Magic Moments:
Exotic Calcium Isotopes in Laser Light

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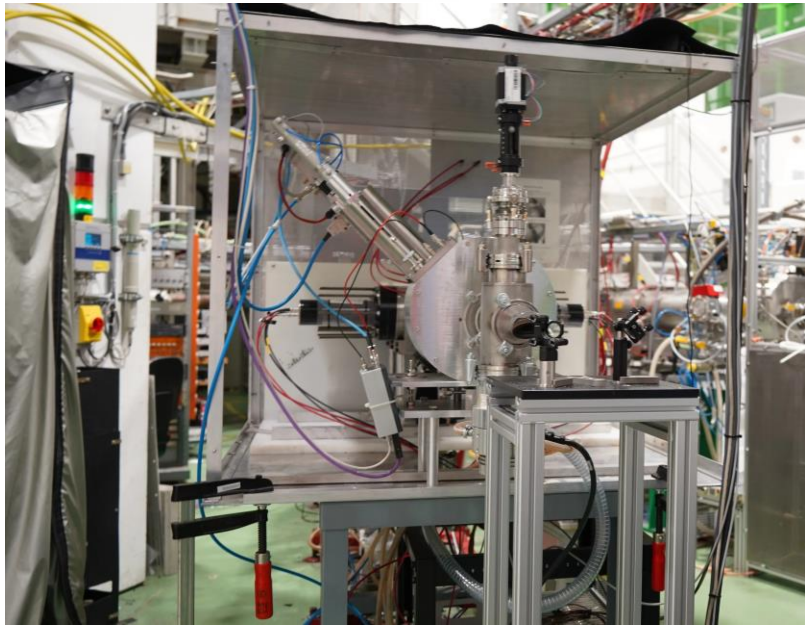
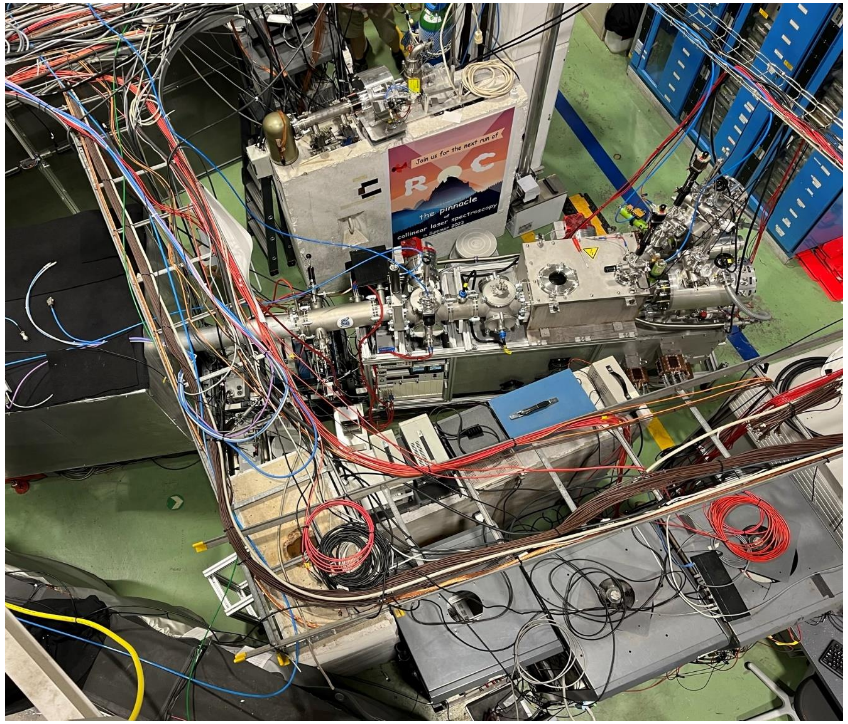
Wilfried Nörtershäuser
On behalf of the COLLAPS Collaboration

COLLAPS





ISOLDE

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

KU LEUVEN

THE UNIVERSITY of LIVERPOOL

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

EURO-LABS
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LASER SpHERe

Outline

- Basics and Motivation

  Nuclear Physics: Fingerprints of Magic Numbers

  Atomic Physics: Nuclear Properties in Optical Spectra

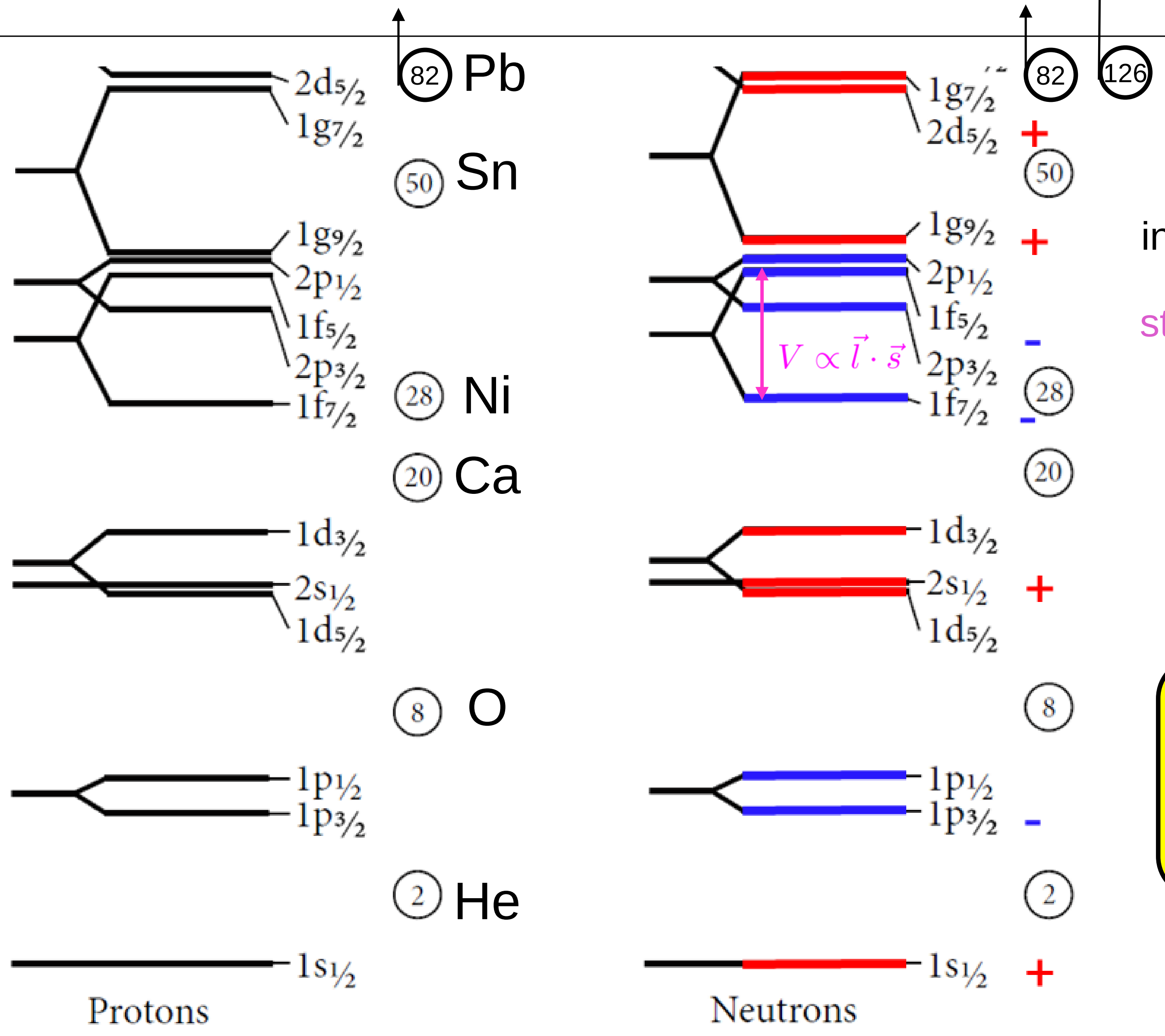
- Nuclear Charge Radii of Calcium Isotopes

  $^{36-52}Ca$: New lessons for theory and a tantalizing question

  Magic moment after a 10-years quest: Laser spectroscopy of $^{53,54}Ca$

- The N=28 Isotones and the Charge Radius of ^{56}Ni

Magic Numbers



intruder state in lower shell

strong spin-orbit coupling

isolated $f_{7/2}$ orbital

^{208}Pb, ^{132}Sn

^{100}Sn, ^{78}Ni

^{56}Ni, ^{48}Ca

^{40}Ca

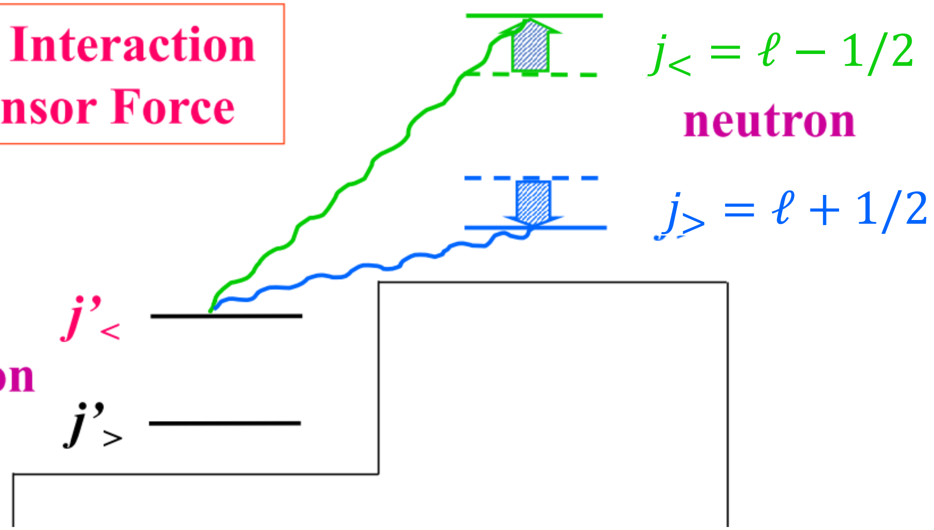
^{16}O

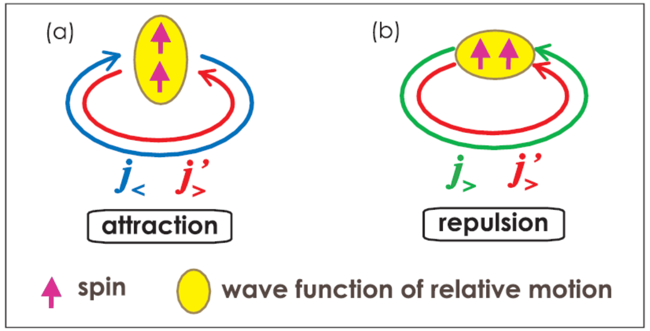
^{4}He

These “traditional” magic numbers arise from investigations of nuclei close to stability.

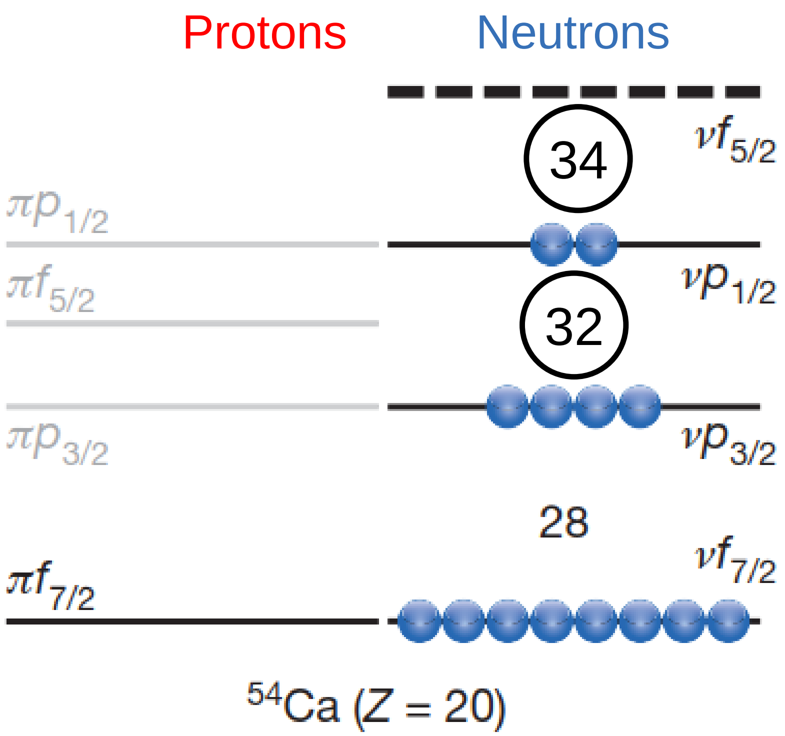
Shell Evolution in the Calcium Region

Monopole Interaction of the Tensor Force





Otsuka, PRL 95, 232502 (2005)



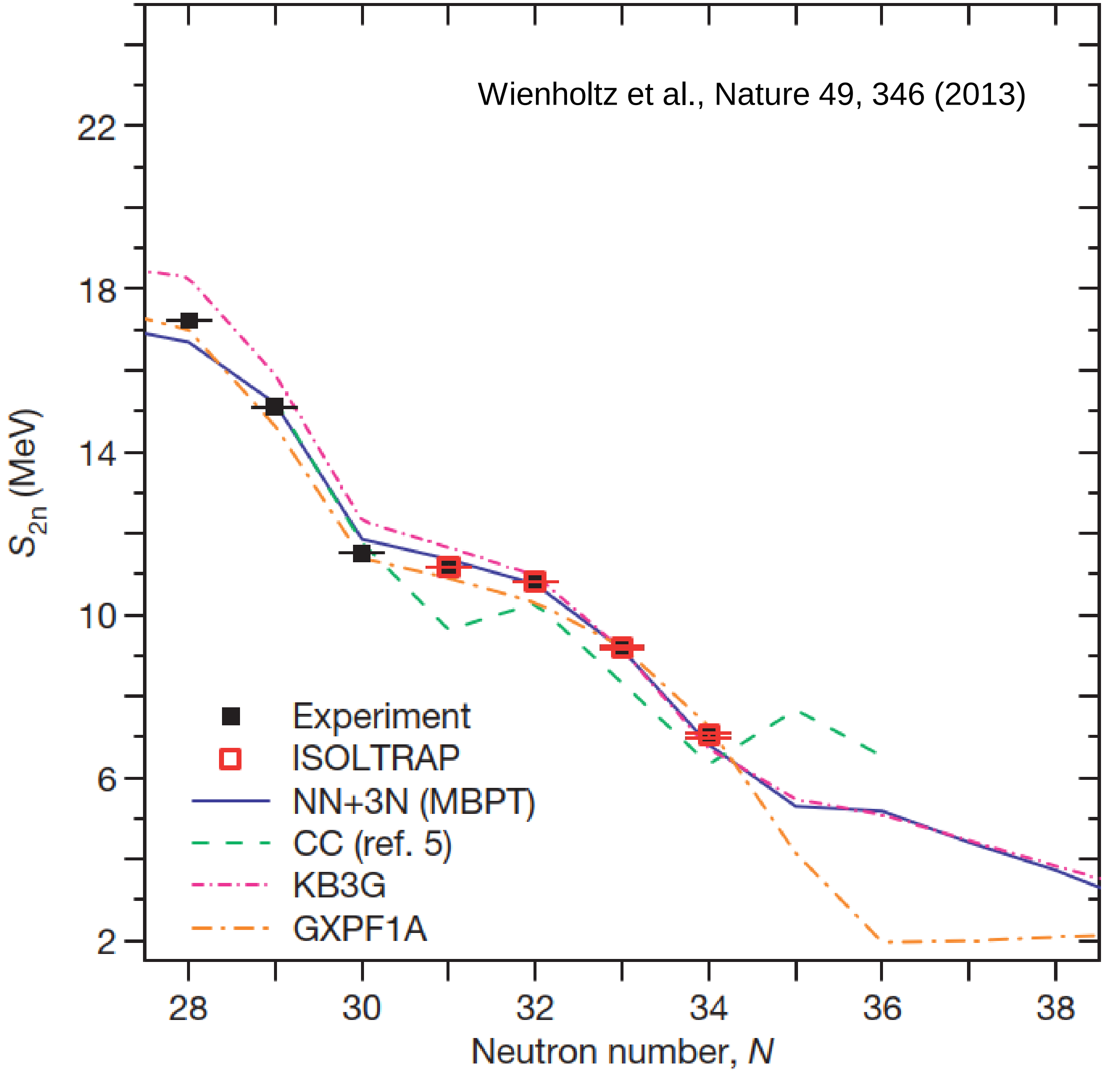
Steppenbeck et al., Nature **502**, 207 (2013)

How to recognize shell closures experimentally ?

