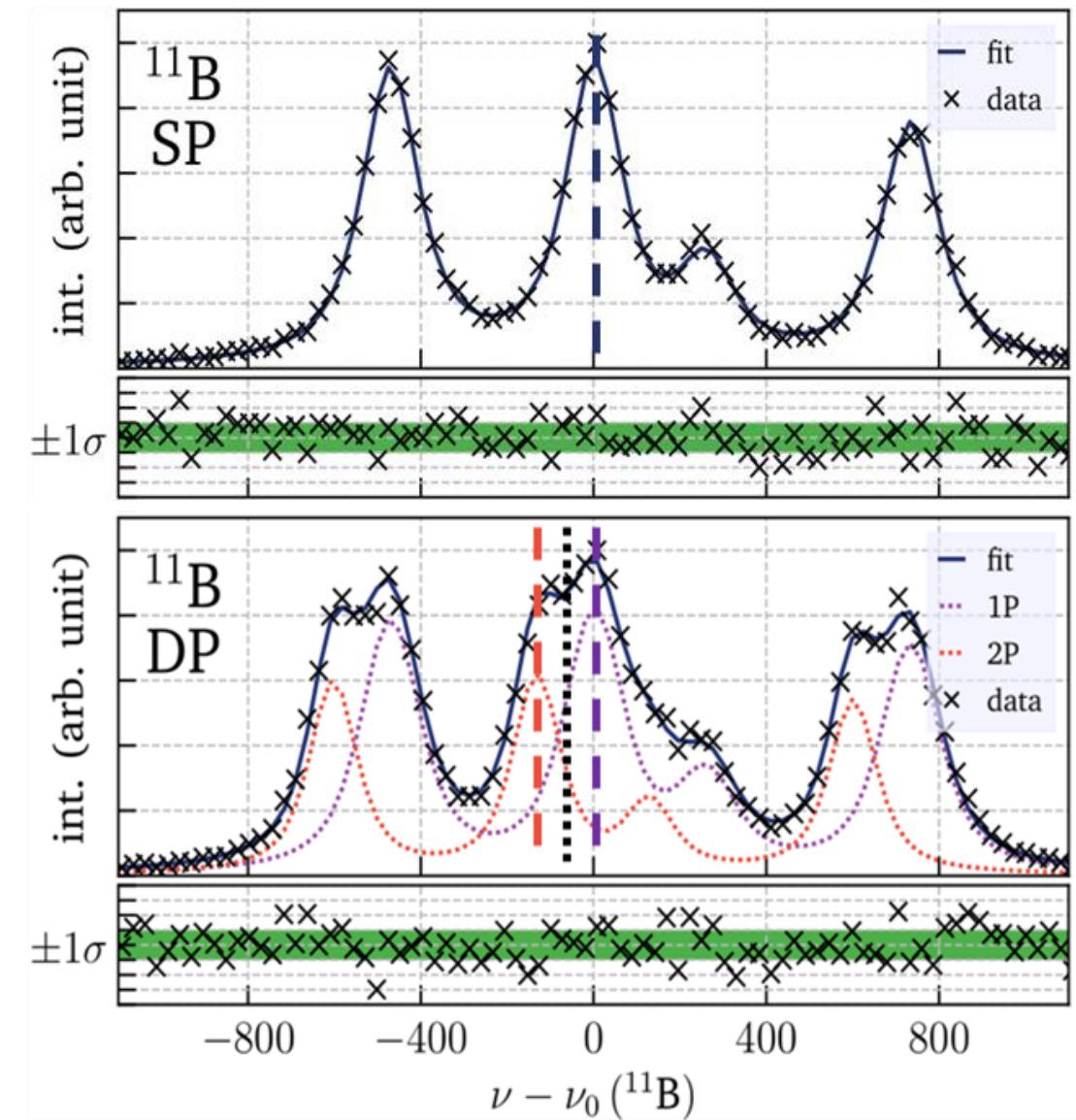
Transition Frequencies



Isotope	Frequency (MHz)	Ref.
¹⁰ B	1 200 363 905 (120)	[A]
	1 200 364 066.2 (1.7)	<i>this work</i>
¹¹ B	1 200 358 689 (90)	[A]
	1 200 354 700 (7400)	[B] – Theory
	1 200 359 033.9 (1.4)	<i>this work</i>

A: [Johansson et al., *Astroph. J.* 403, L25 (1992)]

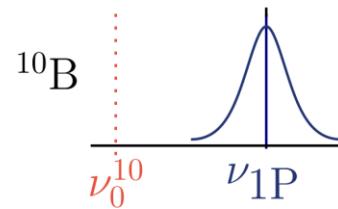
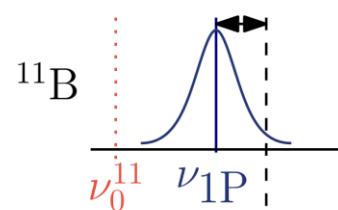
B: [Puchalski et al., *Phys. Rev. A* 92, 062501 (2015)]



[Maaß et al., *Phys. Rev. Lett.* 122, 182501 (2019)]

Isotope Shift

$$\sim \nu_0 \varphi [\beta(^{10}\text{B}) / \beta(^{11}\text{B})]$$



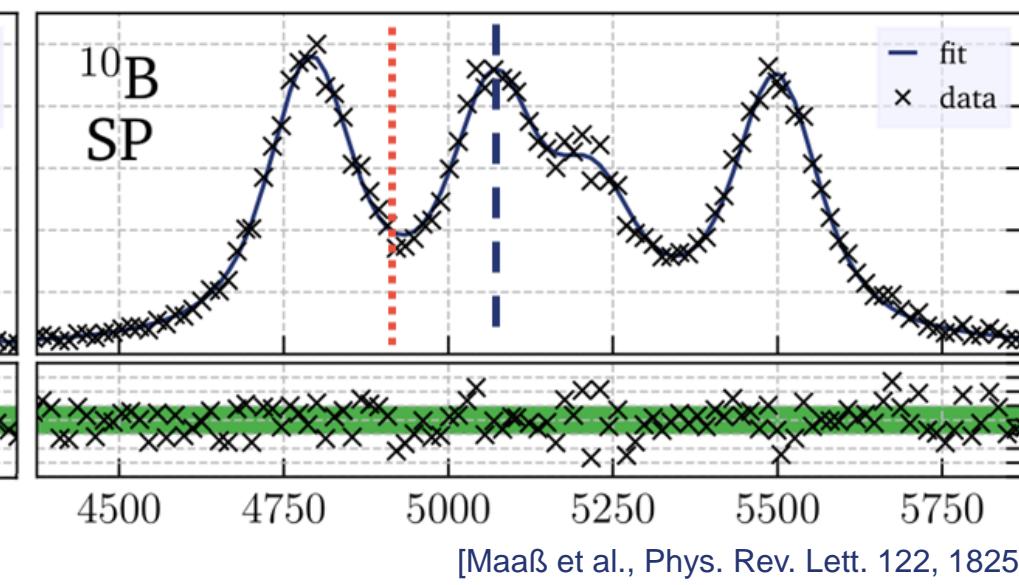
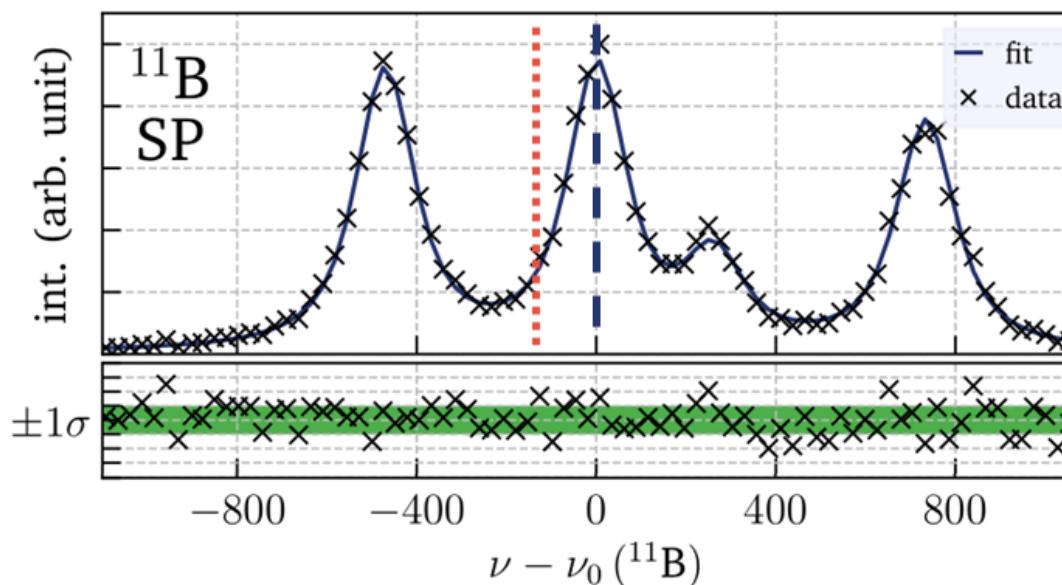
Since angle $\varphi = \text{const.}$:

$$\Delta\nu_{\text{IS}} = \nu_0(^{11}\text{B}) - \nu_0(^{10}\text{B})$$

$$= \nu_{1\text{P}}(^{11}\text{B}) - \nu_{1\text{P}}(^{10}\text{B}) + \nu_0 \varphi [\beta(^{10}\text{B}) / \beta(^{11}\text{B})]$$

and for a thermal source

$$[\beta(^{10}\text{B}) / \beta(^{11}\text{B})] = \sqrt{\frac{11\text{ u}}{10\text{ u}}}$$



