

CRIS of neutron-rich ^{52}K to explore the nature of $N=32$

PhD student at KU Leuven

KU LEUVEN

Laser spectroscopy at the frontiers of RIB production

Laser spectroscopy of proton-rich Cr, Fe and Co



Postdoctoral researcher
University of Liverpool

Measurement of the charge radii of $^{33,34}\text{Al}$



Research fellow

Development of a novel laser spectroscopy setup for high-precision studies

KU LEUVEN
sckcen

Assistant professor

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Continuous developments of techniques for the measurements of charge radii

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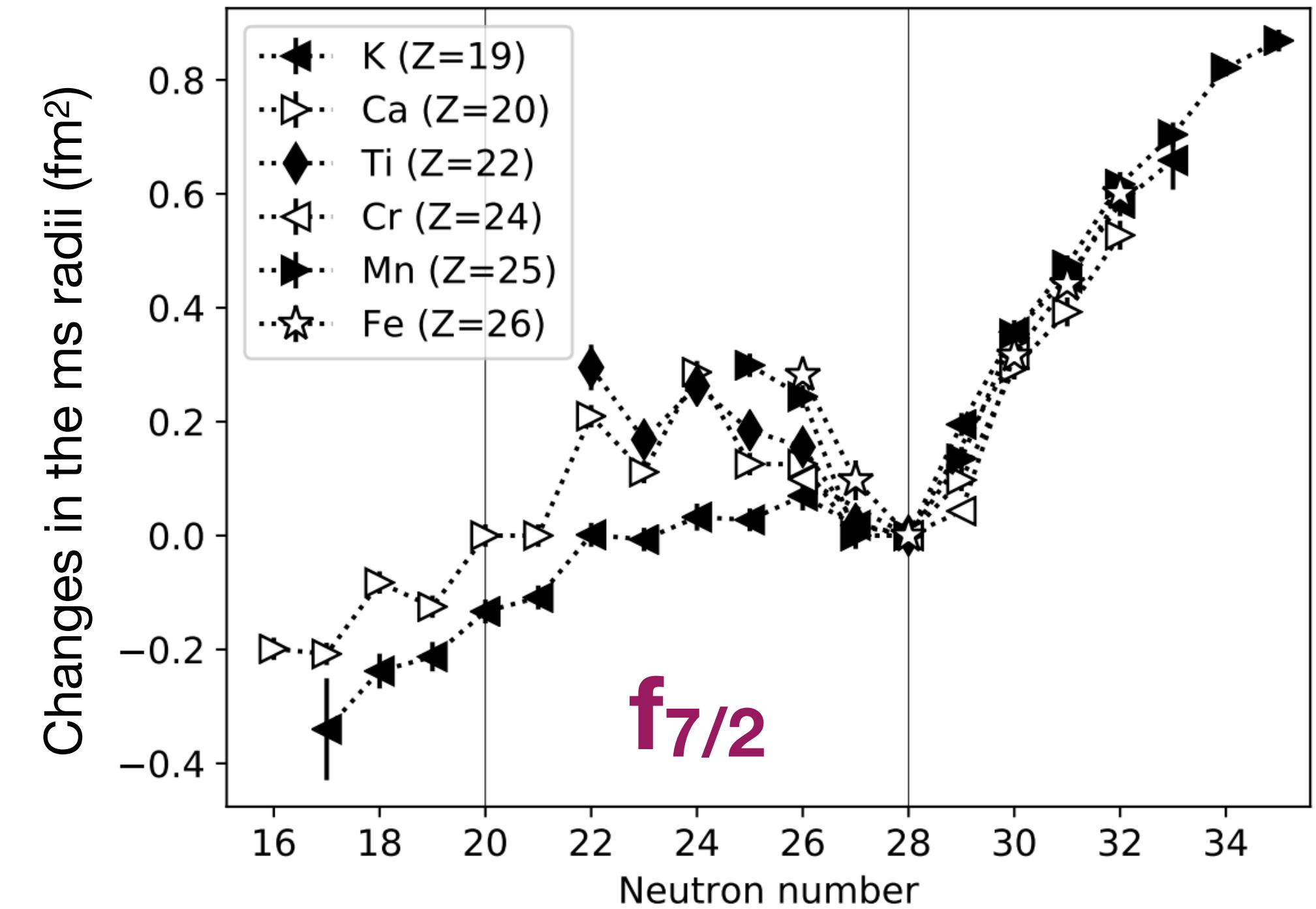
Assistant professor