Fingerprints of (Doubly) Magic Nuclei

Decrease in S_{2n} energies

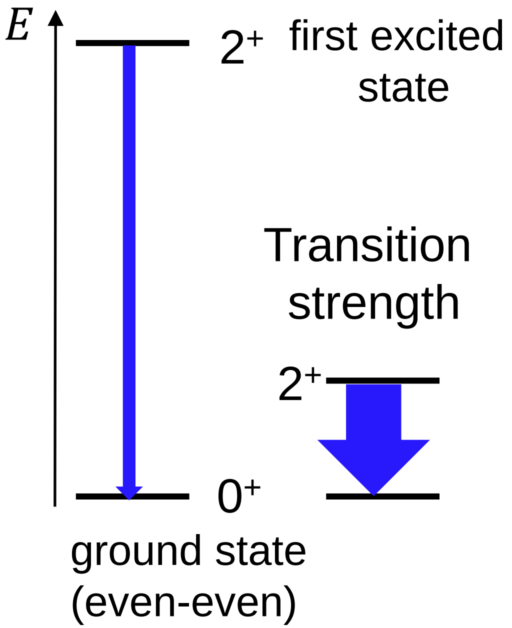
$$S_{2n} = E_B(Z,N) - E_B(Z,N-2)$$

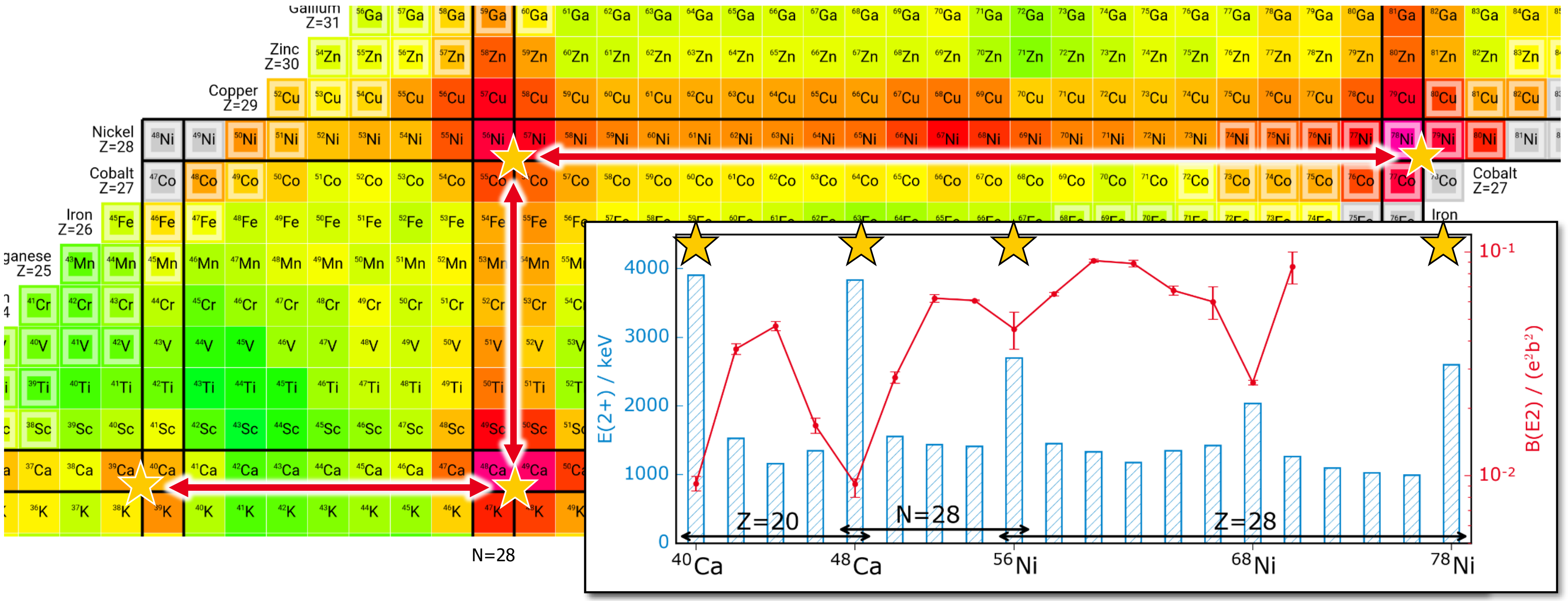


Fingerprints of (Doubly) Magic Nuclei

Decrease in S_{2n} energies

High energy of first excited (2^+) state
Weak transition $2^+ \rightarrow 0^+$





$$B(\mathrm{E2}) \propto |\langle \mathrm{I_f} \| \mathrm{M(E2)} \| \mathrm{I_i} \rangle|^2$$

$$\tau[\mathrm{ns}] = \frac{1}{1.22 E_\gamma^5 [\mathrm{Mev}] B(\mathrm{E2}) [\mathrm{e^2 fm^4}]}$$

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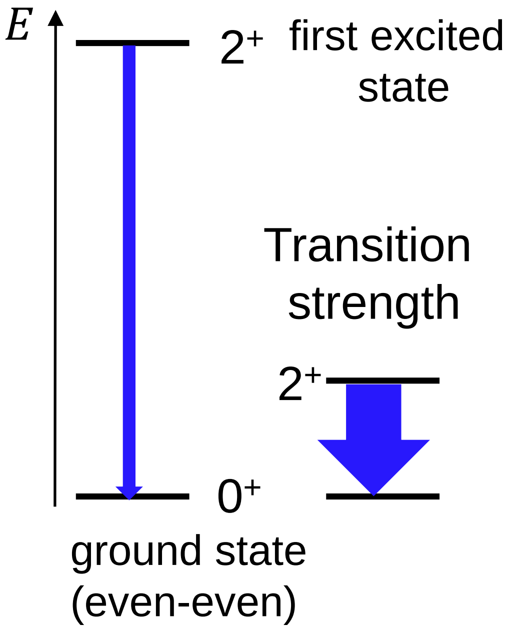

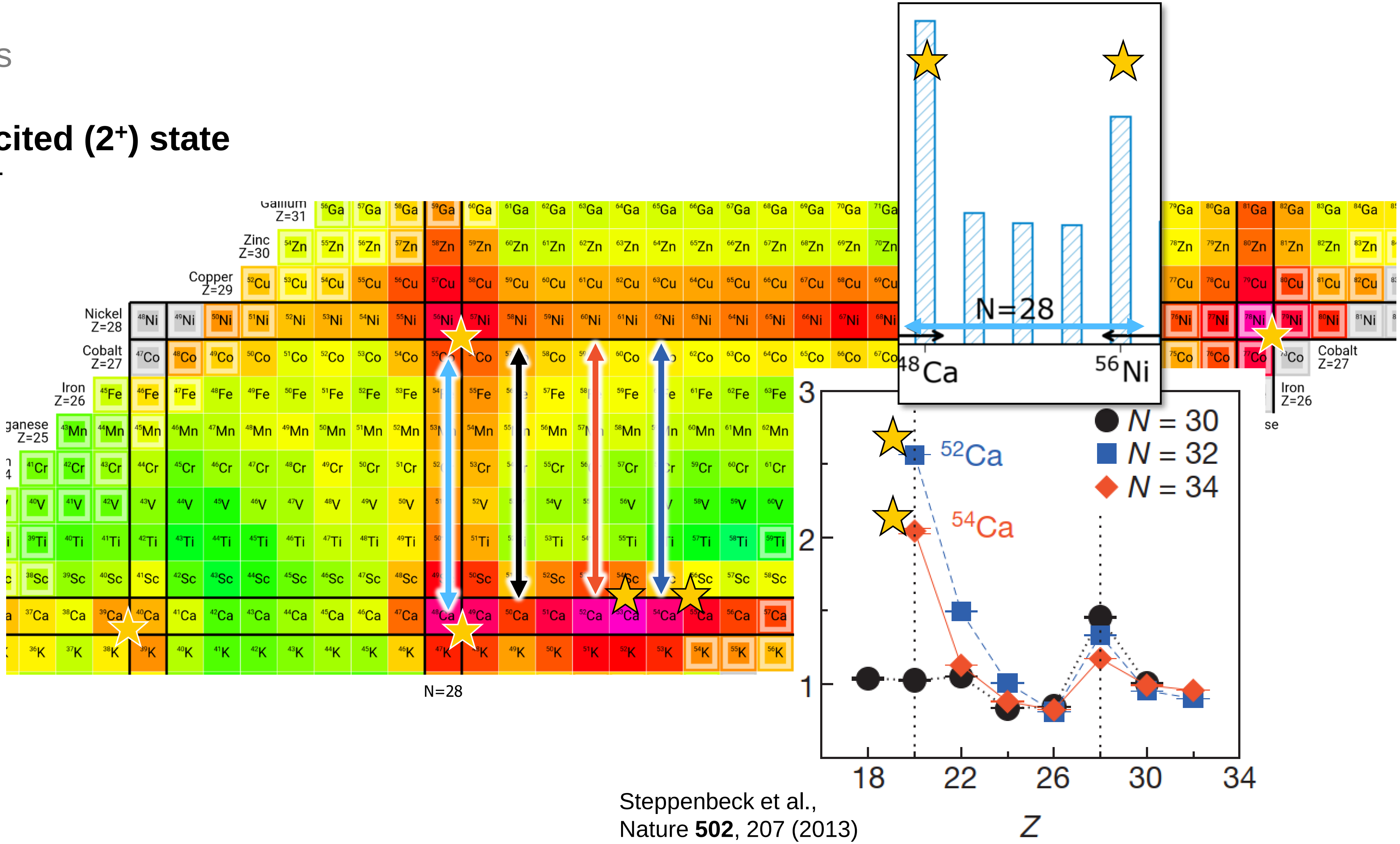

Steppenbeck et al.,
Nature **502**, 207 (2013)

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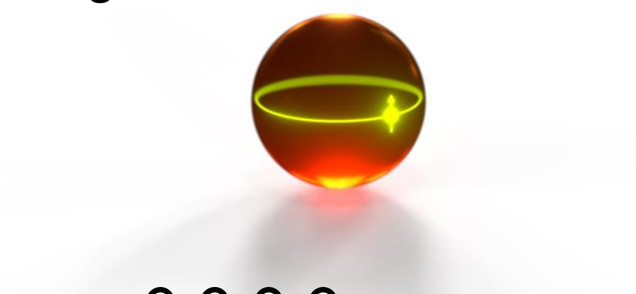
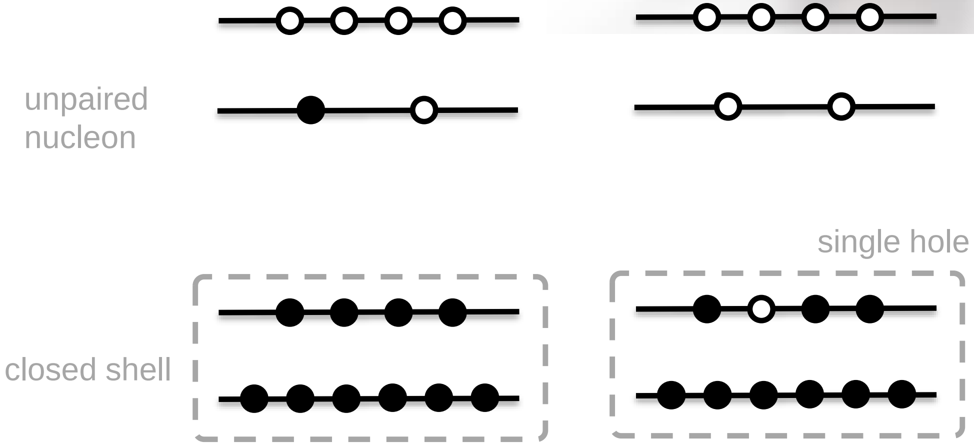
Fingerprints of (Doubly) Magic Nuclei

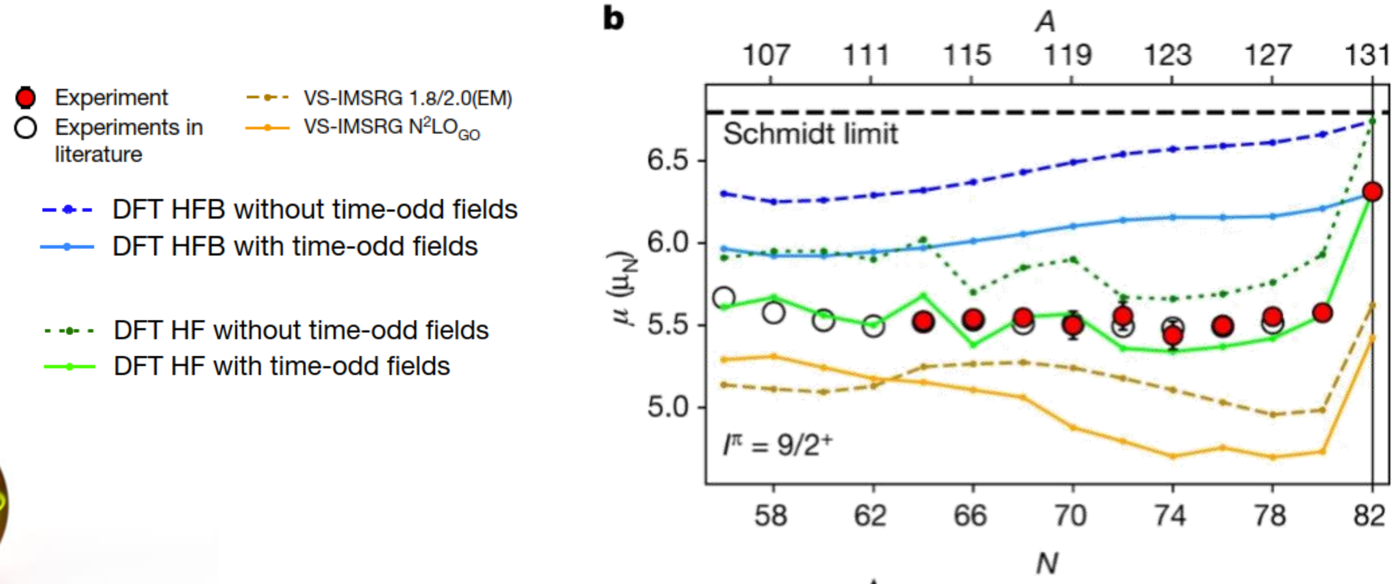
Decrease in S_{2n} energies

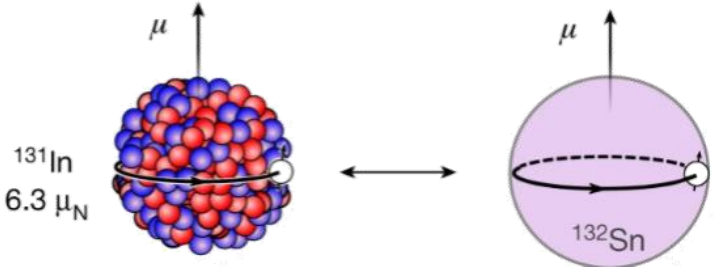
High energy of first excited (2^+) state
Transition strength $2^+ \rightarrow 0^+$ weak

Magnetic moments of doubly magic ± 1









Vernon *et al.*, Nature **607**, 260 (2022)

Magnetic moments and quadrupole moments of doubly magic ± 1 isotopes are more shell-model like (Schmidt value) than isotopes further away.