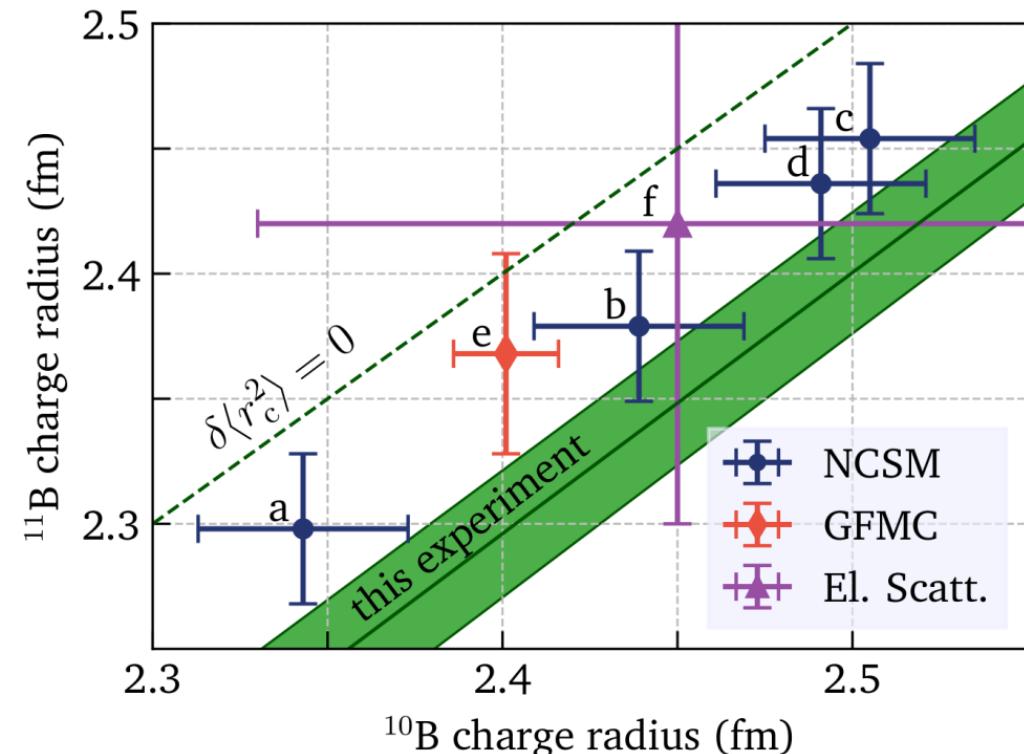
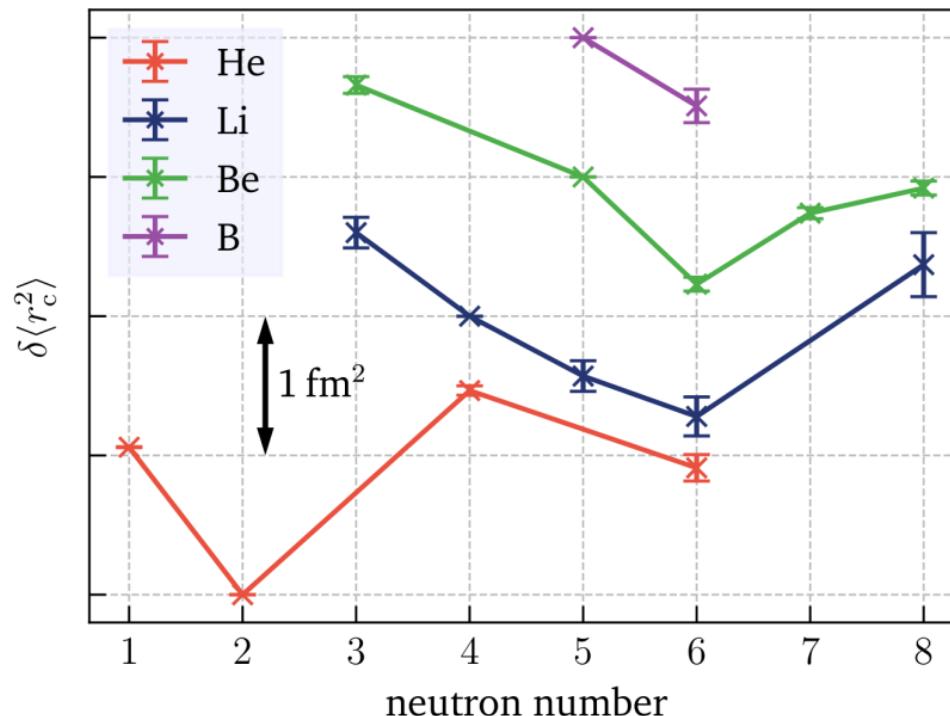
Results

$$\delta\nu_{\text{IS}} = 5031.3(2.0) \text{ MHz}$$

$$\delta\nu_{\text{FS}} = \delta\nu_{\text{IS}} - \delta\nu_{\text{MS}} = -8.3(2.0) \text{ MHz}$$

$$K_{\text{FS}} = 16.91(9) \text{ MHz/fm}^2$$

$$\delta\langle r_c^2 \rangle = \langle r_c^2 \rangle^{11} - \langle r_c^2 \rangle^{10} = -0.49(12) \text{ fm}^2$$