Scientific goals

Nuclear magic number and nuclear structure

Investigating the charge radii across:

- $N=32$ in potassium isotopes ($Z=19$)
- the neutron and proton $f_{7/2}$ shell, Cr ($Z=24$), Fe ($Z=26$) and Co ($Z=27$)
- $N=20$ in aluminium isotopes ($Z=13$)

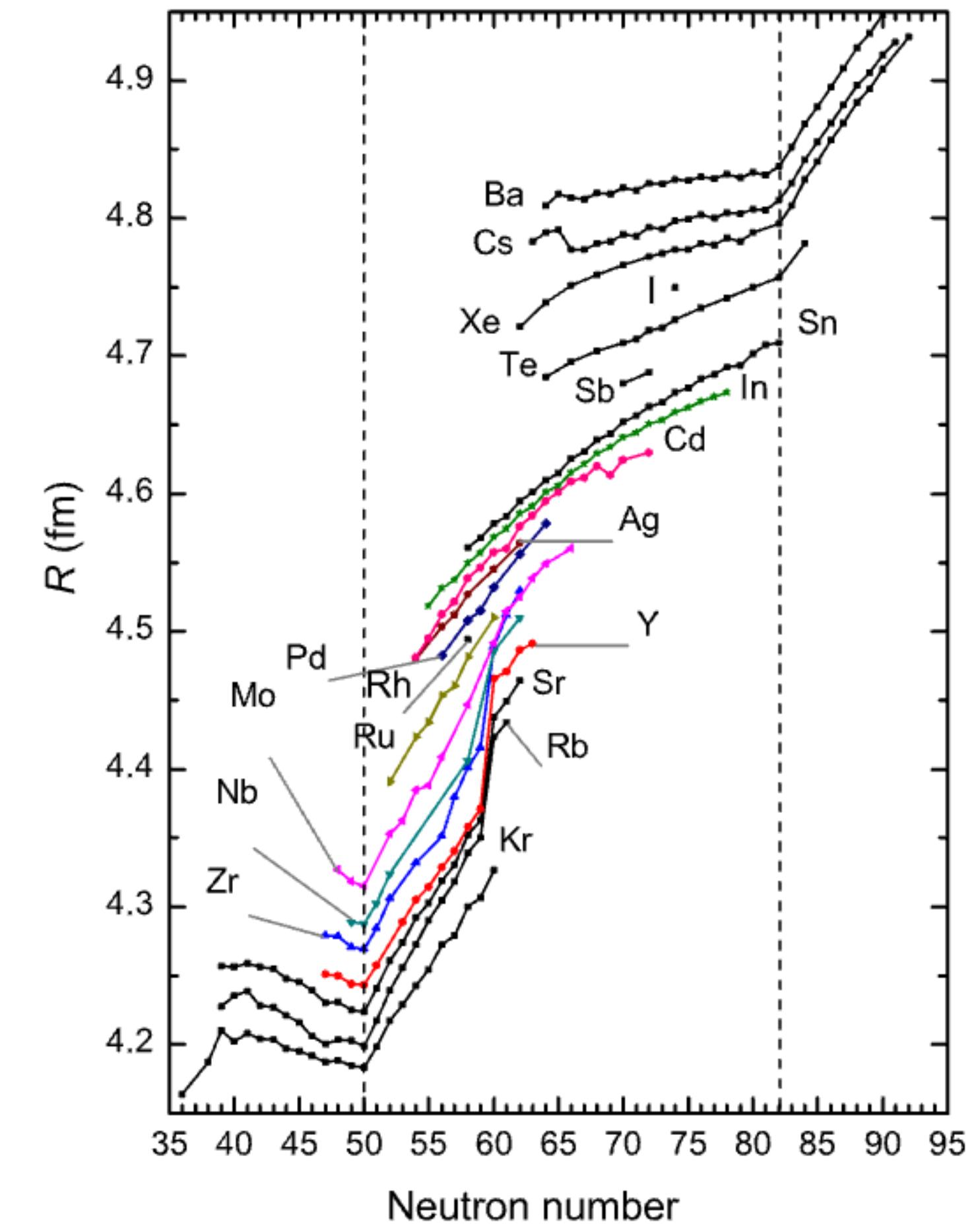
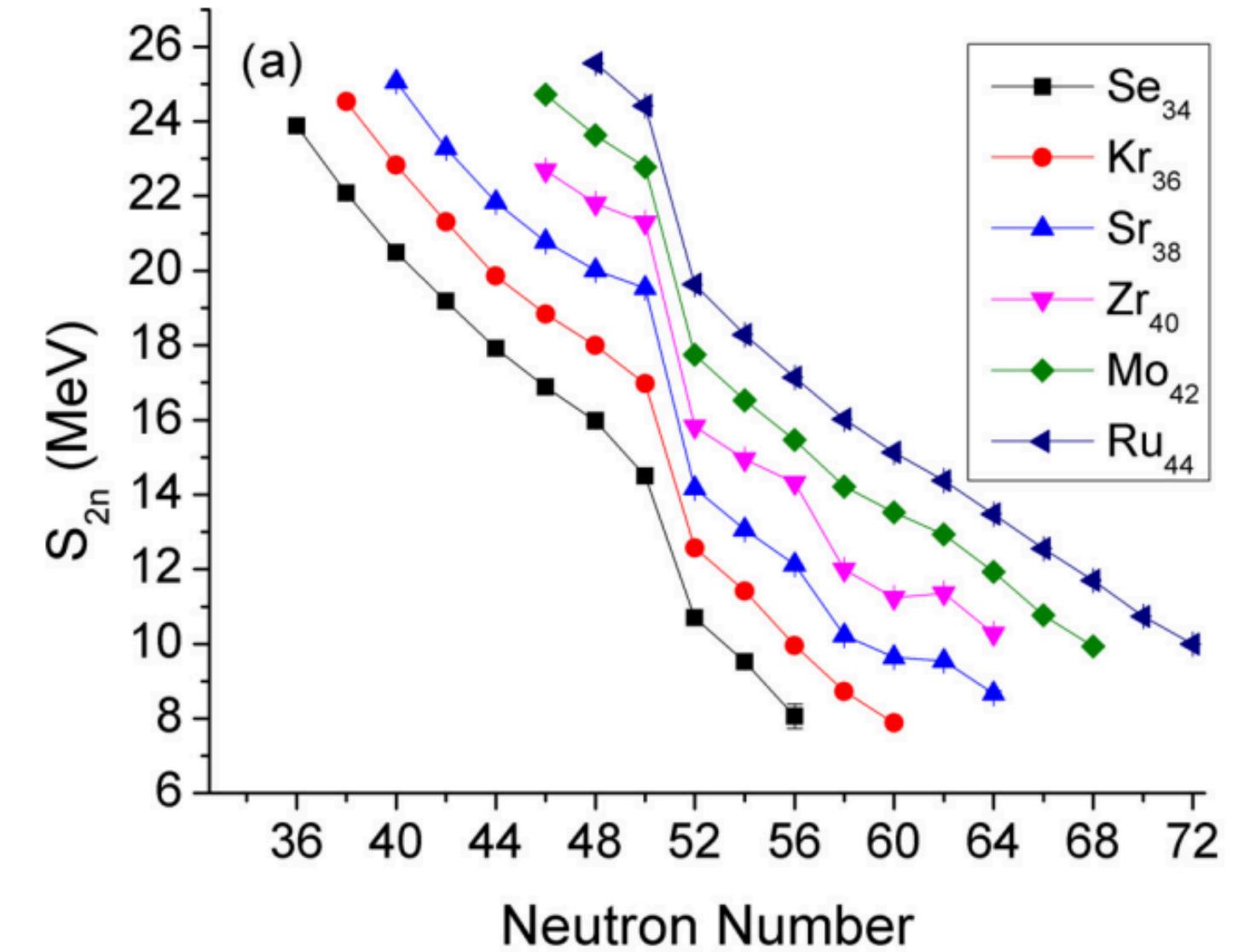