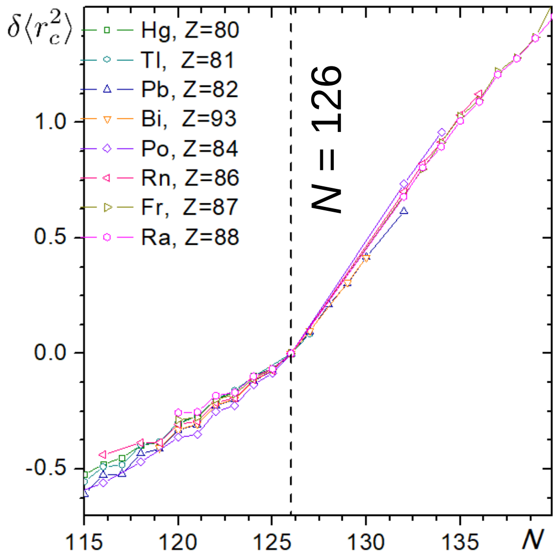
Fingerprints of (Doubly) Magic Nuclei

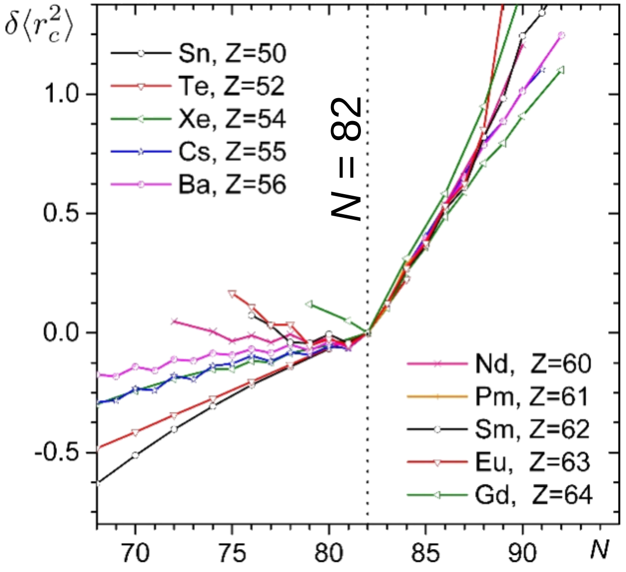
Decrease in S_{2n} energies

High energy of first excited (2^+) state
Transition strength $2^+ \rightarrow 0^+$ weak

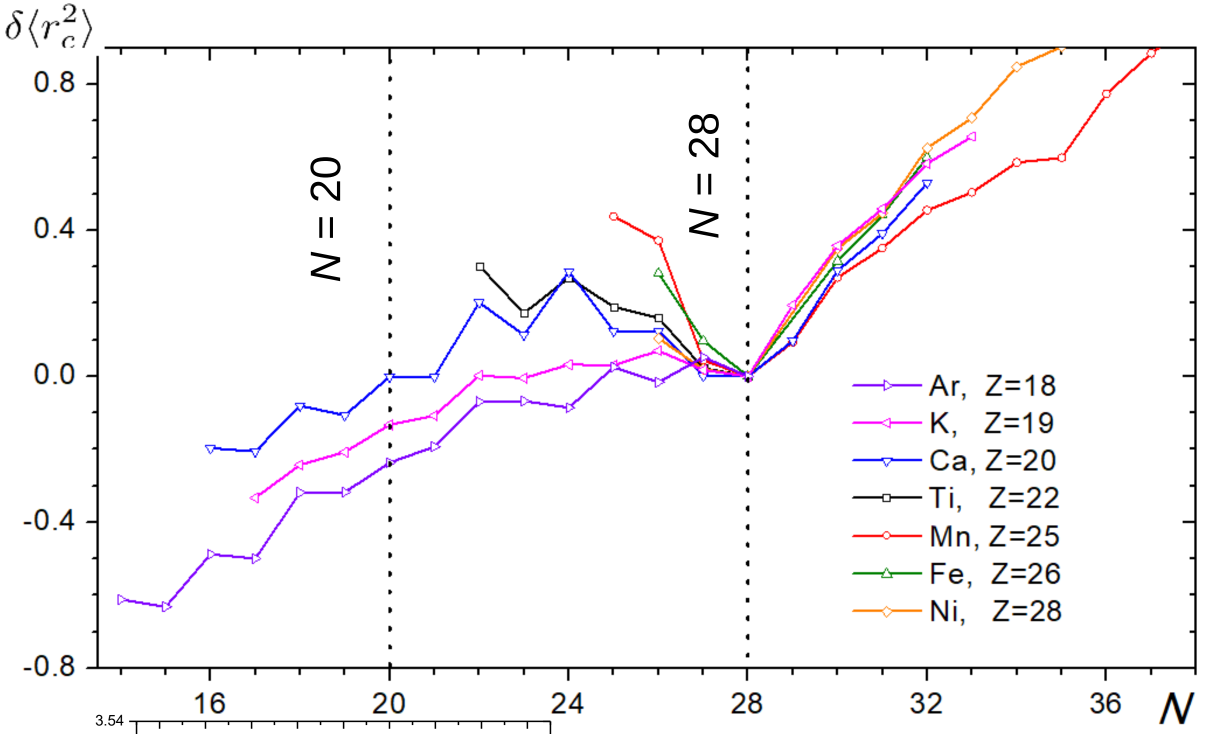
Magnetic moments of doubly magic □ 1

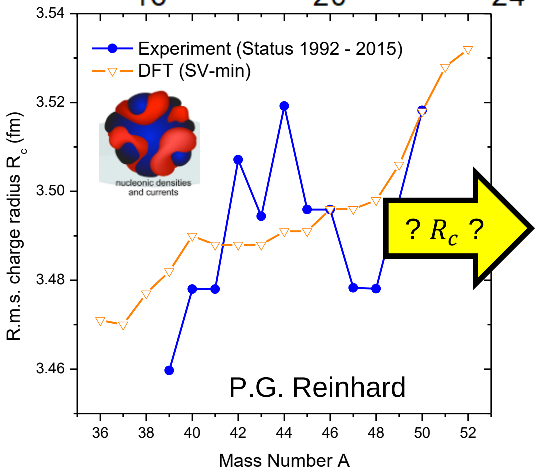
Charge radius „kink“

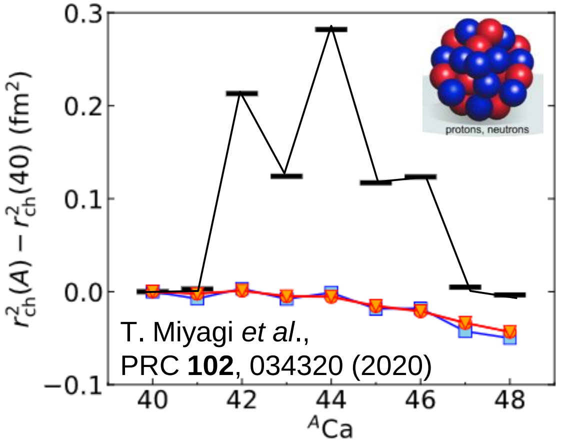




How can we determine charge radii and moments of short-lived isotopes?







Nuclear Observables in the Optical Hyperfine Structure

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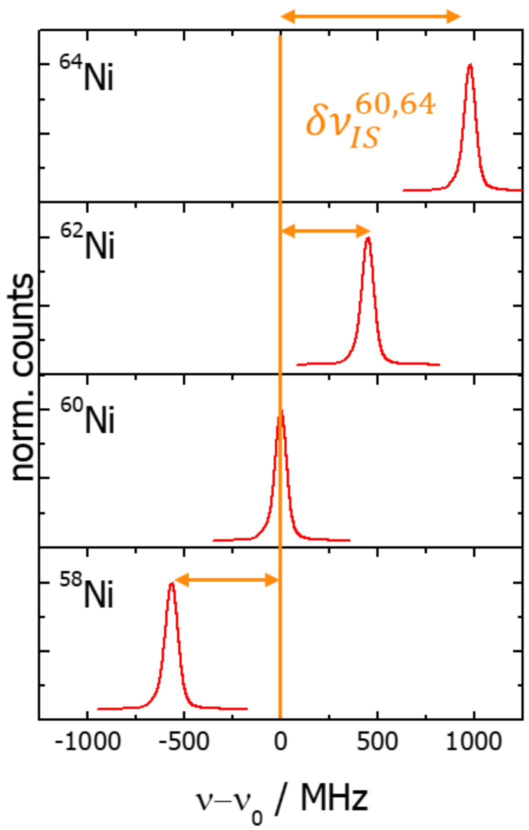
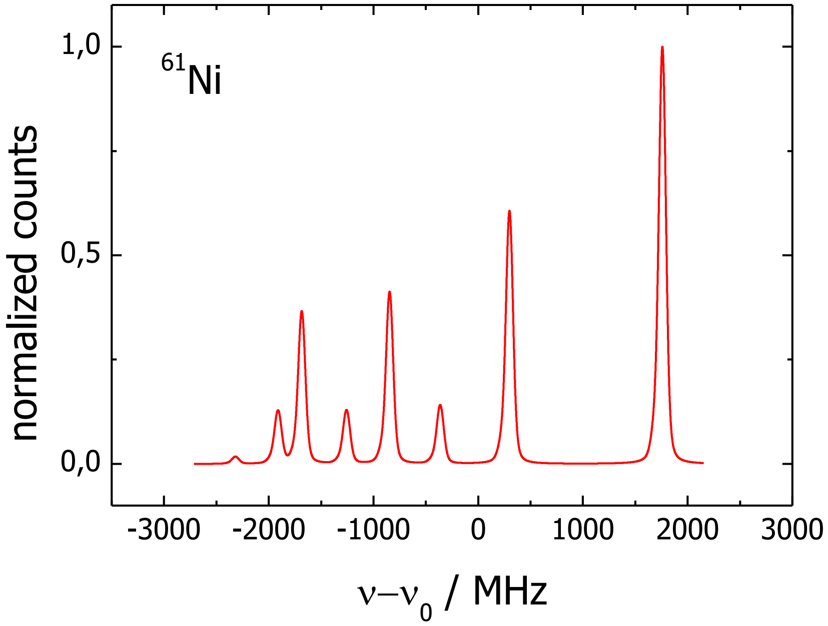
Isotope Shift

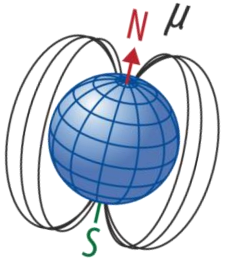


Hyperfine Splitting

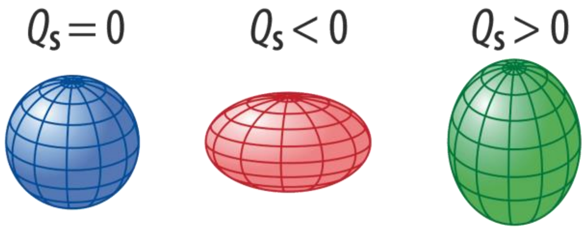


Spin I

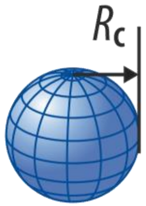
Magnetic Dipole Moment $\boldsymbol{\mu}$