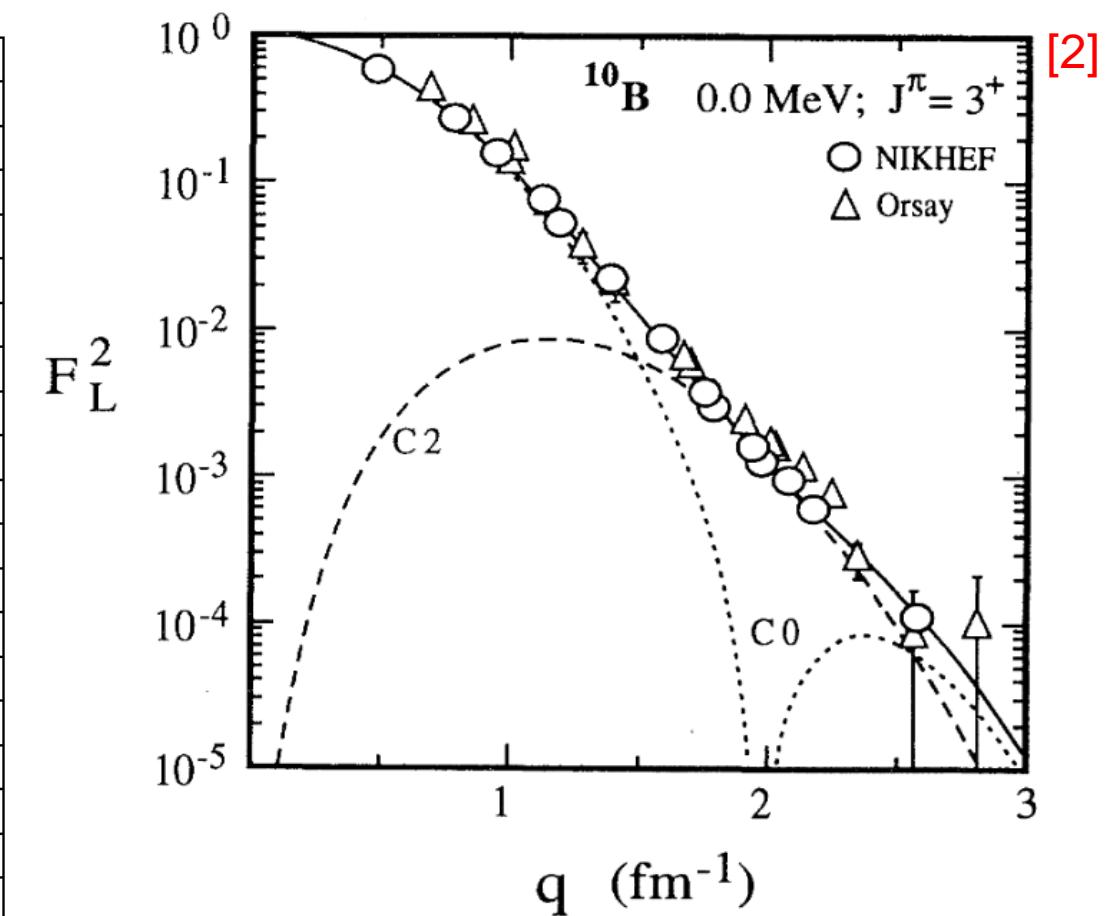
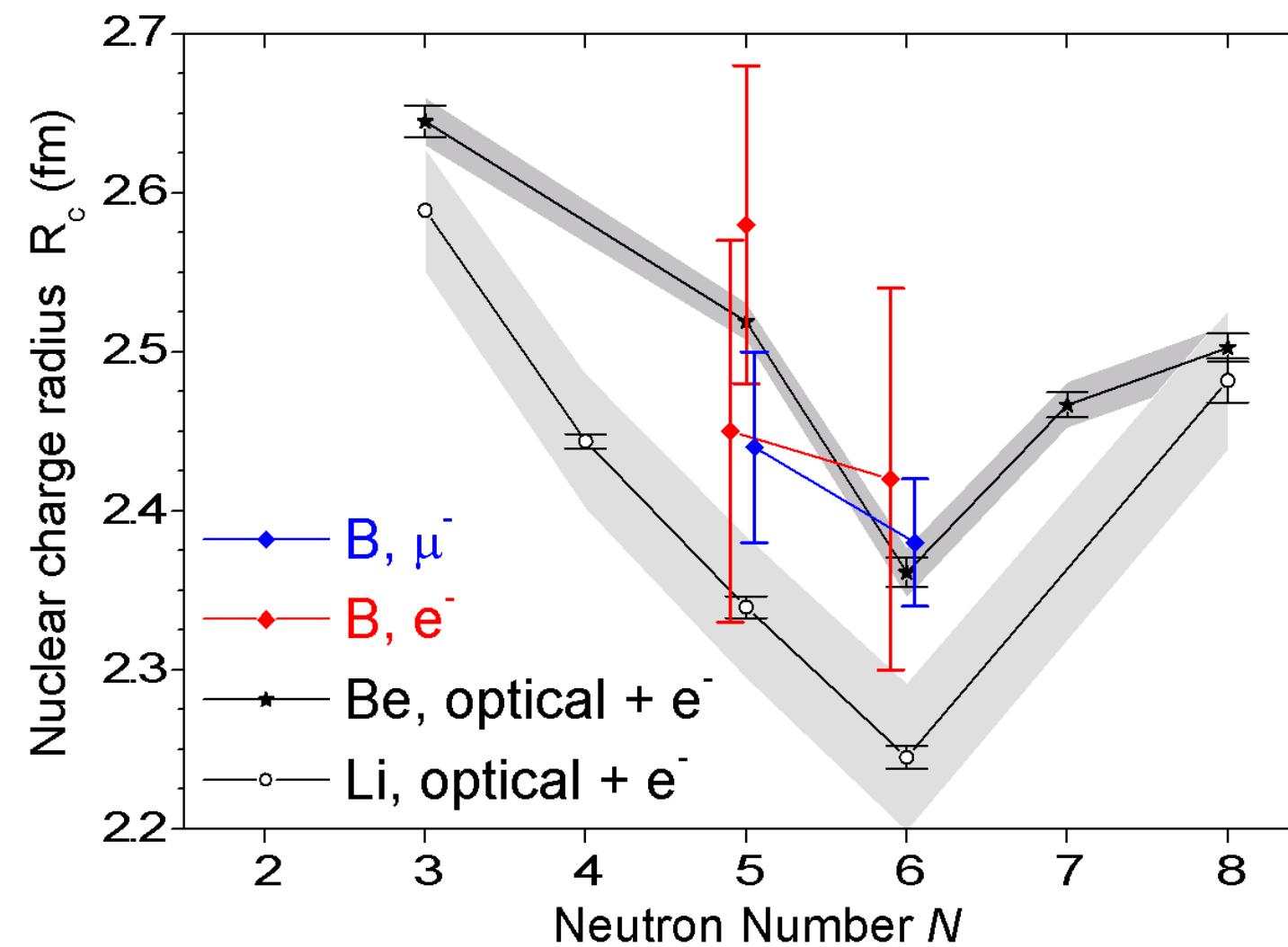
NCSM: No-Core Shell Model

Robert Roth, Thomas Hüther, TU Darmstadt

GFMC: Greens function Monte-Carlo

R.B. Wiringa, A. Lovato, ANL

The „Tragedy of Boron“ Reference Radii



[1] Stovall, Nucl. Phys. 86, 225 (1966)

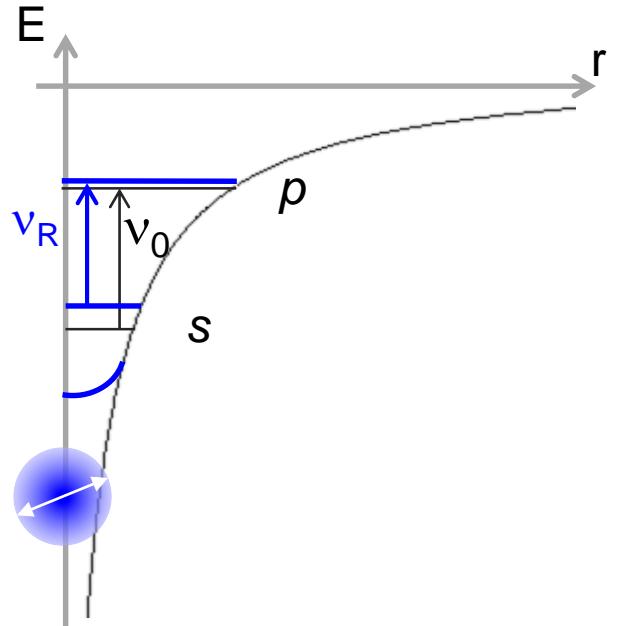
[2] Cichocki et al., PRC 51, 2406 (1995)

[3] Schaller et al., Nucl. Phys. A 343, 333 (1980)

[4] Olin et al., Nucl. Phys. A 360, 426 (1981)

The Idea of All-Optical Absolute Charge Radii

(see K. Pachucki, yesterday)



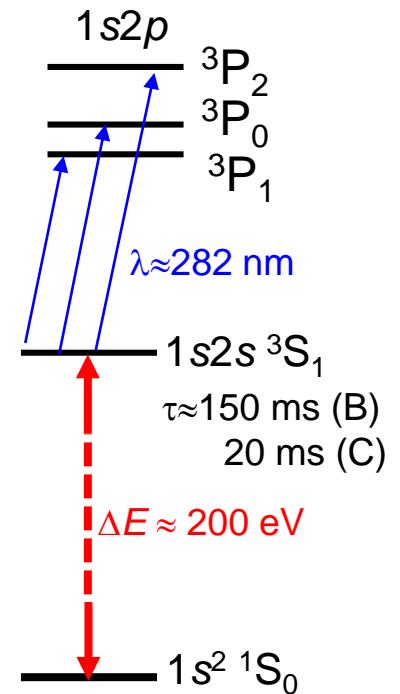
$$\delta\nu_{\text{FS}} = -\frac{Ze^2}{6\varepsilon_0} \Delta |\Psi_e(0)|_{i \rightarrow f}^2 \times \langle r_c^2 \rangle$$

Electronic Factor
(\rightarrow Wavefunction)

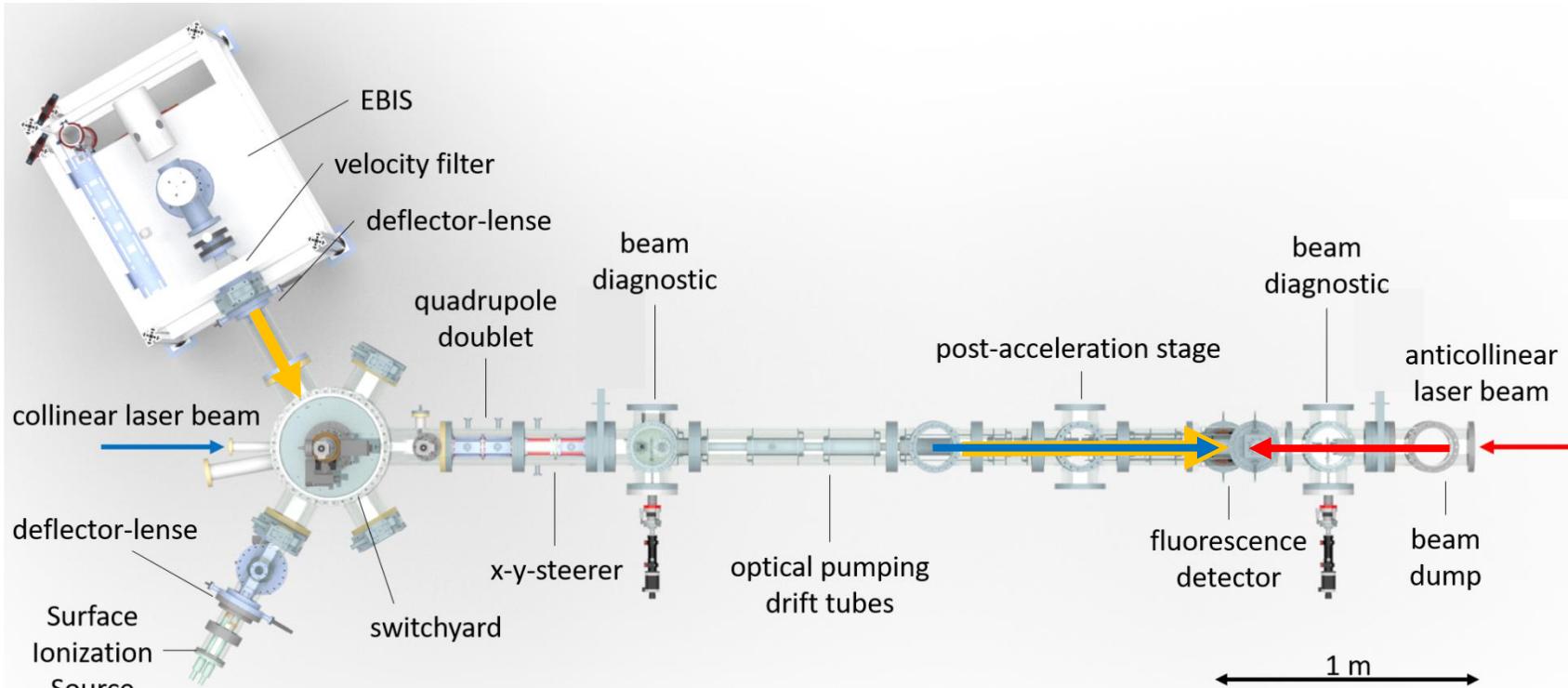
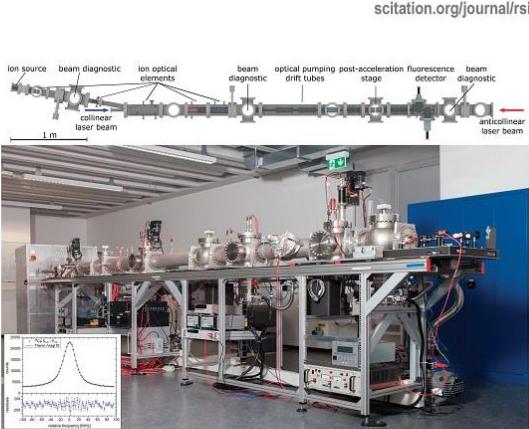
$$= F_{i \rightarrow f} \langle r_c^2 \rangle$$