Probes to explore the nuclear structure

(Relevant for this presentation)

Questions about the sensitivity of a particular observable to the changes in the nuclear structure.

Odd Z isotopes: the binding energies and radii are excellent probes



R.P. de Groote et al. Nature Physics 16 (6), 620-624 (2020) - Cu ($Z=29$)

Á. Koszorus et al. Nature Physics, 17, 439–443 (2021) - K ($Z=19$)

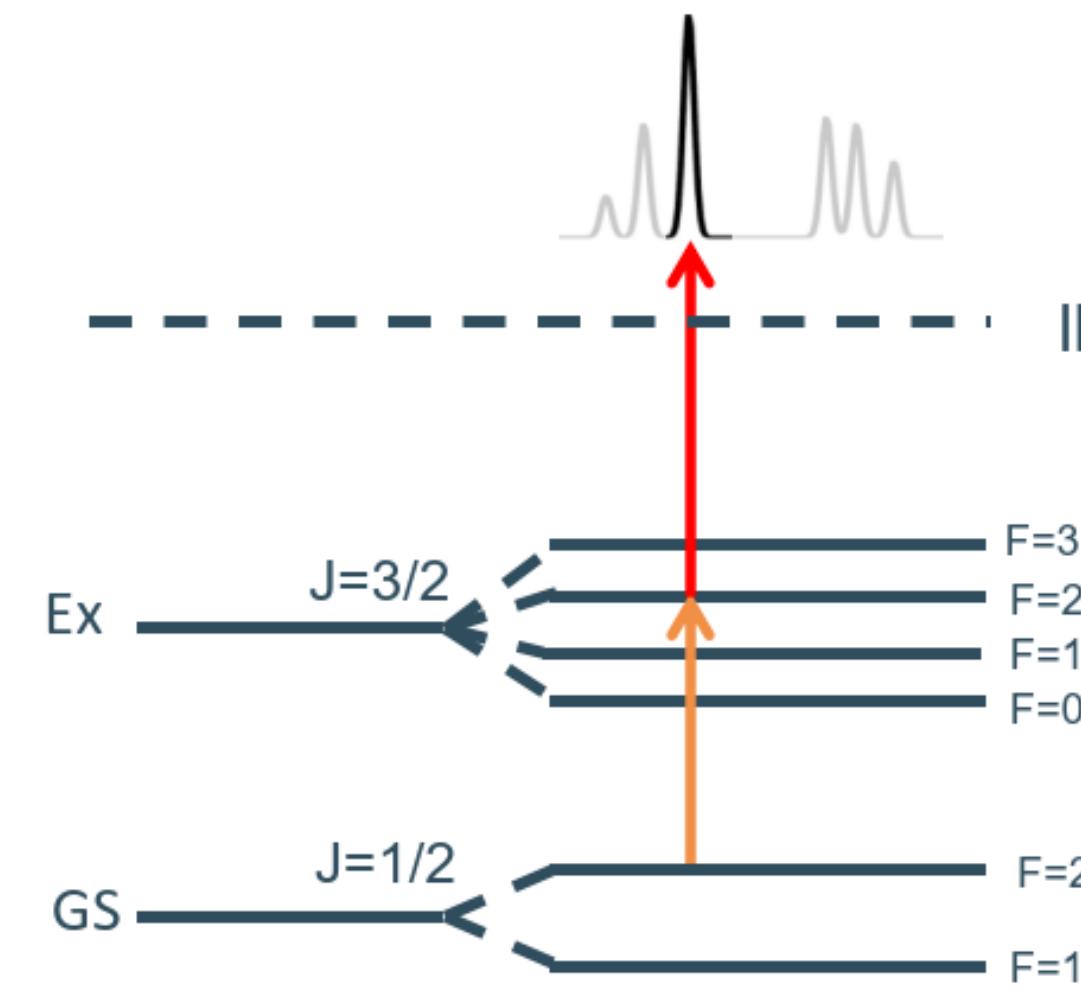
R.P. de Groote et al. in preparation - Ag ($Z=47$)