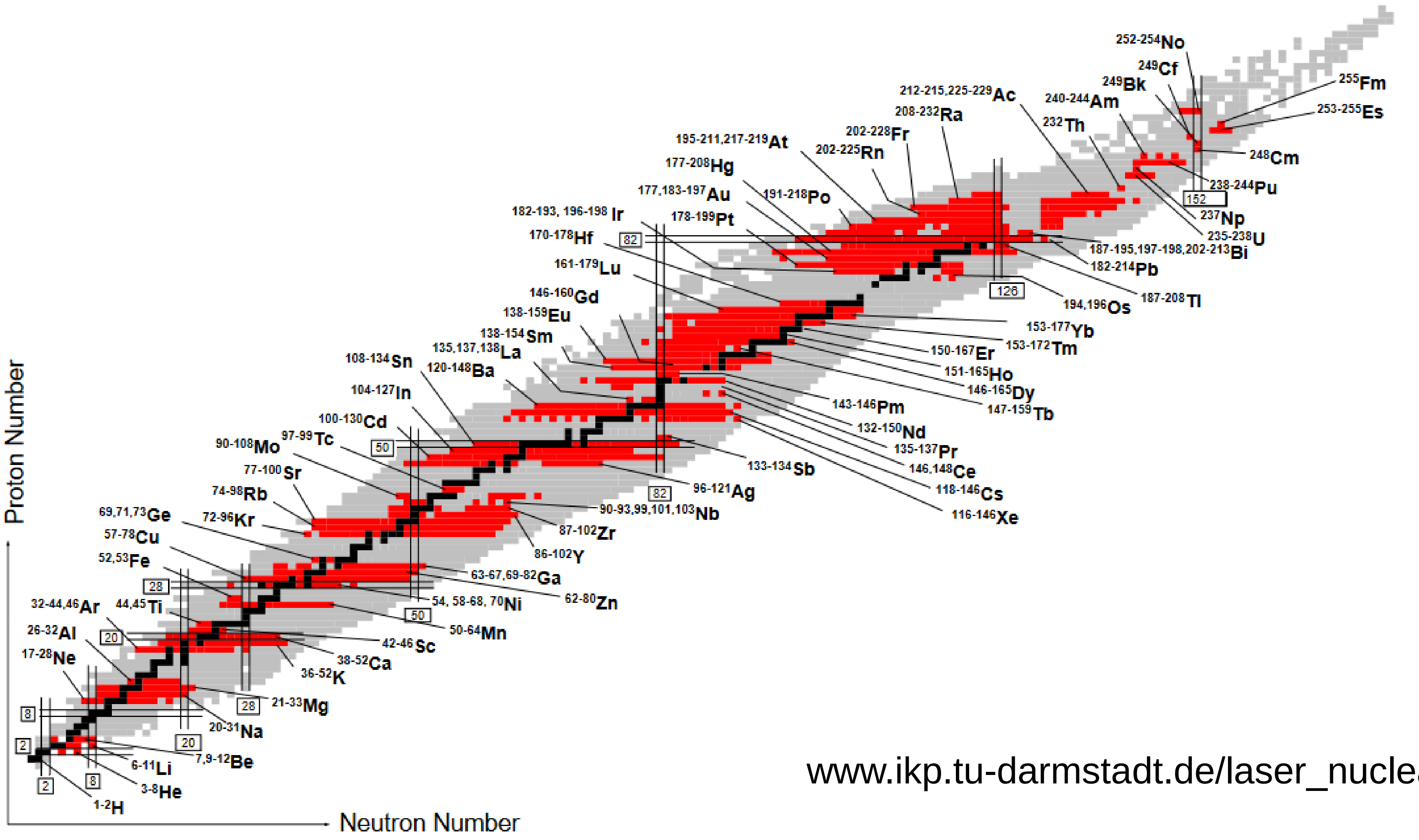
Electric Quadrupole Moment $\boldsymbol{Q_s}$



Nuclear Size $\delta \left\langle r_c^2 \right\rangle^{AA'}$



The Laser Nuclear Chart



www.ikp.tu-darmstadt.de/laser_nuclear_chart

Measurement of $^{49-52}$Ca using Collinear Laser Spectroscopy and Bunched-Beam Detection

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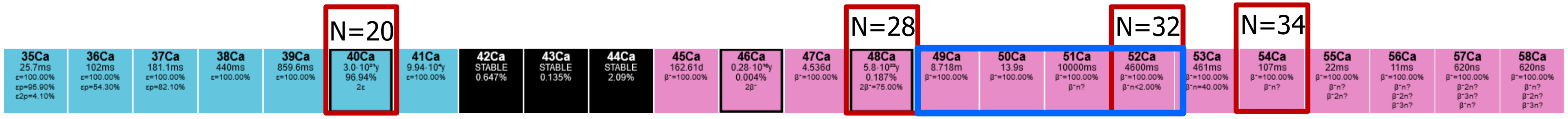
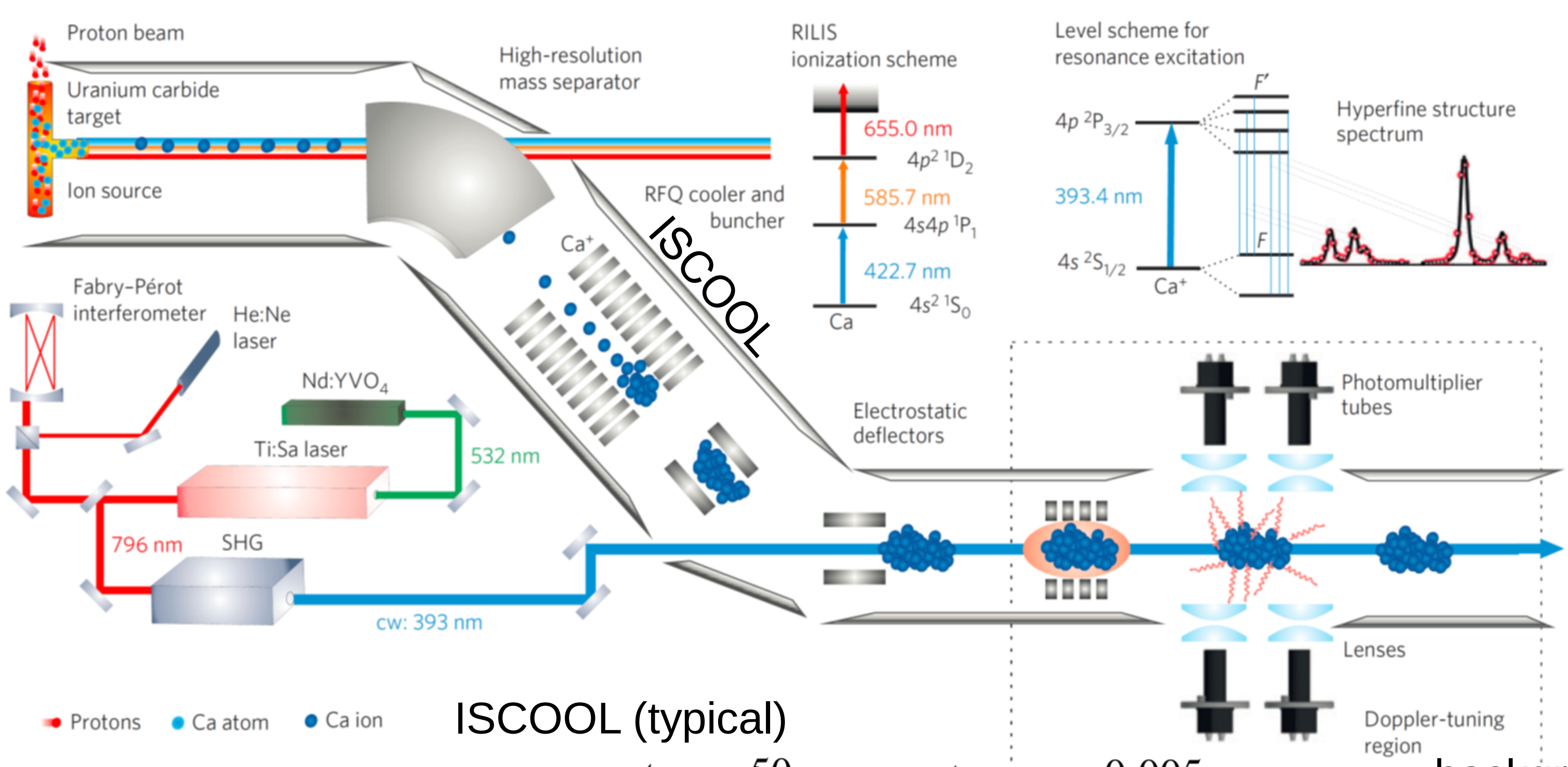
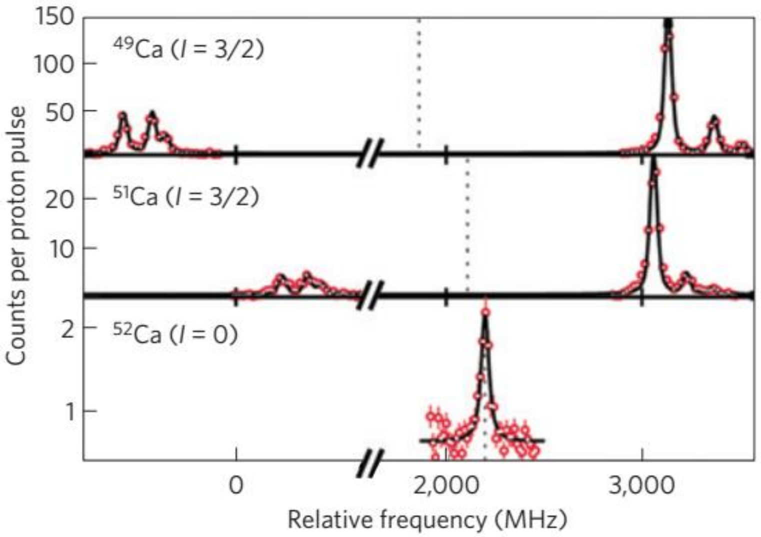
Z=20







R.F. Garcia Ruiz et al., Nature Physics **12**, 594 (2016)

ISCOOL (typical)

$$t_{\text{acc}} = 50\,\text{ms}$$
$$t_{\text{bunch}} = 5\,\mu\text{s}$$

$$\frac{t_{\text{bunch}}}{t_{\text{acc}}} = \frac{0.005\,\text{ms}}{50\,\text{ms}} = 10^{-4}$$

background reduction ⇒ **Sensitivity improved 100 x**

Unexpected Strong Rise up to ^{52}Ca

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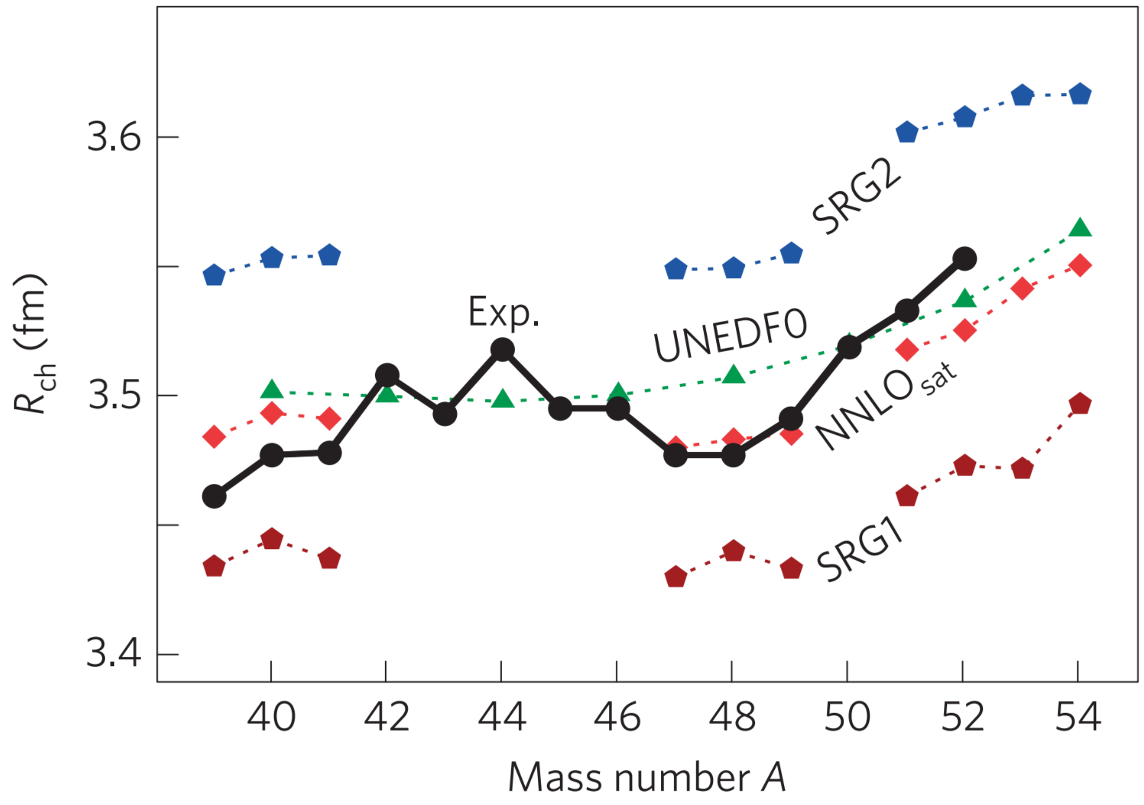
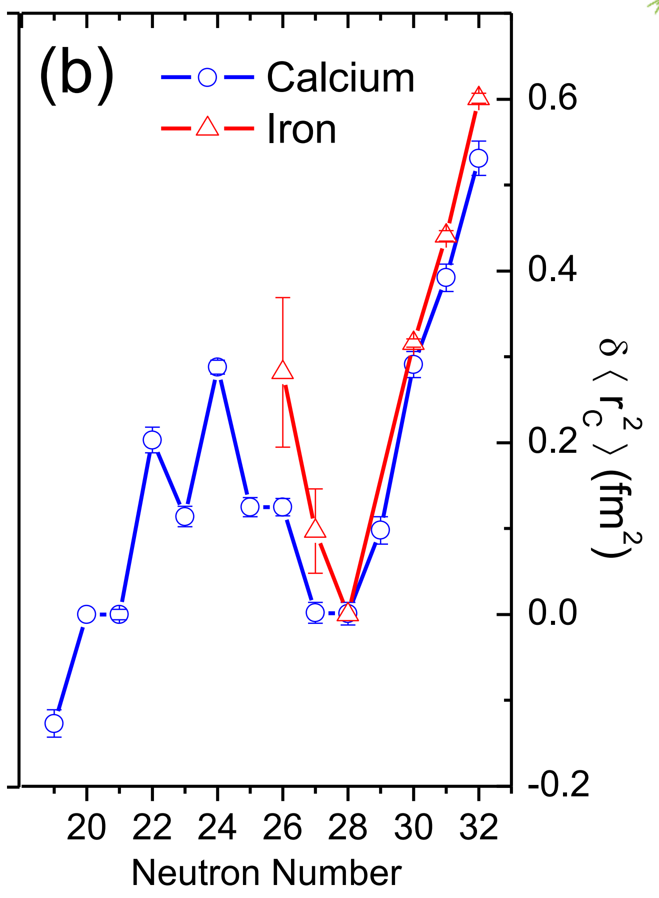


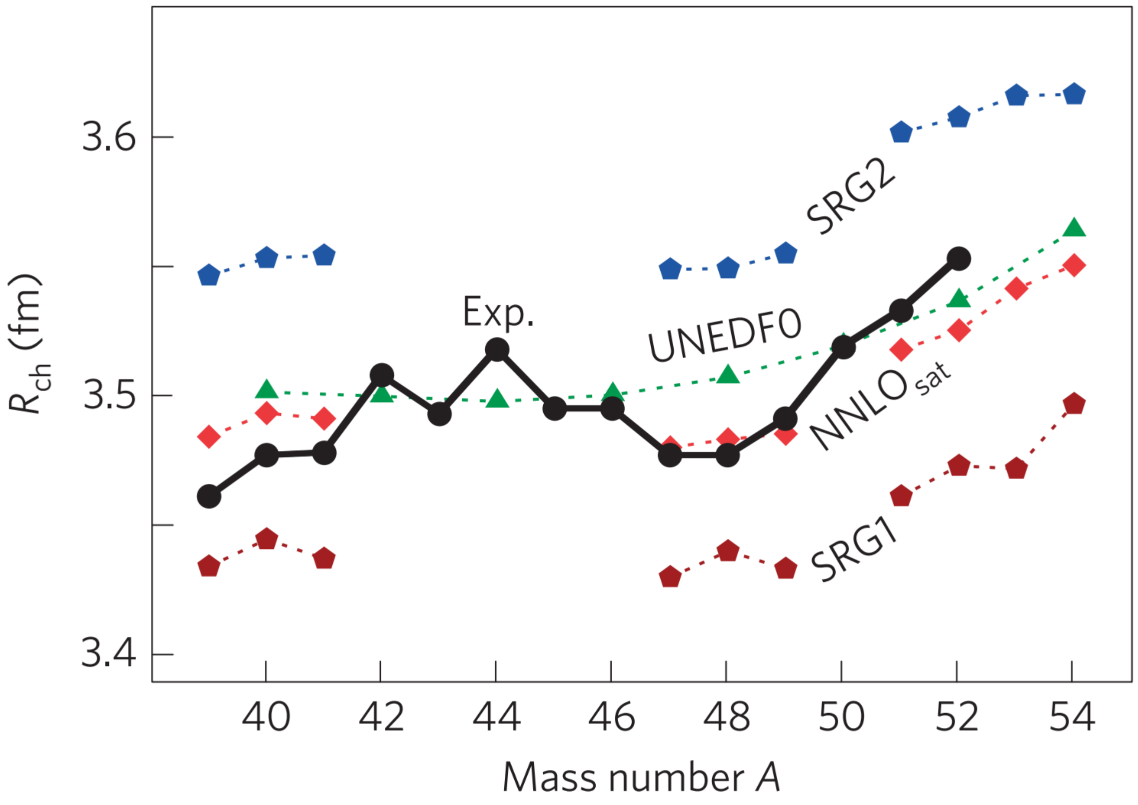


EFT-based interaction NNLO$_{sat}$ does a particularly good job for absolute charge radii.