- Measure **transition frequency** ν_R
- Compare with high precision atomic calculation for a point-like nucleus ν_0
- Difference $\nu_R - \nu_0$ is finite-size effect and **proportional to the ms charge radius**
- So far applied **only for H-like systems**, i.e., H, μ H and μ He
- Two-electron system requires elaborate QED calculations, which are now in reach
Yerokhin, Patkóš & Pachucki, PRA 98, 032503 (2018)
Patkóš, Yerokhin & Pachucki,, PRA 103, 042809 (2021)

Address He-like systems:
Li⁺, Be²⁺, B³⁺, C⁴⁺, N⁵⁺



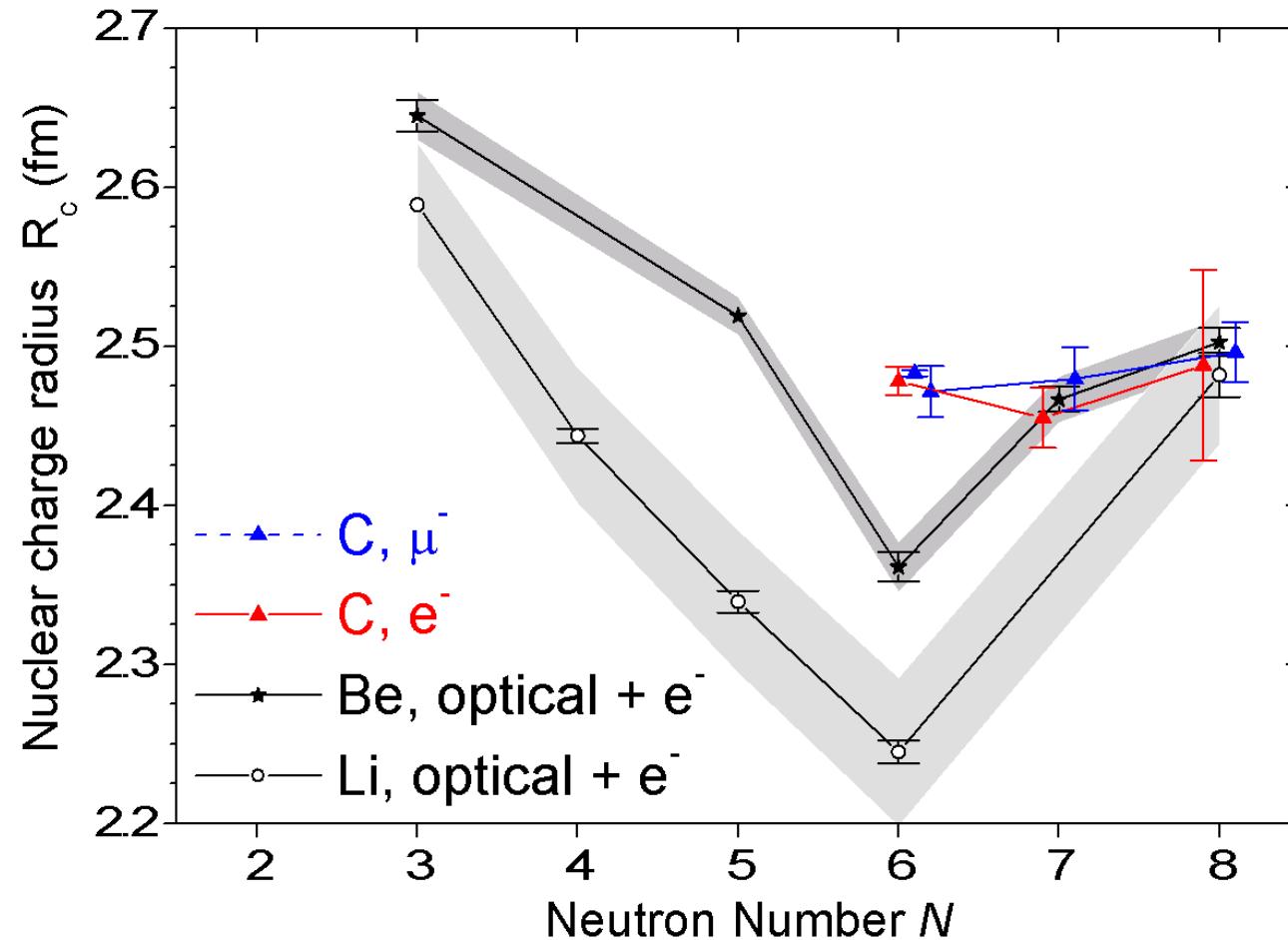
Measuring principle @ COALA, TU Darmstadt



$$\left. \begin{aligned} v_c &= v_0 \gamma (1 + \beta) \\ v_a &= v_0 \gamma (1 - \beta) \end{aligned} \right\}$$

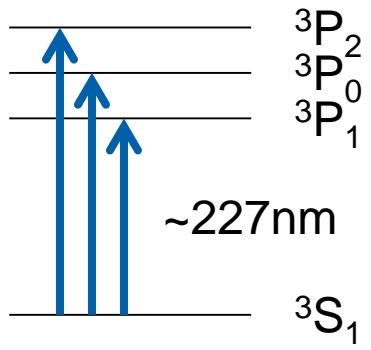
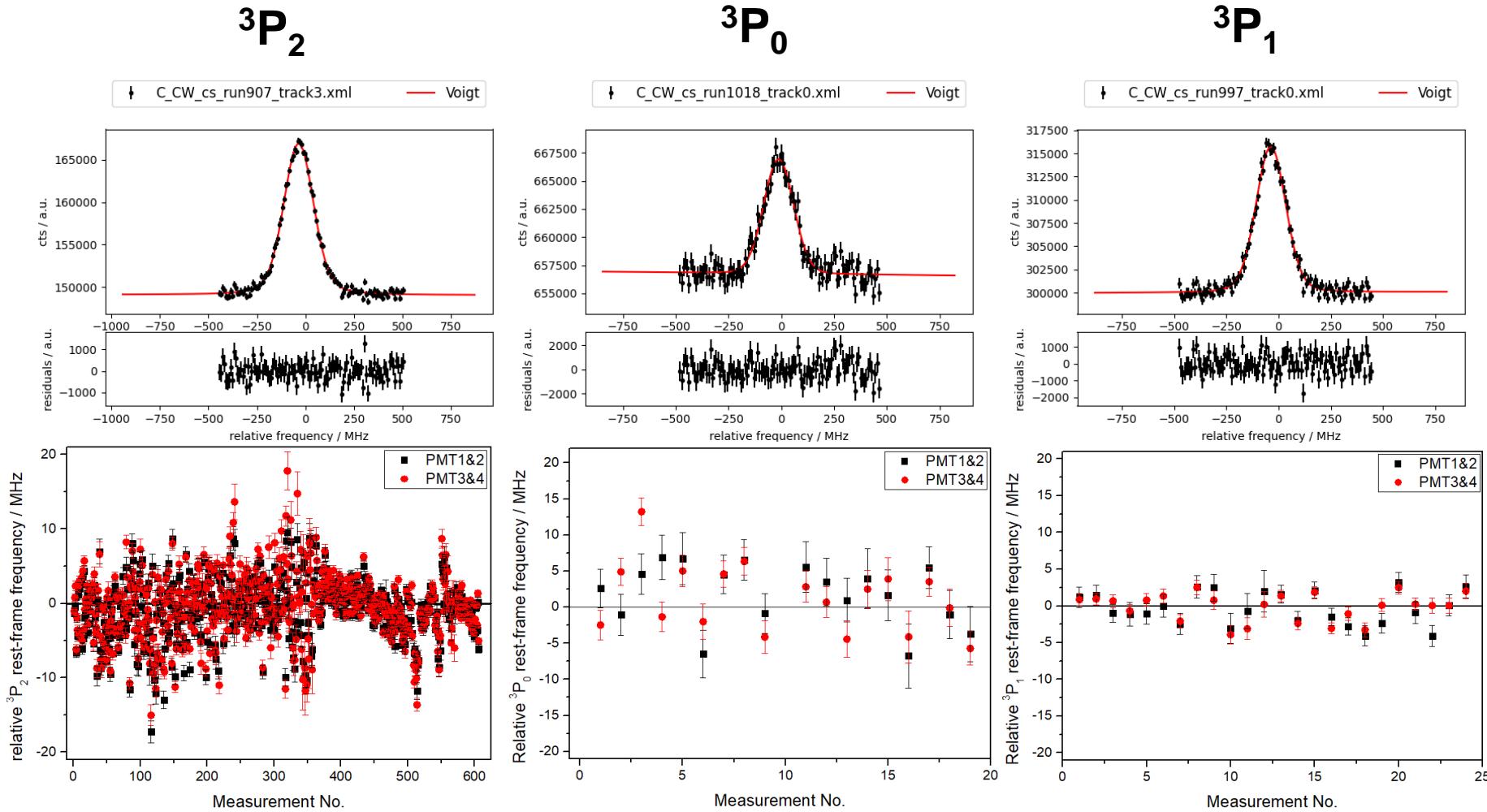
$$v_c \cdot v_a = v_0^2 \gamma^2 \cdot (1 + \beta)(1 - \beta) = v_0^2$$