A. Vernon et al. in preparation - In ($Z=49$)

Atomic Data and Nuclear Data Tables 99,1
2013, 69-95

PHYSICAL REVIEW C 93, 044337 (2016)

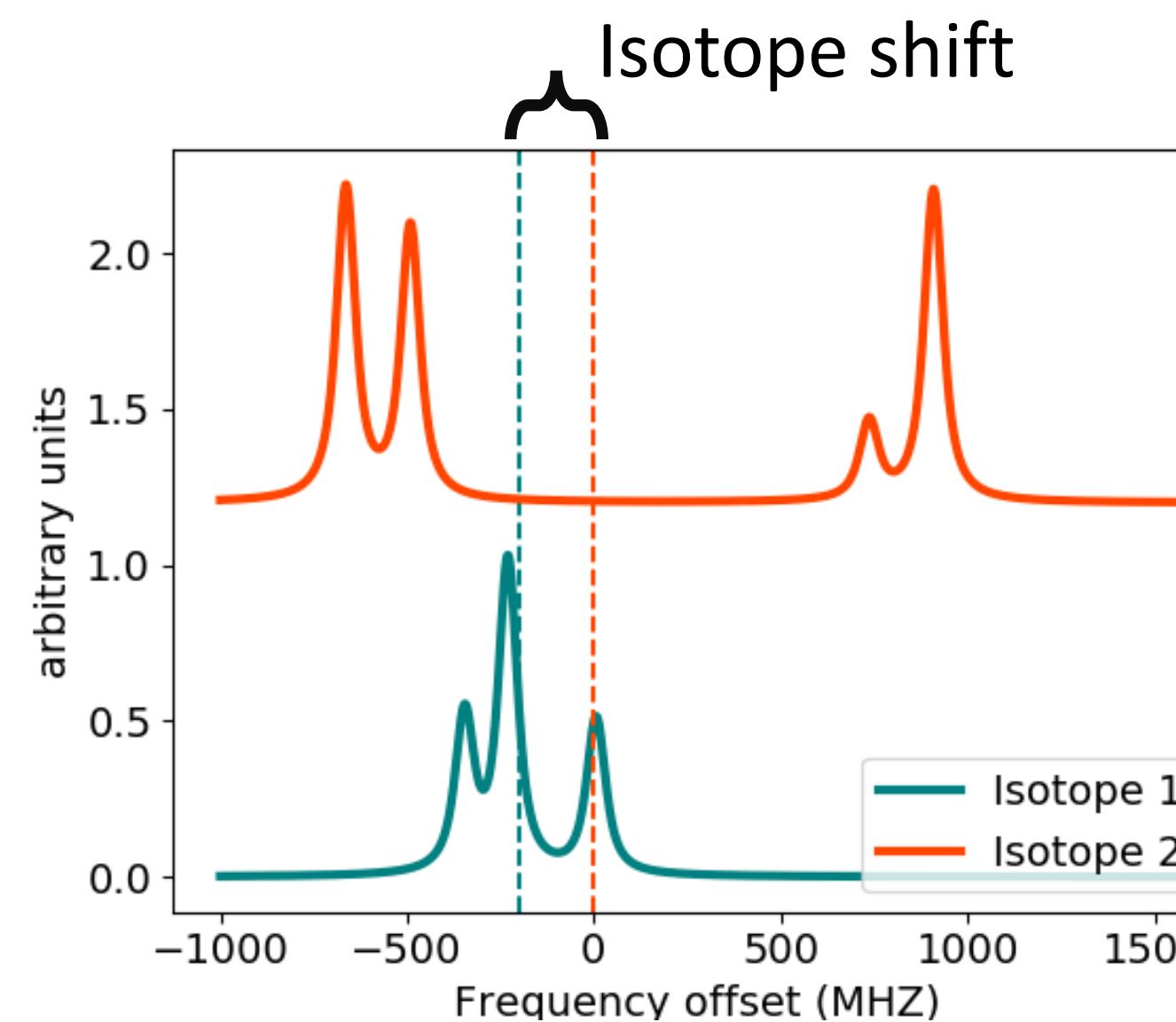
Laser spectroscopy



- ❖ Nuclear spin I
- ❖ Magnetic dipole moment μ
- ❖ Electric quadrupole moment Q