No significant difference to charge radii with more protons in $f_{7/2}$ shell
→ **no indication for a shell-closure at *N*=32**

R.F. Garcia Ruiz et al., Nature Physics **12**, 594 (2016)

Unexpected Strong Rise up to ^{52}Ca



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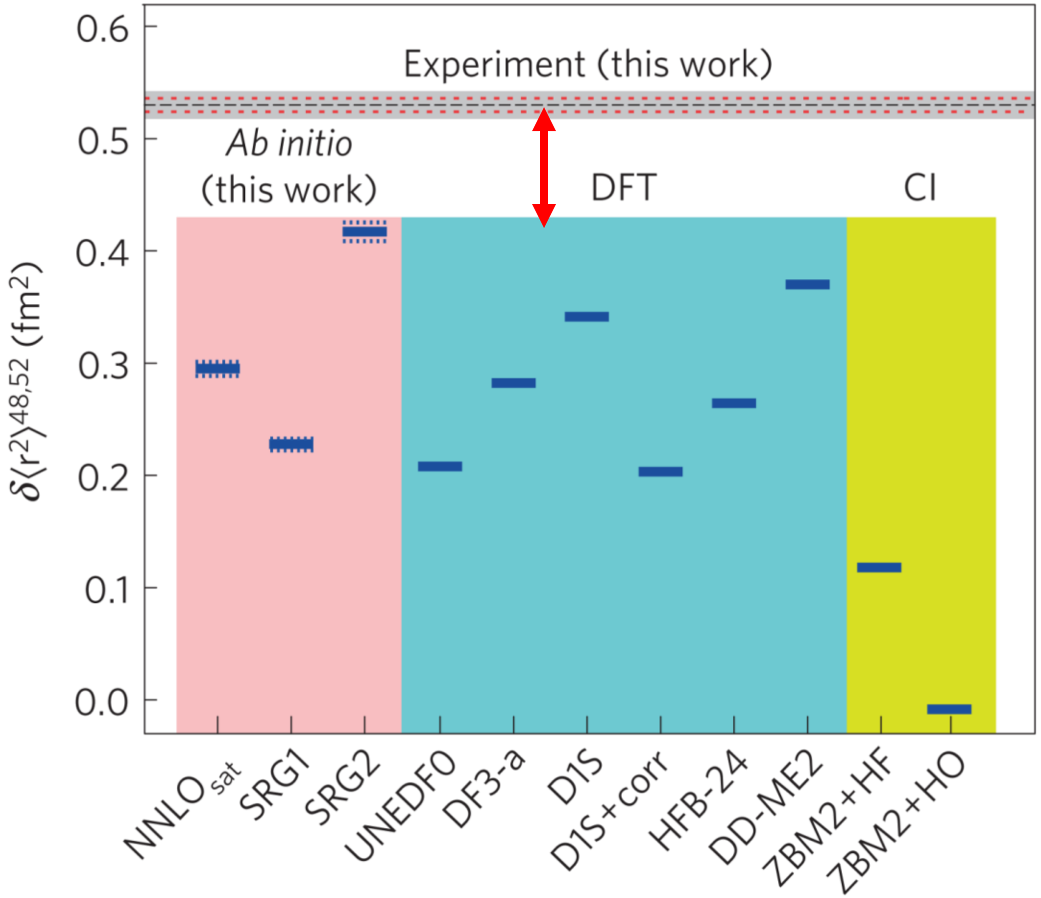


But all theories underestimate rise of charge radii.

R.F. Garcia Ruiz et al., Nature Physics **12**, 594 (2016)

The Fayans Functional

$$\mathcal{E}_{\rm Fy} = \mathcal{E}^{\rm v}_{\rm Fy}(\rho) + \mathcal{E}^{\rm s}_{\rm Fy}(\rho) + \mathcal{E}^{\rm s}_{\rm Fy}(\rho, \boldsymbol{J}) + \mathcal{E}^{\rm pair}_{\rm Fy}(\rho, \breve{\rho})$$

$$\mathcal{E}^{\rm pair}_{{\rm Fy},q} = \frac{4\varepsilon_F}{3\rho_{\rm sat}} \breve{\rho}_q^{\,2} \left[f^{\xi}_{{\rm ex},+} + h^{\xi}_{1+} x^{\gamma}_{\rm pair} + h^{\xi}_{\nabla} r_s^2 \left(\boldsymbol{\nabla} x_{\rm pair}\right)^2 \right]$$

pairing density

gradient term in pairing density

Fayans et al., Nucl. Phys. A **676**, 49 (2000)

$\rho_0 = \rho_n + \rho_p$, $\rho_1 = \rho_n - \rho_p$

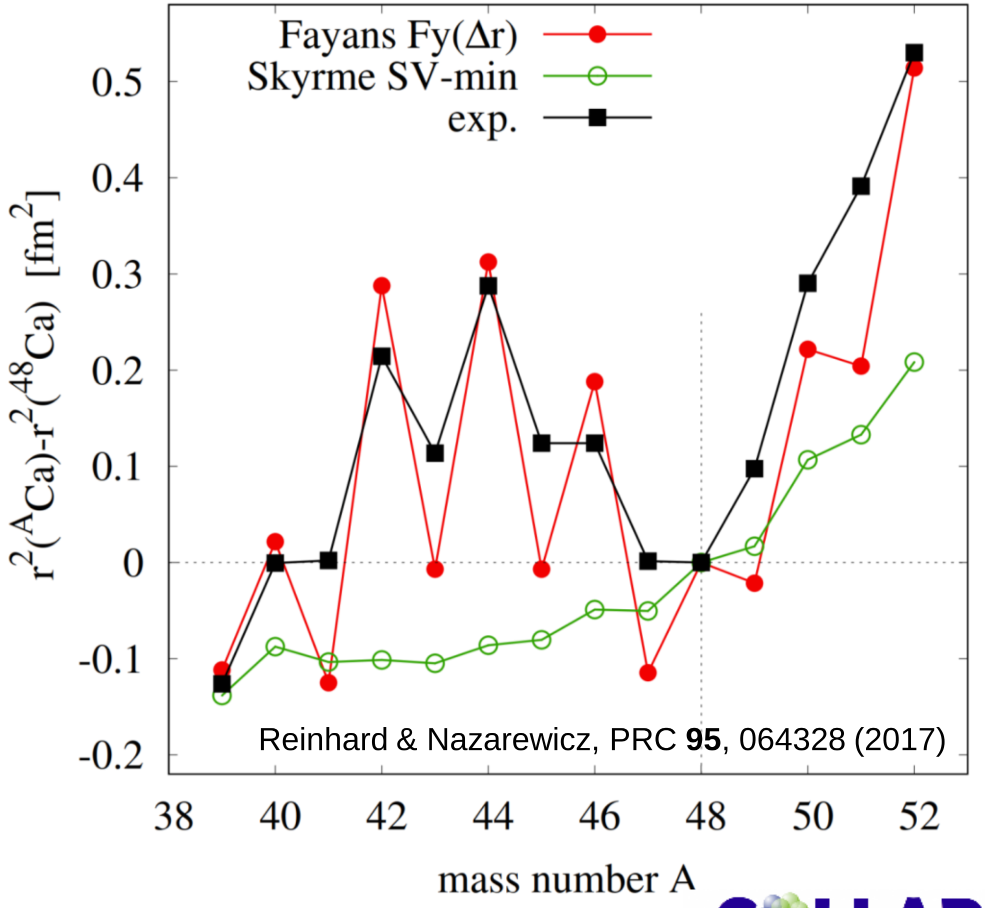
isoscalar isovector

$$x_t = \frac{\rho_t}{\rho_{\rm sat}}, \quad x_{\rm pair} = \frac{\rho_0}{\rho_{\rm pair}}$$

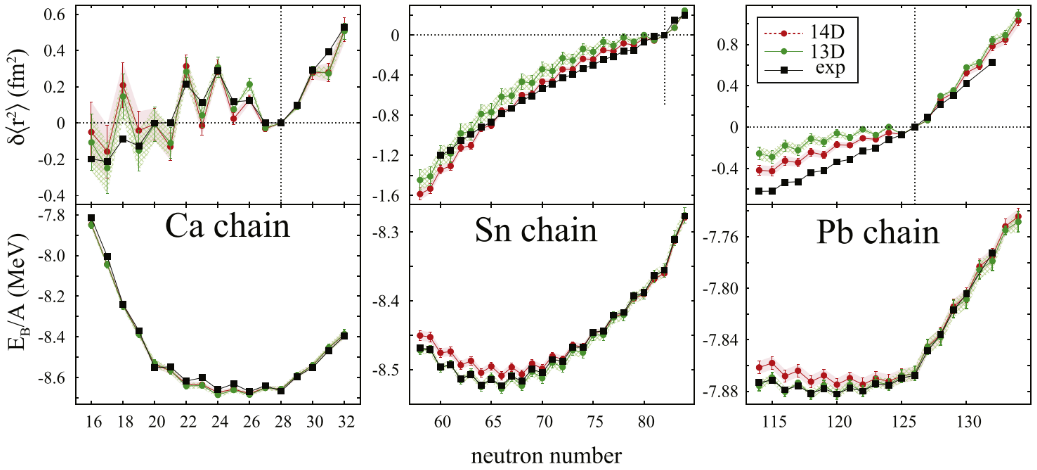
normalized densities

Used Ca radii for optimization:

$$\delta \left\langle r_c^2 \right\rangle^{40,48}, \quad \delta \left\langle r_c^2 \right\rangle^{44,48}, \quad \delta \left\langle r_c^2 \right\rangle^{52,48}$$



Can this **optimized** functional be used in other parts of the nuclear chart ?

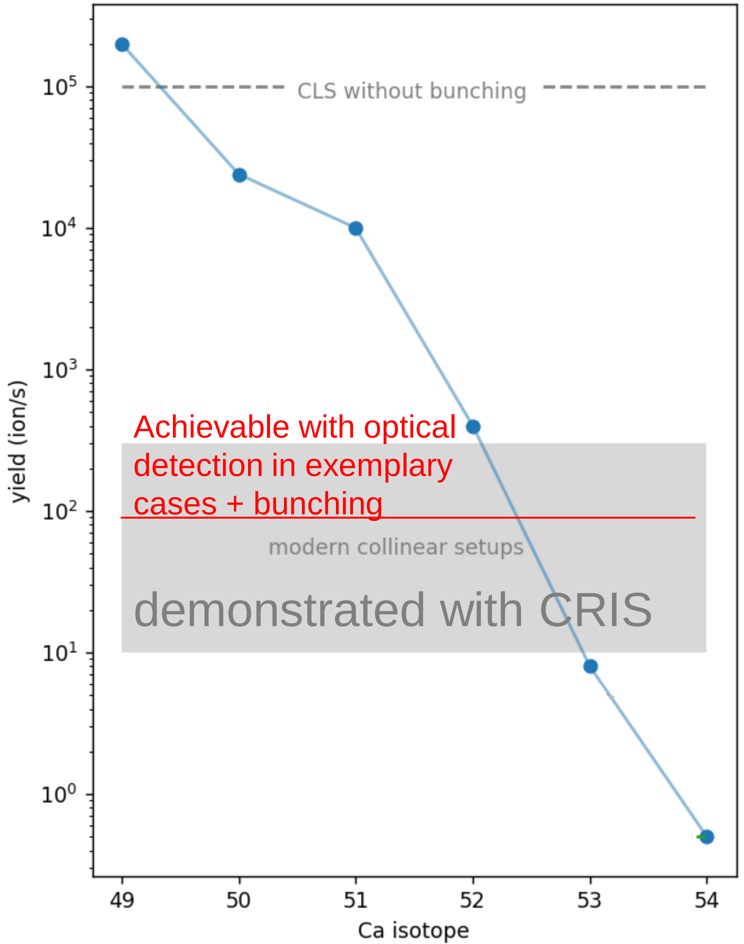


Reinhard et al., J. Phys. G **51**, 105101 (2024)

Towards ^{54}Ca

Expected production rates: 10 1 ions/s

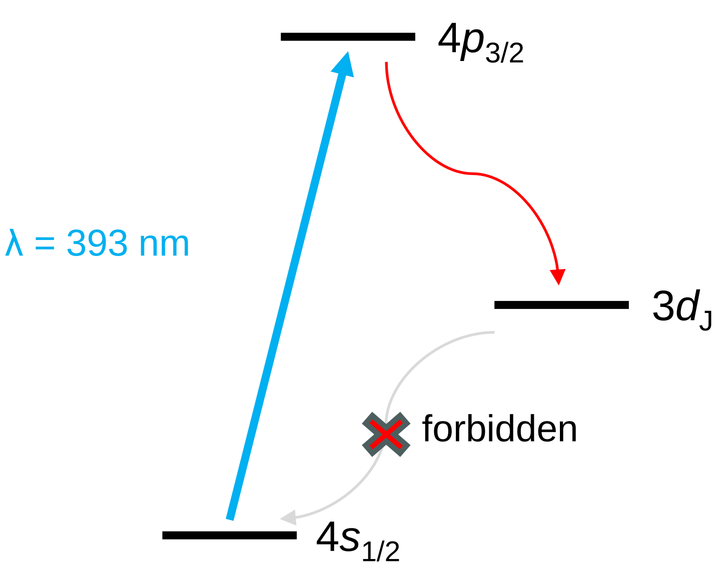
Ca yields and sensitivity of similar setups



Radiation detection after
Optical pumping and state-selective
Charge exchange
Acronym by P. Lievens *et al.*

The ROC Detection Principle

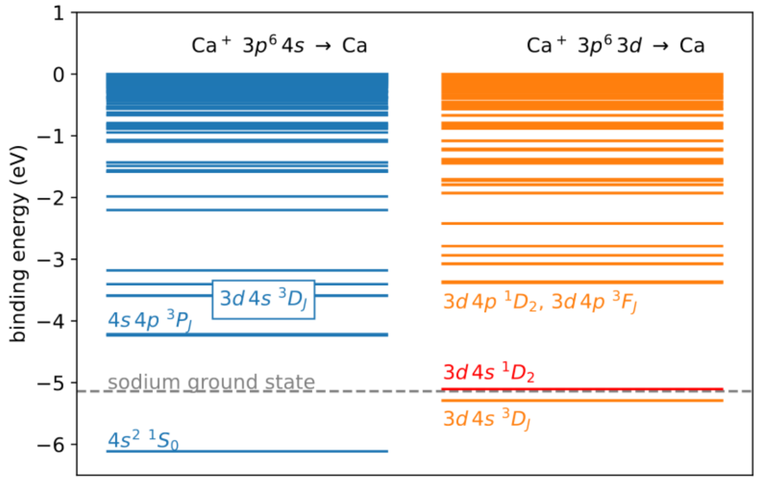
Relevant Ca⁺ level scheme



Optical Pumping

Reaction: $Ca^+ + Na \rightarrow Ca + Na^+ + \Delta E$

ΔE energy depends on initial ionic state!