^{12}C : Proof of Principle & Test of Theory



- Charge Radius of nucleus very well known
→ Test for theory
- Easy to produce in an EBIS
- Transition wavelength of 227 nm
→ Ti:Sa $\times 4$ stabilized to frequency comb
- No hyperfine structure → no hyperfine-induced level mixing
- ^{13}C hyperfine structure requires a more elaborated experiment and theory
- Charge radius of ^{13}C can be improved based on the isotope shift method and compared to direct extraction from transition frequency

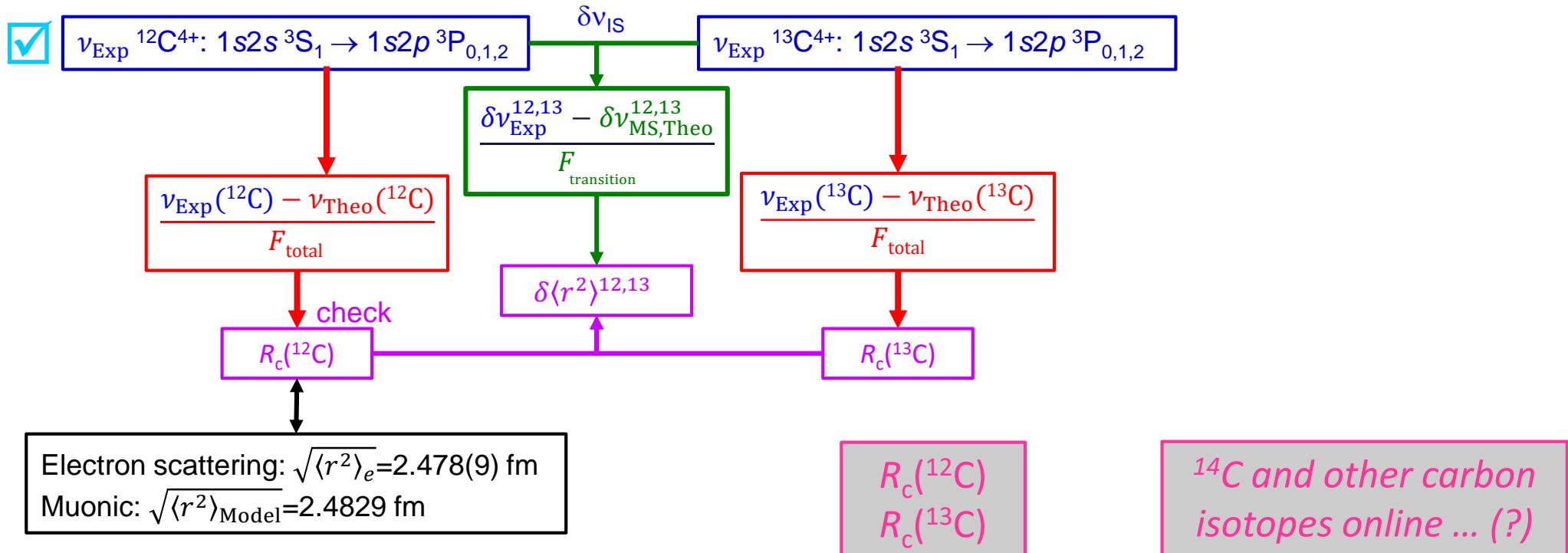
First Preliminary Laser Spectroscopy Results of $^{12}\text{C}^{4+}$



- Calculations for $^{12}\text{C}^{4+}$ in progress
- ^{13}C measurements in preparation