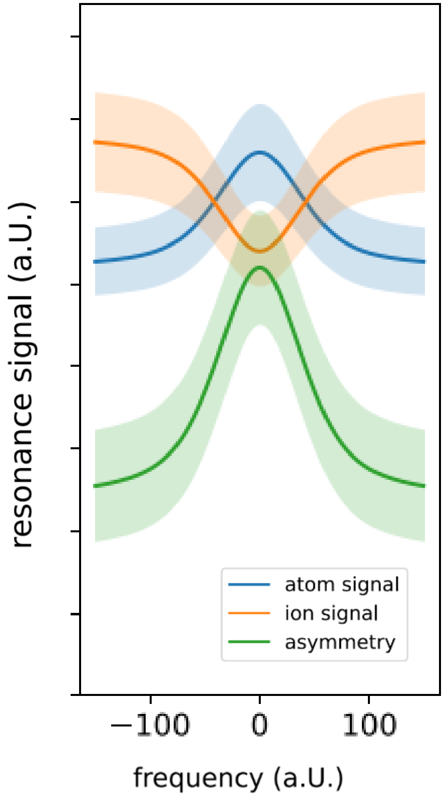


Charge exchange from Ca^+ *d*-state is "quasi-resonant" with the sodium ground state ($\Delta E \approx 0$)

→ Larger cross-section, higher CE probability

State-Selective Charge Exchange

$\varepsilon_{cec,gs}$ = 30%



$$s_{asym} = \frac{s_{atom} - s_{ion}}{s_{atom} + s_{ion}}$$

ROC (Radiation detection after Optical pumping and state selective Charge exchange)

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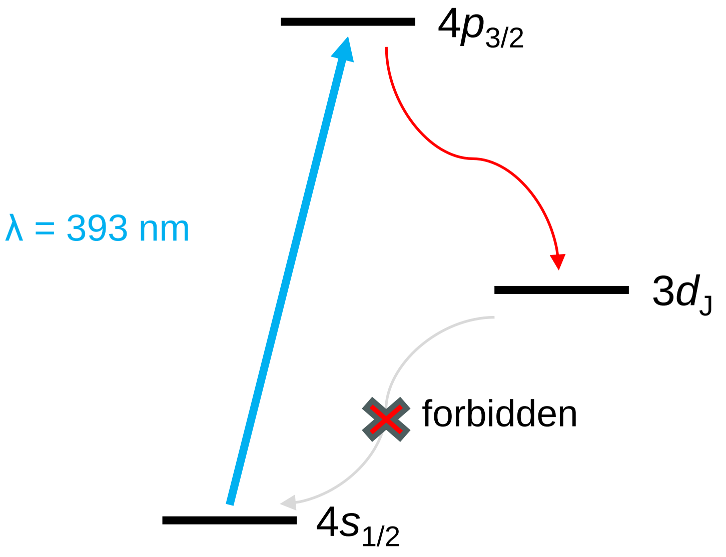
The ROC Detection Principle

Relevant Ca⁺ level scheme



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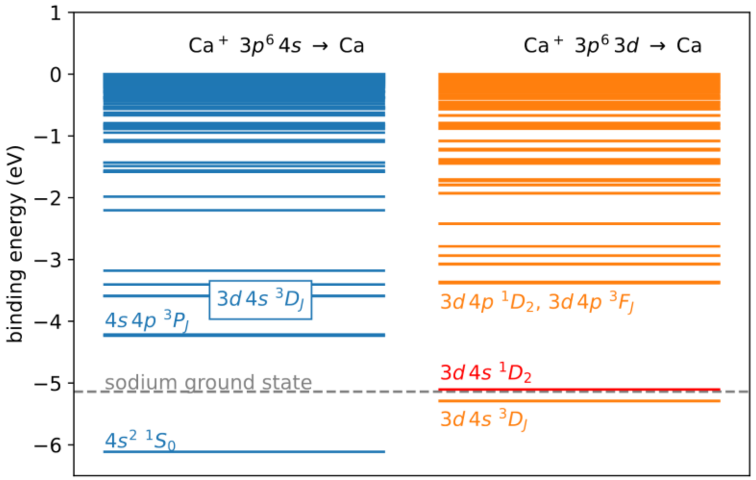

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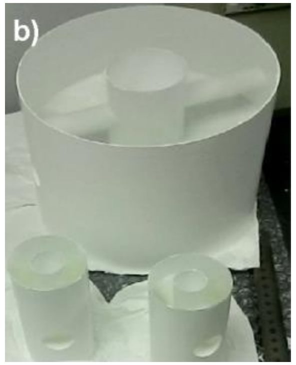
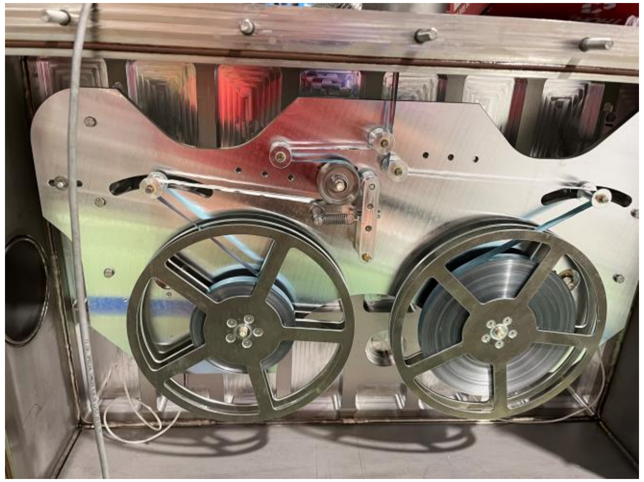




Optical Pumping

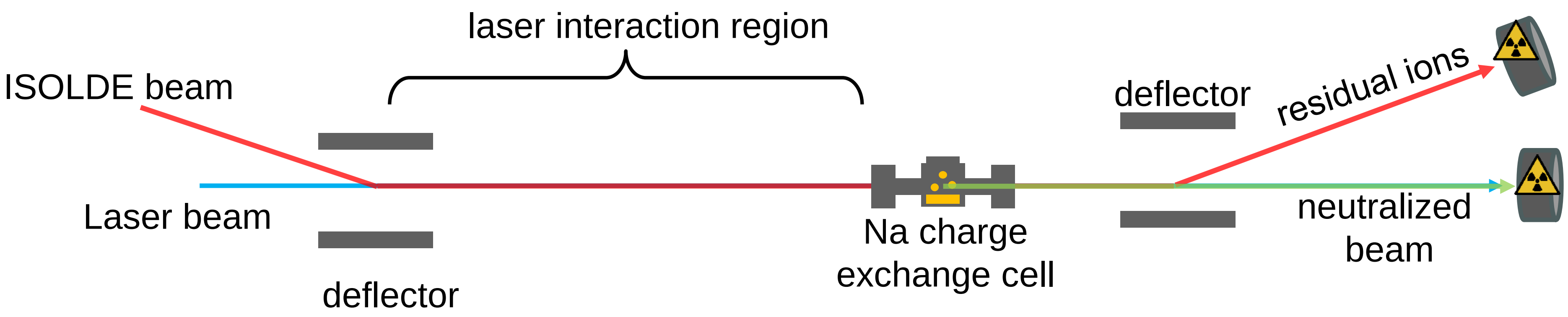
State-Selective **C**harge Exchange

Radiation Detection

ROC (**R**adiation detection after **O**ptical pumping and state selective **C**harge exchange)

ROC – Experimental Setup

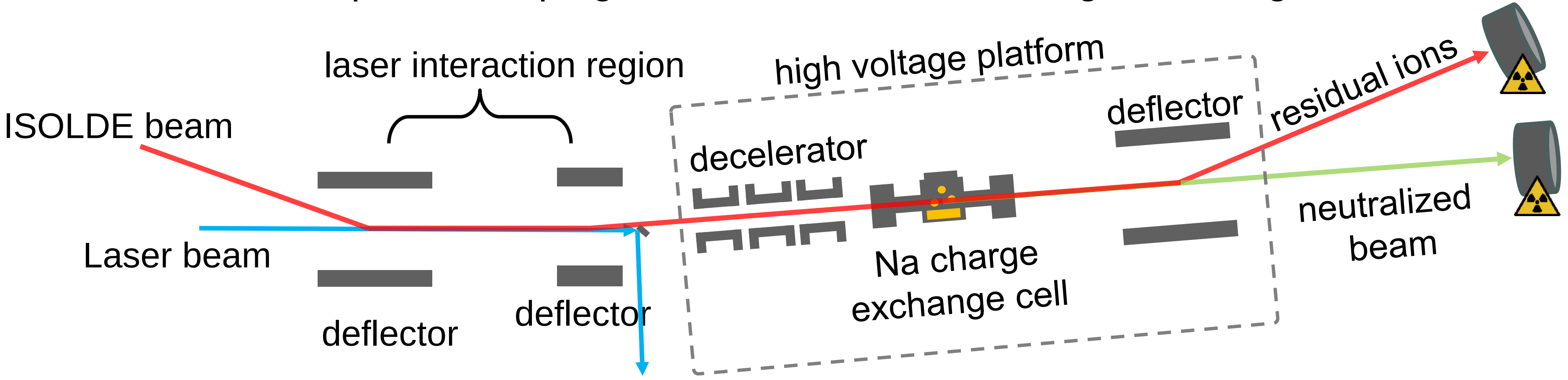
Optical Pumping   State-Selective Charge Exchange   Radiation Detection

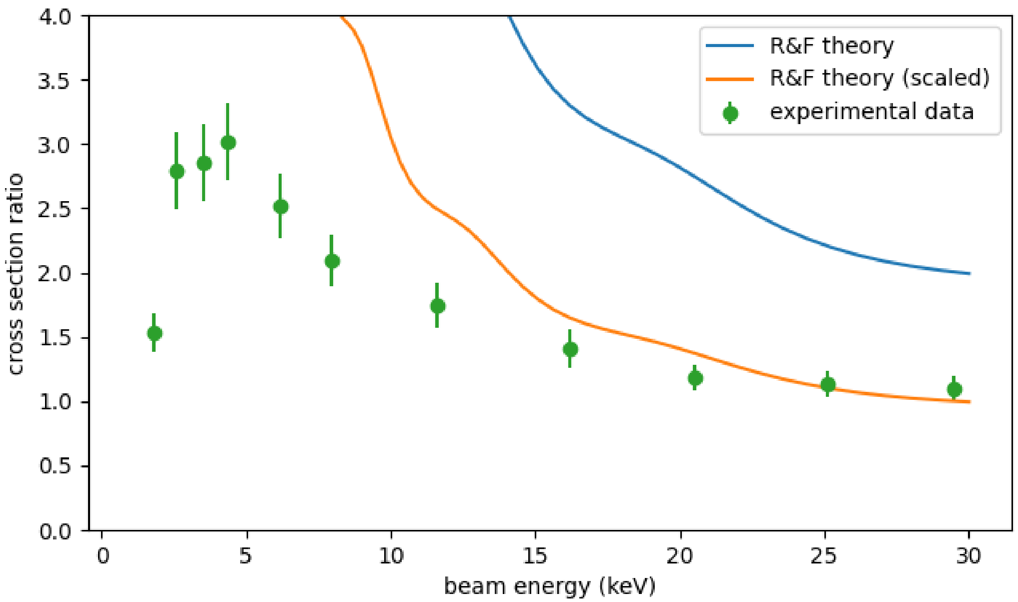


insensitive to stable contaminants
measure β-decay energy
→ discrimate radioactive isobars

Charge exchange as a state detector

Optical Pumping — State-Selective **C**harge Exchange — **R**adiation Detection





insensitive to stable contaminants
measure β-decay energy
→ discrimate radioactive isobars

Engineering Challenge

Maximum difference in charge exchange cross section at **4 keV**
→ beam deceleration
→ CEC on HV platform
→ short HV section, neutralized beam can't be refocussed