stay tuned

Route to All-Optical Charge Radii of Carbon



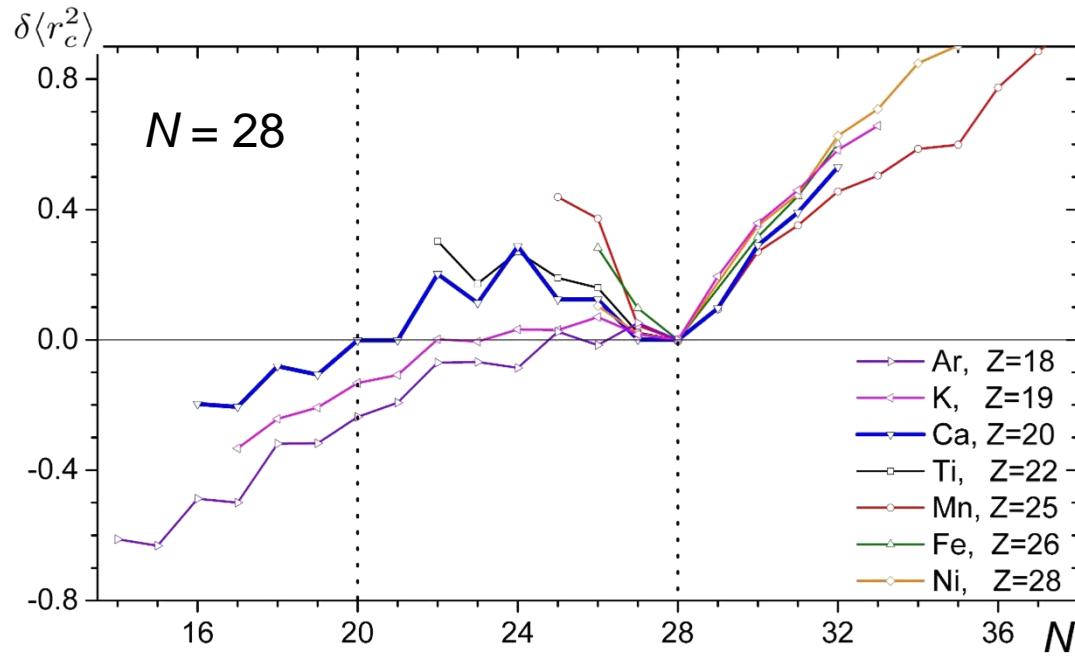
Experimental data, multiply charged

Conventional mass-shift calculations
Theory of He-like systems

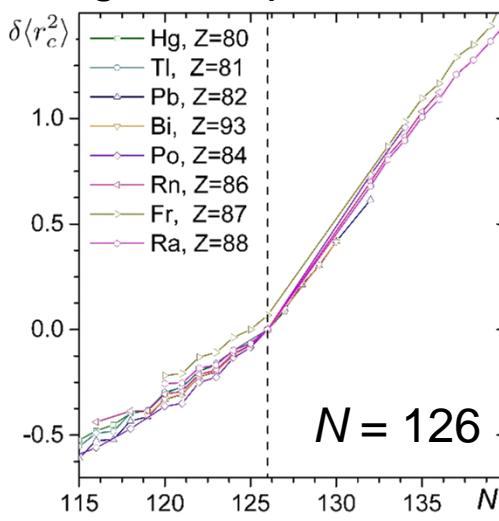
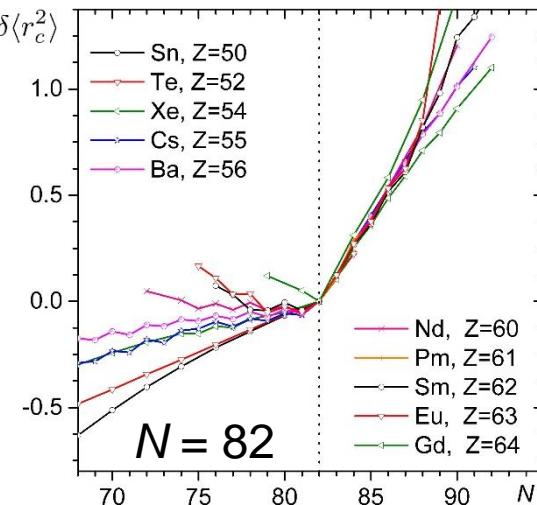
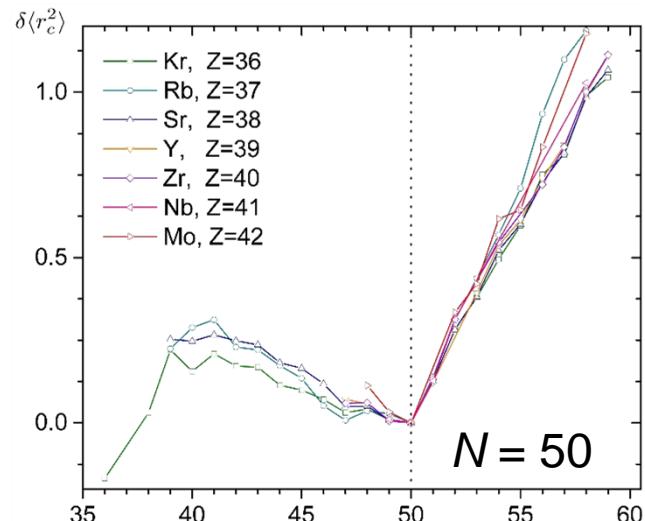
Consistency Checks

Goal

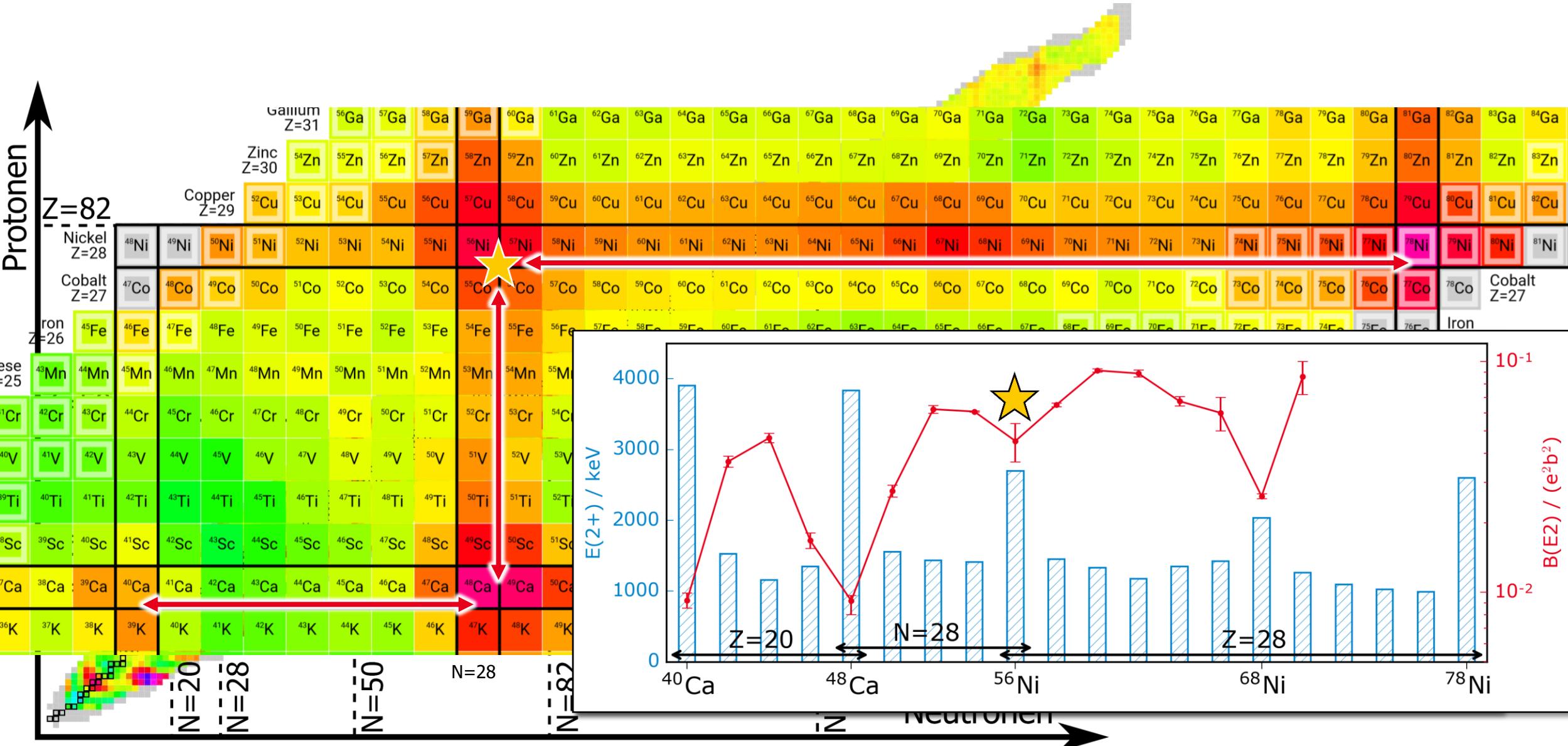
Kinks in Nuclear Charge Radii



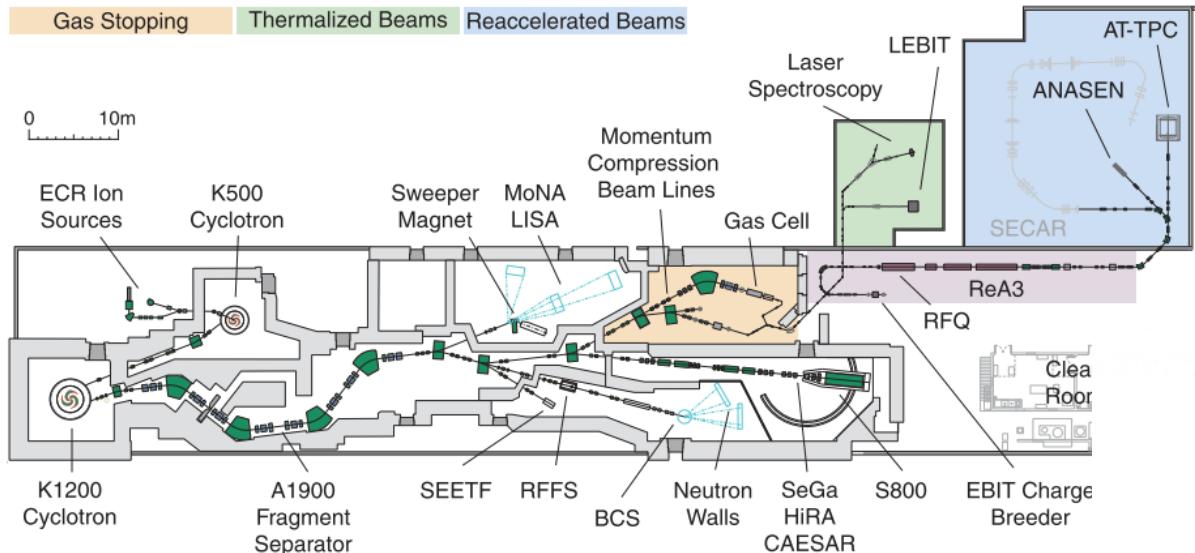
- Kink at shell closure established for all (traditional) magic numbers $N \geq 28$, but not for $N \leq 20$, neither for $N = 32, 34$
- Explanation: pairing and/or spin orbit
- Similar behavior above shell closure, less similarities below
- Experimentally observed only for neutron-rich doubly magic isotopes