Real setup

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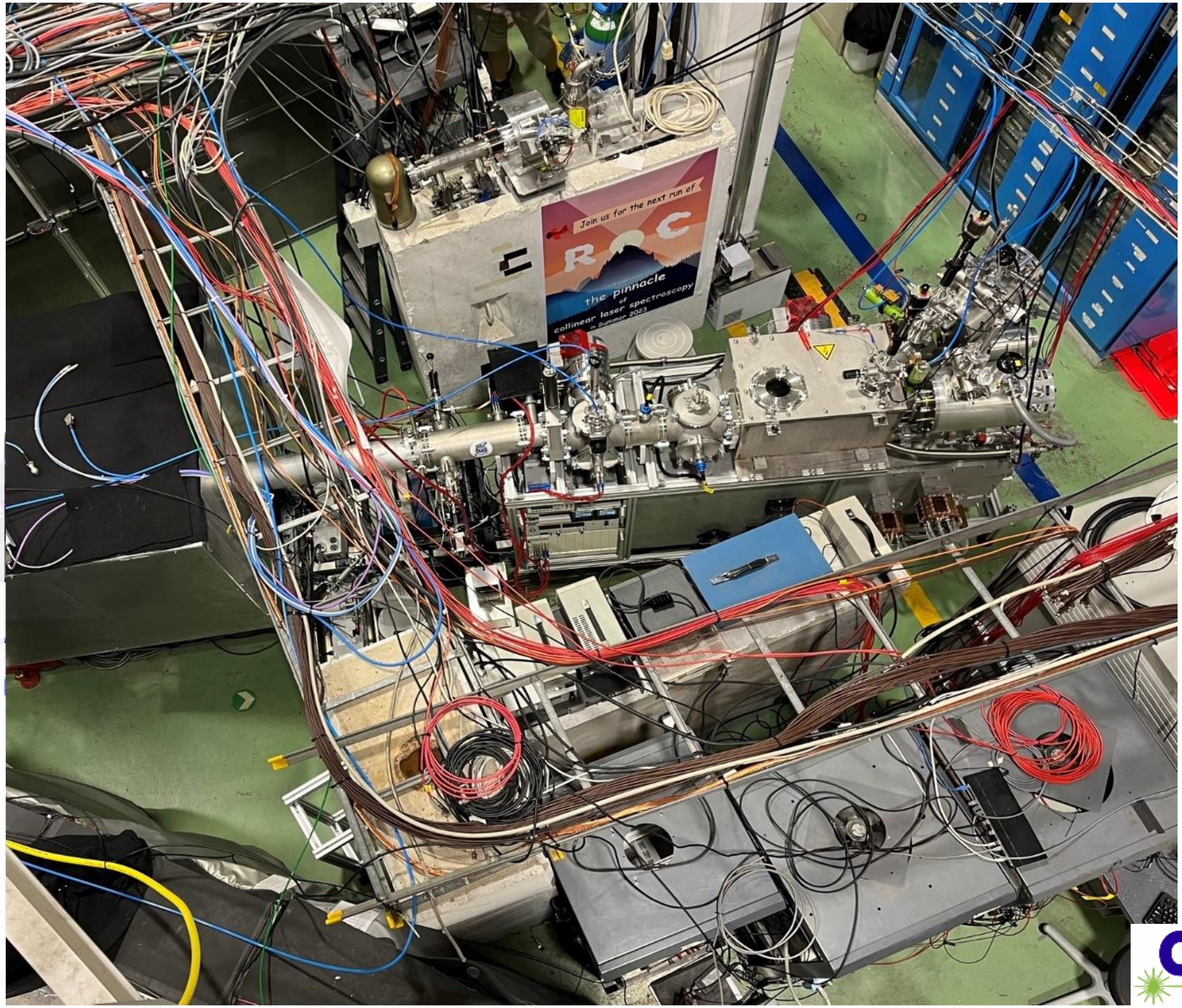
Installed at the COLLAPS setup at ISOLDE/CERN:

Two experimental campaigns:

2023 → ^{53}Ca

2024 → ^{54}Ca



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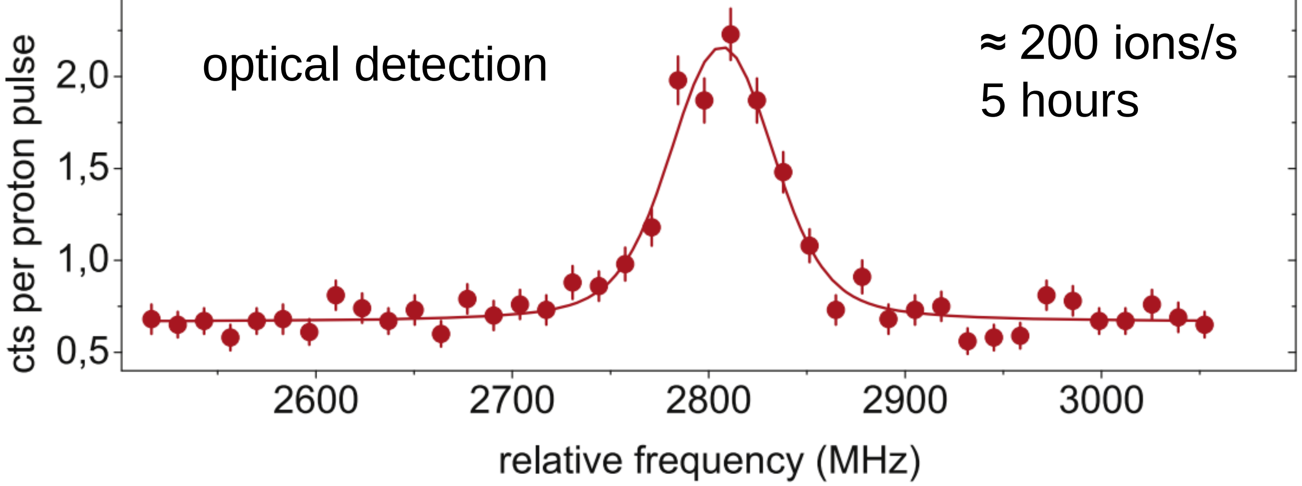
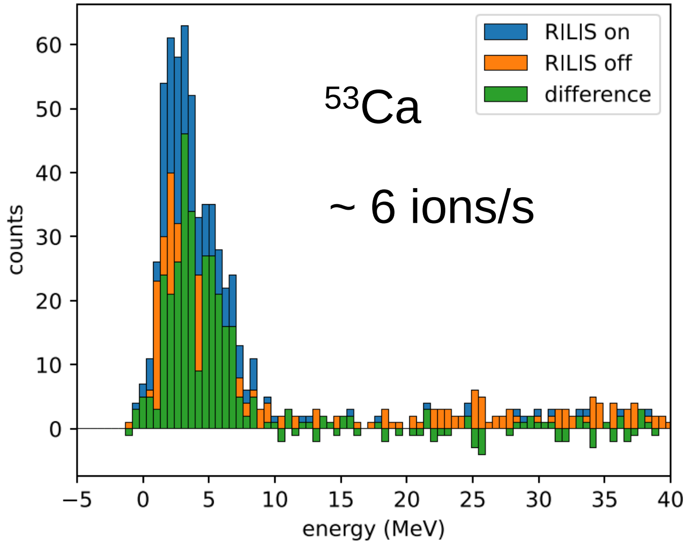
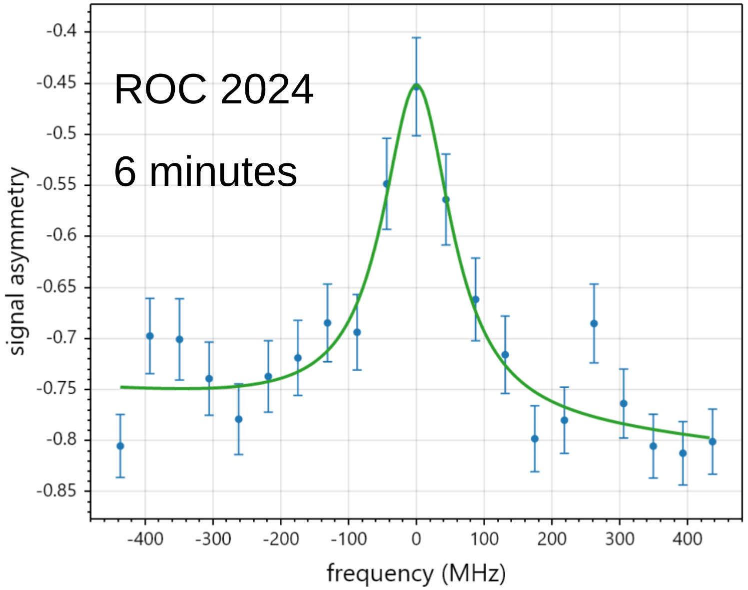
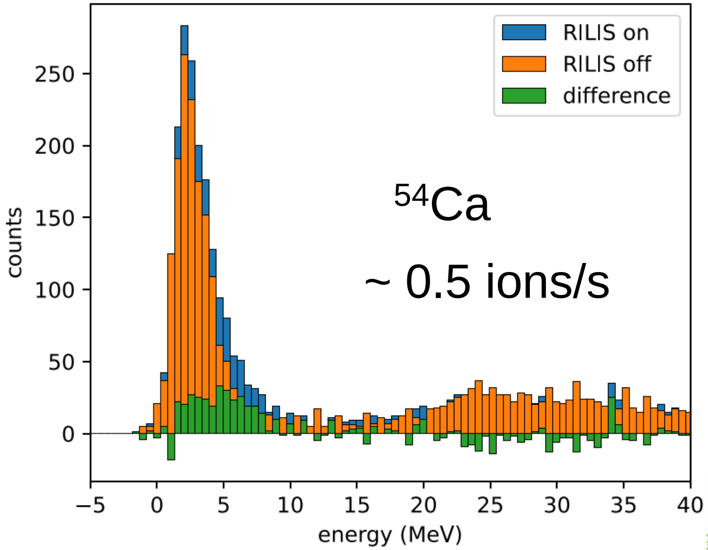
Results: ^{52}Ca as a Sensitivity Test

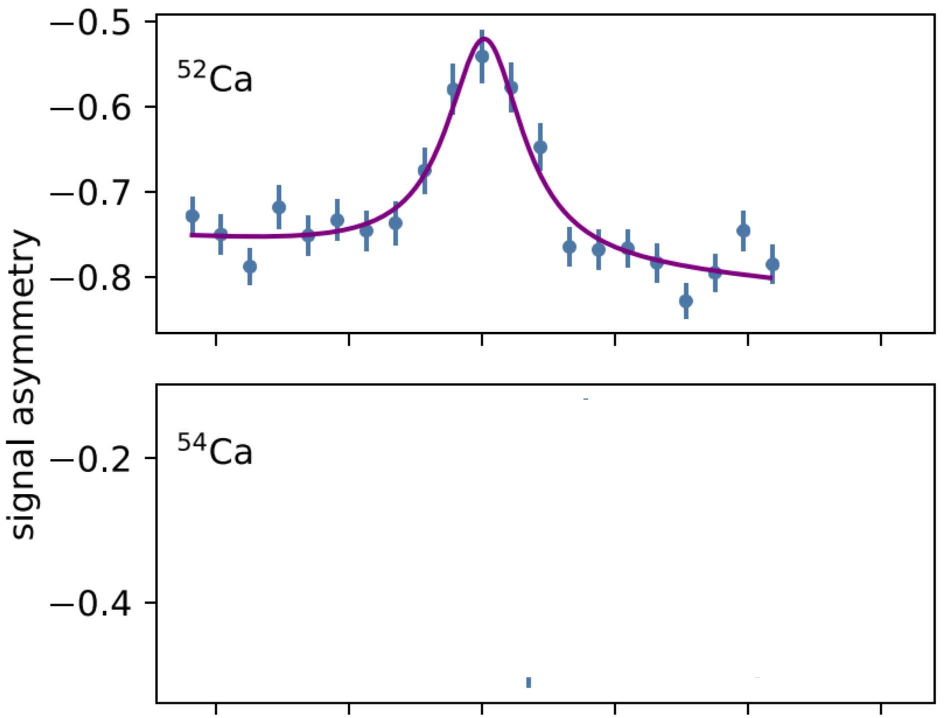




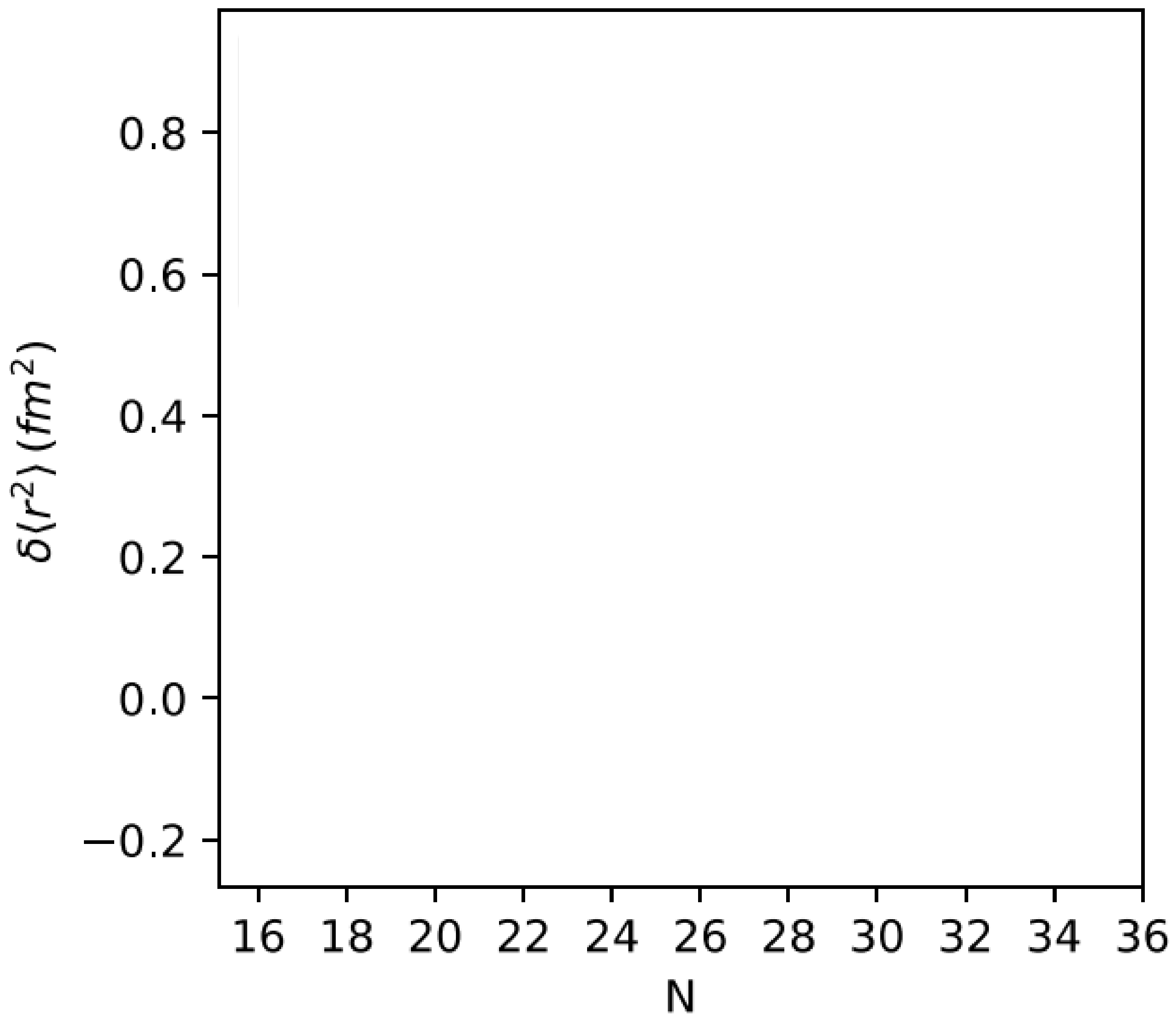




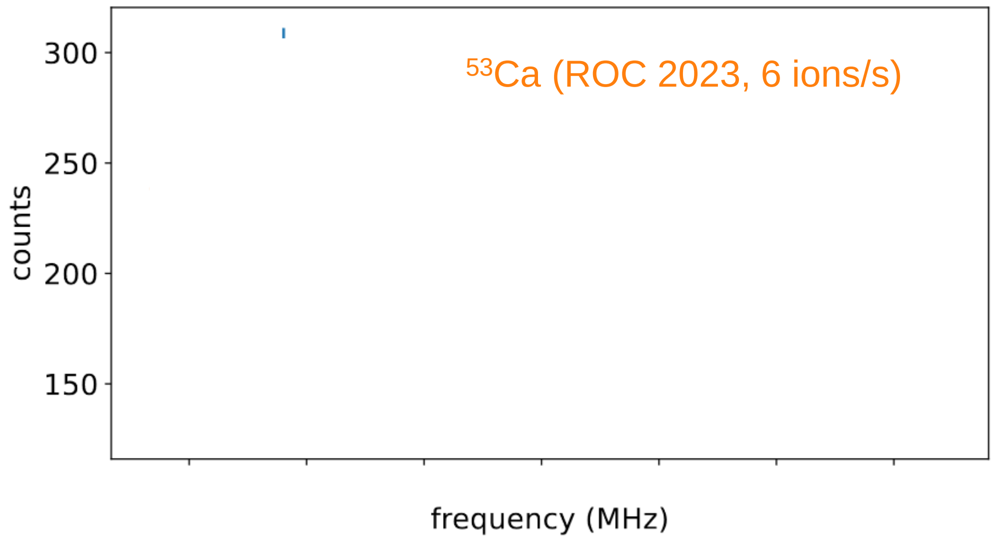
Isotope Shift and Charge Radii of $^{53,54}Ca$



$$\delta \left\langle r^2 \right\rangle^{A,40} = \frac{1}{F} \cdot \left(\delta\nu^{A,40} - K \cdot \frac{m_A - m_{40}}{m_A \cdot m_{40}} \right)$$



The Magnetic Moment of ^{53}Ca



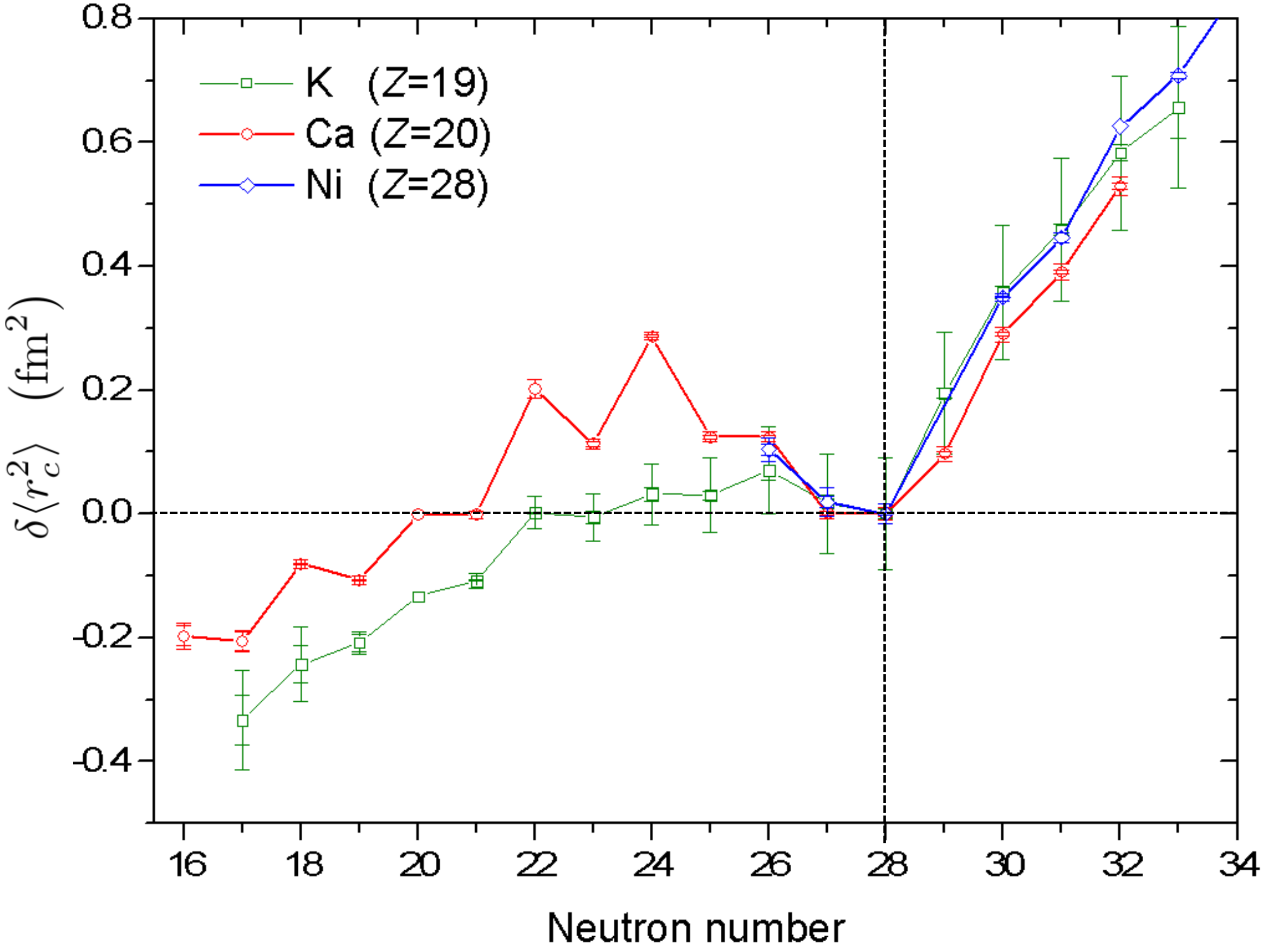
$$\mu(^{53}\mathrm{Ca}) = \mu(^{43}\mathrm{Ca}) \cdot \frac{A(^{53}\mathrm{Ca}) \cdot I(^{53}\mathrm{Ca})}{A(^{43}\mathrm{Ca}) \cdot I(^{43}\mathrm{Ca})}$$

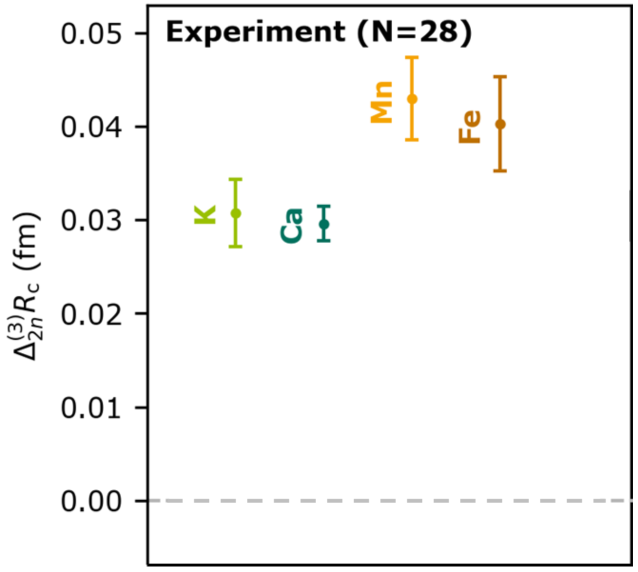
Comparison to Nickel

Three-point two-neutron difference:

$$\Delta_{2n}^{(3)} R_c(N) \equiv \frac{1}{2}\left[(R_c(N+2) - R_c(N)) - (R_c(N) - R_c(N-2))\right]$$

$$\Delta_{2n}^{(3)} R_c(N) \equiv \frac{1}{2}\left[R_c(N+2) - 2R_c(N) + R_c(N-2)\right]$$

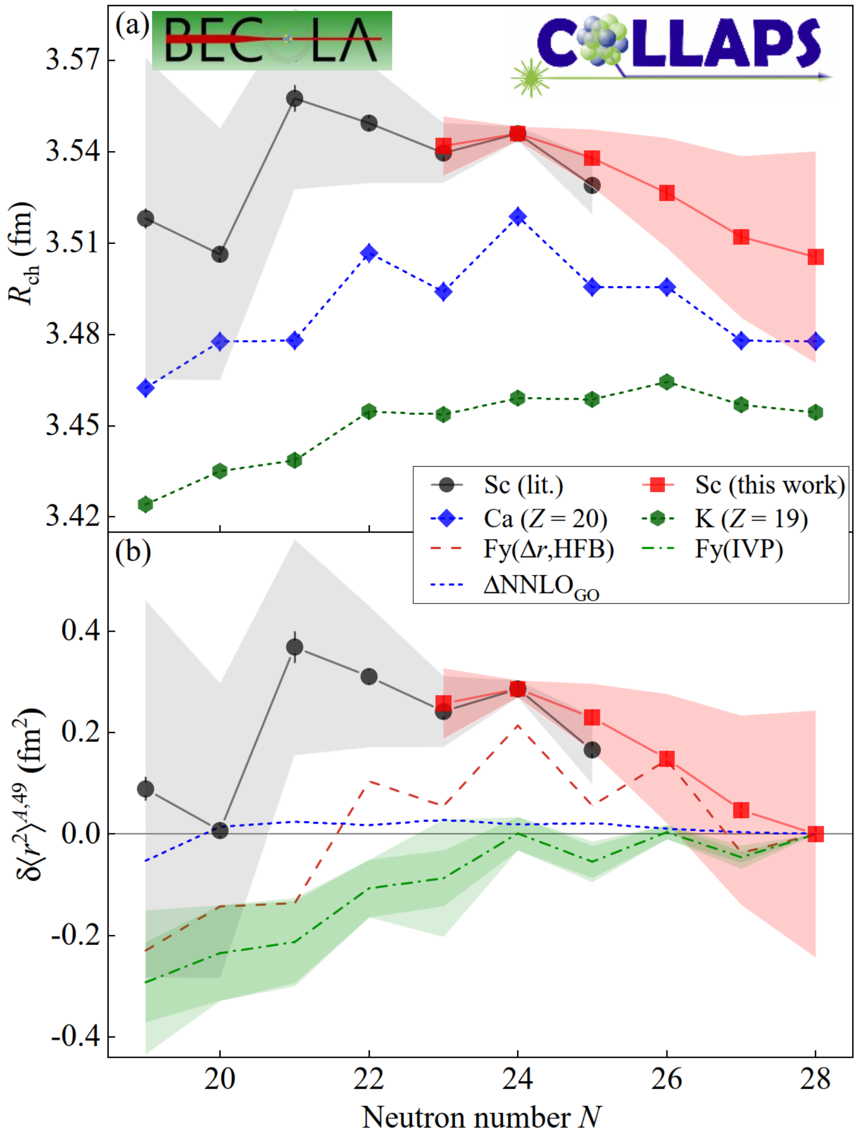


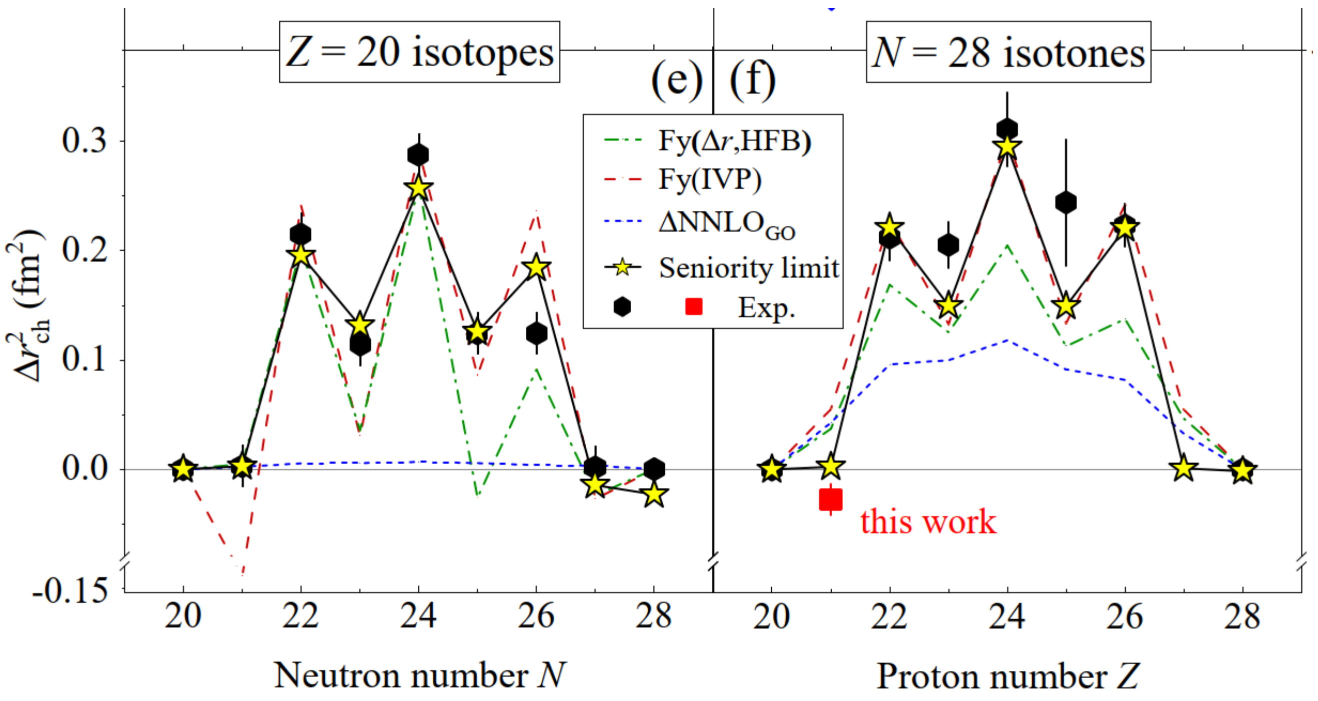


F. Sommer et al., Phys. Rev. Lett. 129 132501 (2022)

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

Scandium (Z=21) Results and the N=28 Isotones





In Sc (Z=21) a kink appears at $N = 20$.

König et al., PRL **131**, 102501 (2023)

A similar pattern as in Ca appears: $R_c(^{49}Sc) \approx R_c(^{41}Sc)$

Removing a linear trend in the charge radii along the N=28 isotones, gives a similar trend from Z=20 to Z=28 as in the Ca isotopes from N=20 to N=28

S.W. Bai et al., submitted to PRL (2025)

Summary

Laser spectroscopy is a „universal tool“ to study charge radii and nuclear moments

Charge radii changes are very sensitive to nuclear structure details and *can* herald indications for shell closures

The interplay between measurements and theory has lead to an improved understanding of nuclear structure and a continuous development of theoretical tools

We have proven the ROC technique being sensitive at the 1 atom/s level and determined the moments and charge radii of $^{53,54}Ca$

The microscopic origin of the kink and the odd-even staggering is still not fully understood.

Mi, 14:00 HK 25: Focus Session II: Accurate Nuclear Charge Radii of Light Elements

K. König: First laser spectroscopic measurements of charge radii along the carbon isotope chain

F. Wauters: Precision radii of light elements using Metallic Magnetic Calorimeters

R. Roth: Precision Radii from the No-Core Shell Model via Neural Networks

THANK YOU

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