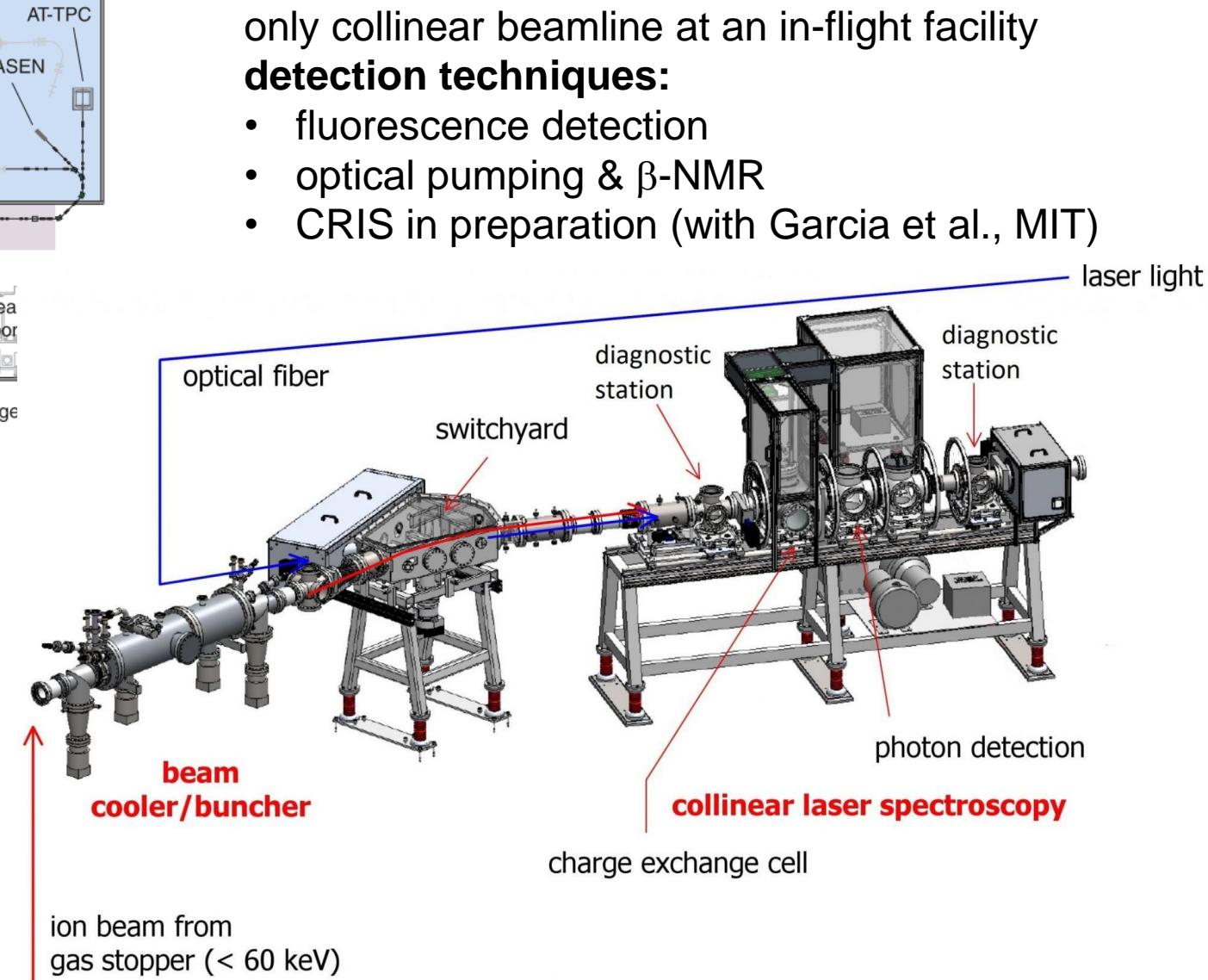
Charge Radii in the N=28 Region



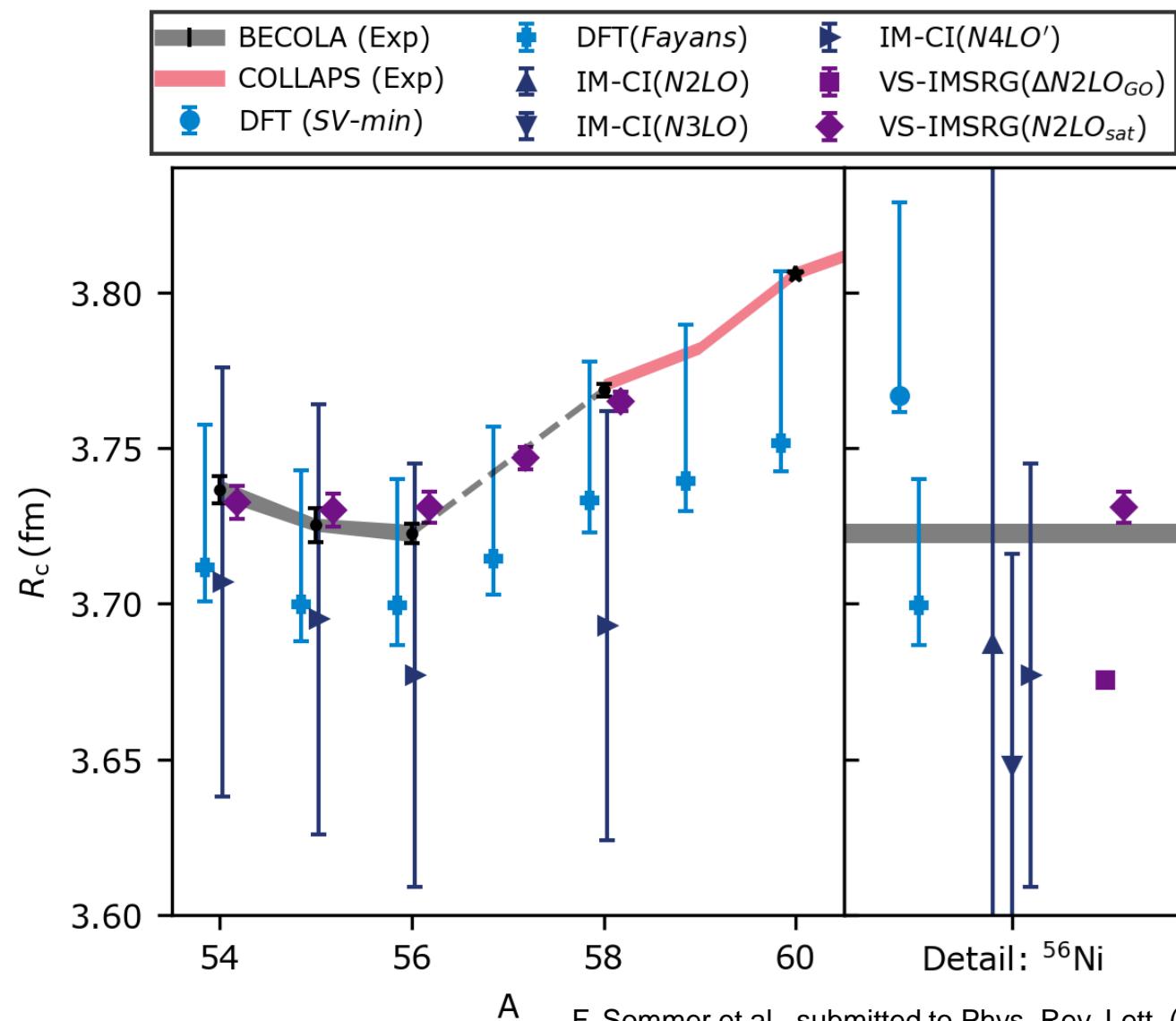
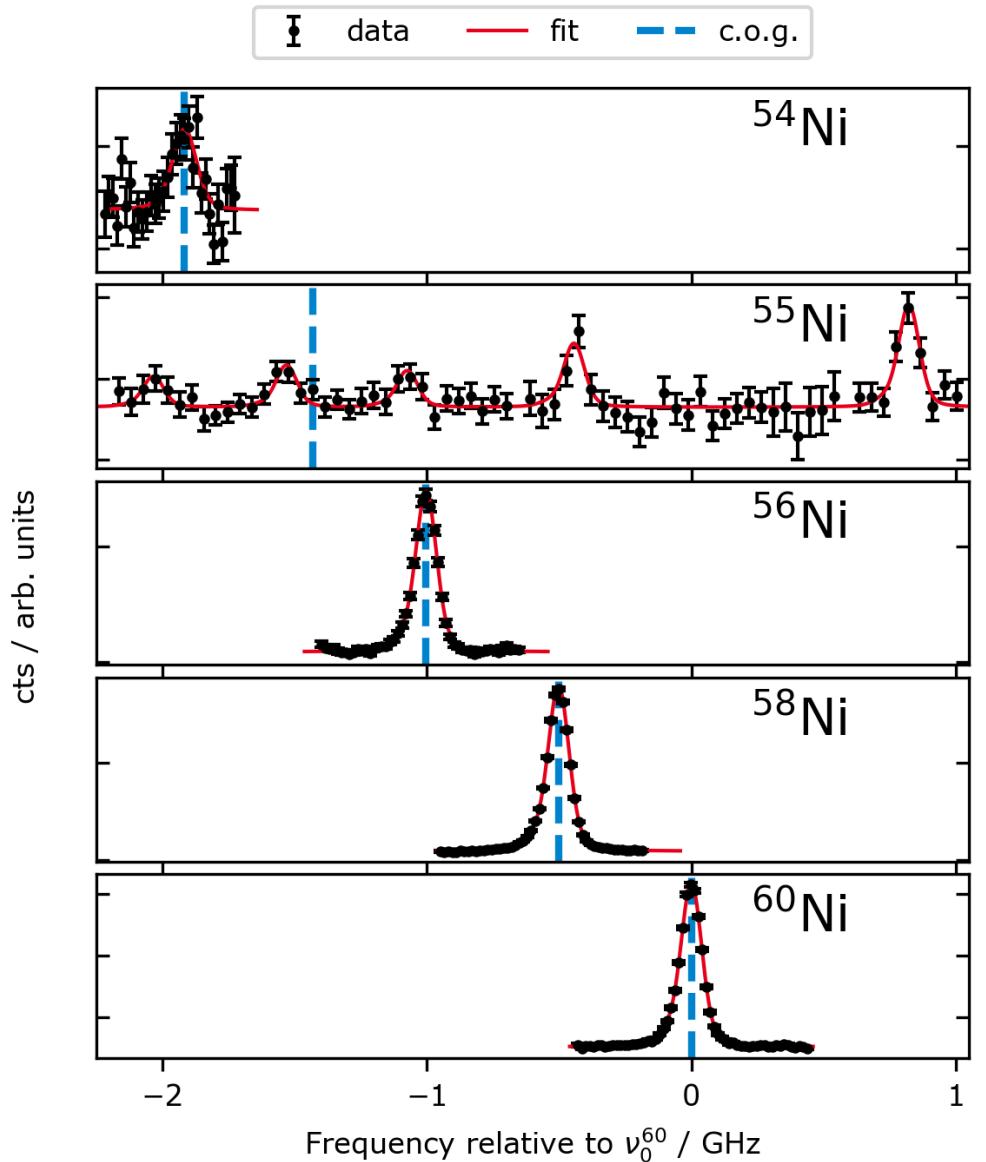
BECOLA @ NSCL / FRIB / MSU



- ^{58}Ni beam of 10 pnA, 160 MeV/u from K1200
- fragmentation on Be target
- separation in A1900 fragment separator
- stopping and thermalization in a gas cell
- extraction
- transport to an RFQ-cooler and buncher at BECOLA

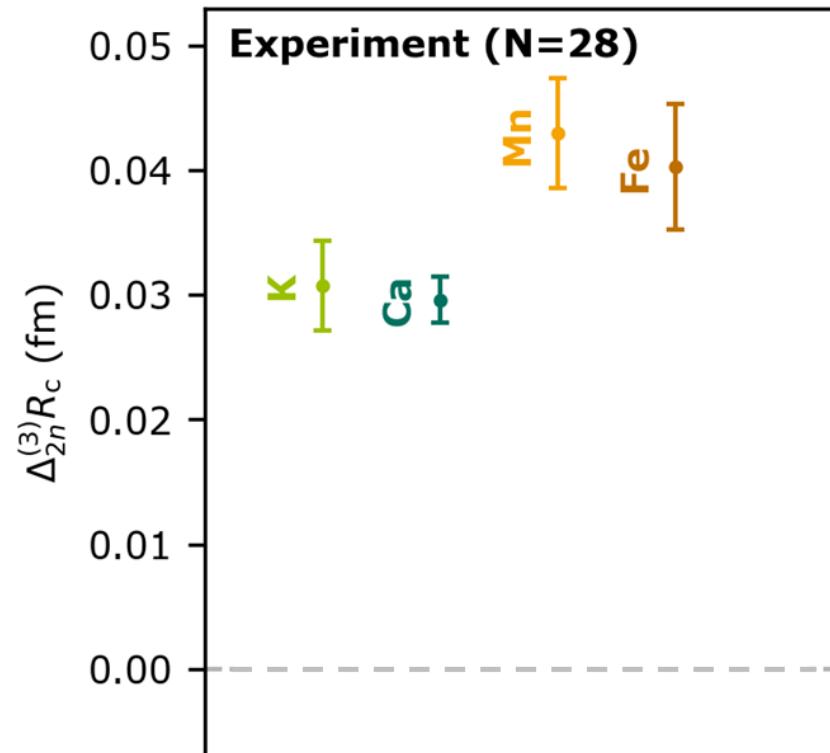
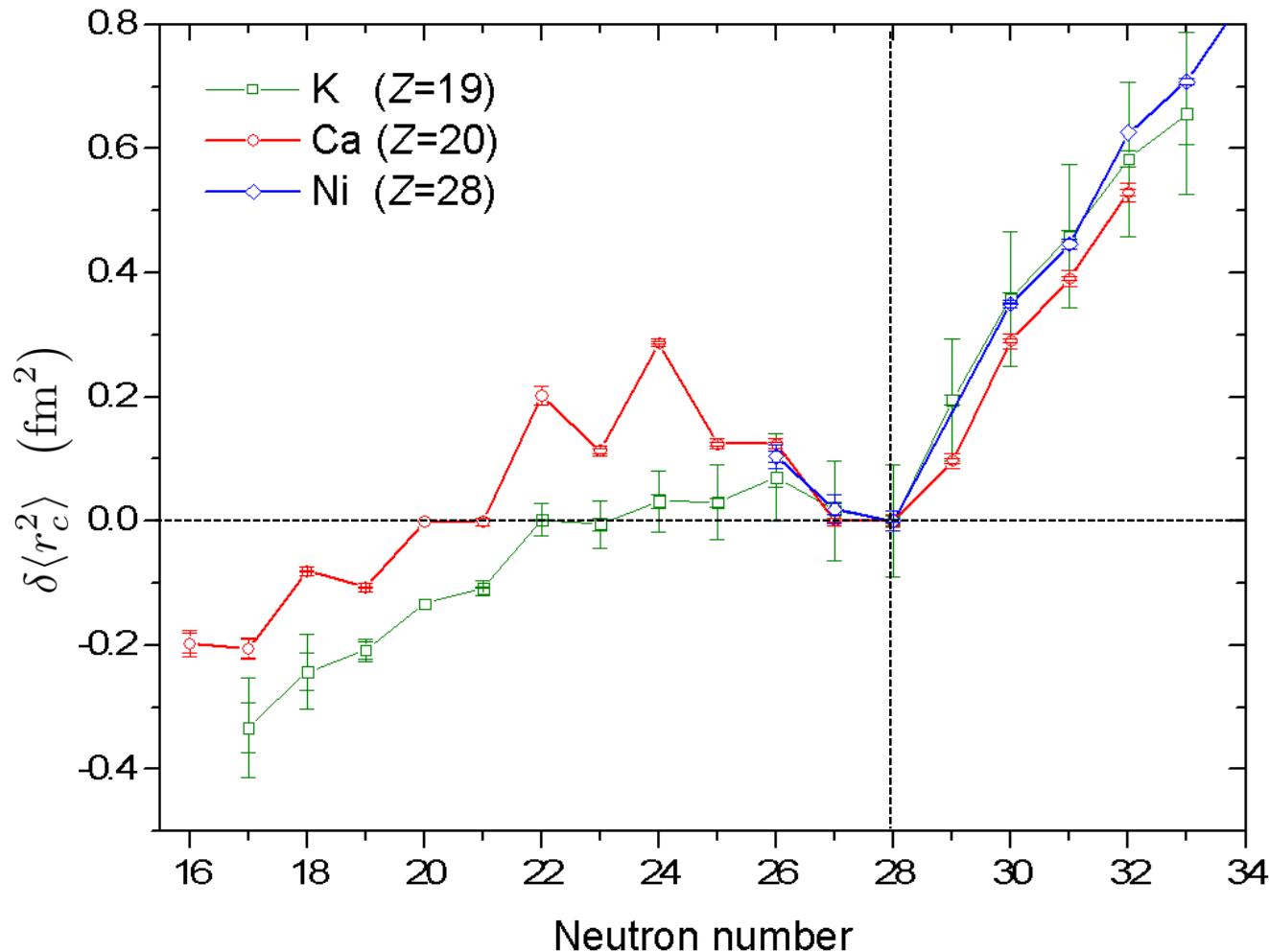


Charge Radii of Light Nickel Isotopes



The N=28 Kink at Calcium and Nickel

Three-point two-neutron difference: $\Delta_{2n}^{(3)} R_c(N) \equiv \frac{1}{2} [R_c(N+2) - 2R_c(N) + R_c(N-2)]$



F. Sommer et al., submitted to Phys. Rev. Lett. (2022)

Even though N=28 is only a „weak“ shell closure in Ni, the „strength“ of the kink is identical to Ca!

Conclusion & Outlook

Laser Spectroscopy of He-like systems in combination with NR-QED calculations will provide all-optical charge radii of beryllium, boron and carbon isotopes.

This will allow a measurement of the ${}^8\text{B}$ proton halo from the charge radius difference of ${}^7\text{Be}$ and ${}^8\text{B}$ difference

Several consistency checks are possible to test NR-QED Calculations

Measurements of N^{5+} ions and on-line measurements (${}^7\text{Be}$, ${}^{14}\text{C}$) might be feasible as well

The kink in r^2 at ${}^{56}\text{Ni}$ is surprisingly similar with that of ${}^{48}\text{Ca}$ even though the shell closure is much weaker. This is well described by ab initio theories and DFT using a Fayans functional.

Thank you!



LaserSpHERe Group

especially
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Kristian König
(Bernhard Maaß)
Patrick Müller

....

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(Kristian König)
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Skyy Pineda
(Dominic Rossi)

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Guy Savard
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Robert Roth
Achim Schwenk
Robert B. Wiringa
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