- ❖ Changes in the mean square charge radii $\delta\langle r^2 \rangle$

$$\Delta E = A \cdot K/2 + B \cdot \{3K(K+1)/4 - I(I+1)J(J+1)\} / \{2(2I-1)(2J-1)IJ\}$$

$$K = F(F+1) - I(I+1) - J(J+1)$$

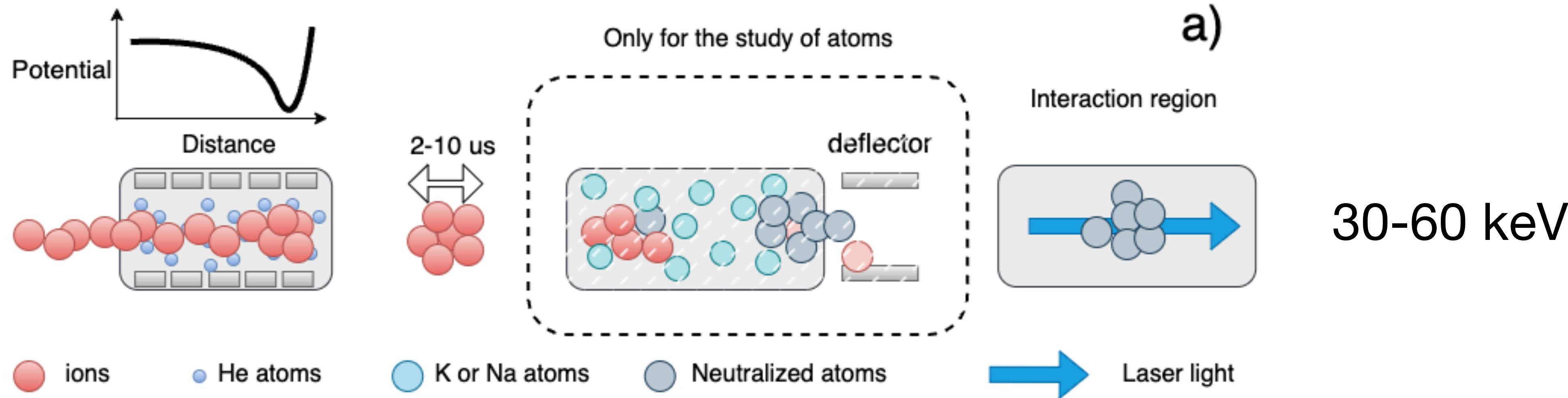


$$A = \frac{\mu_I B_J}{IJ}$$

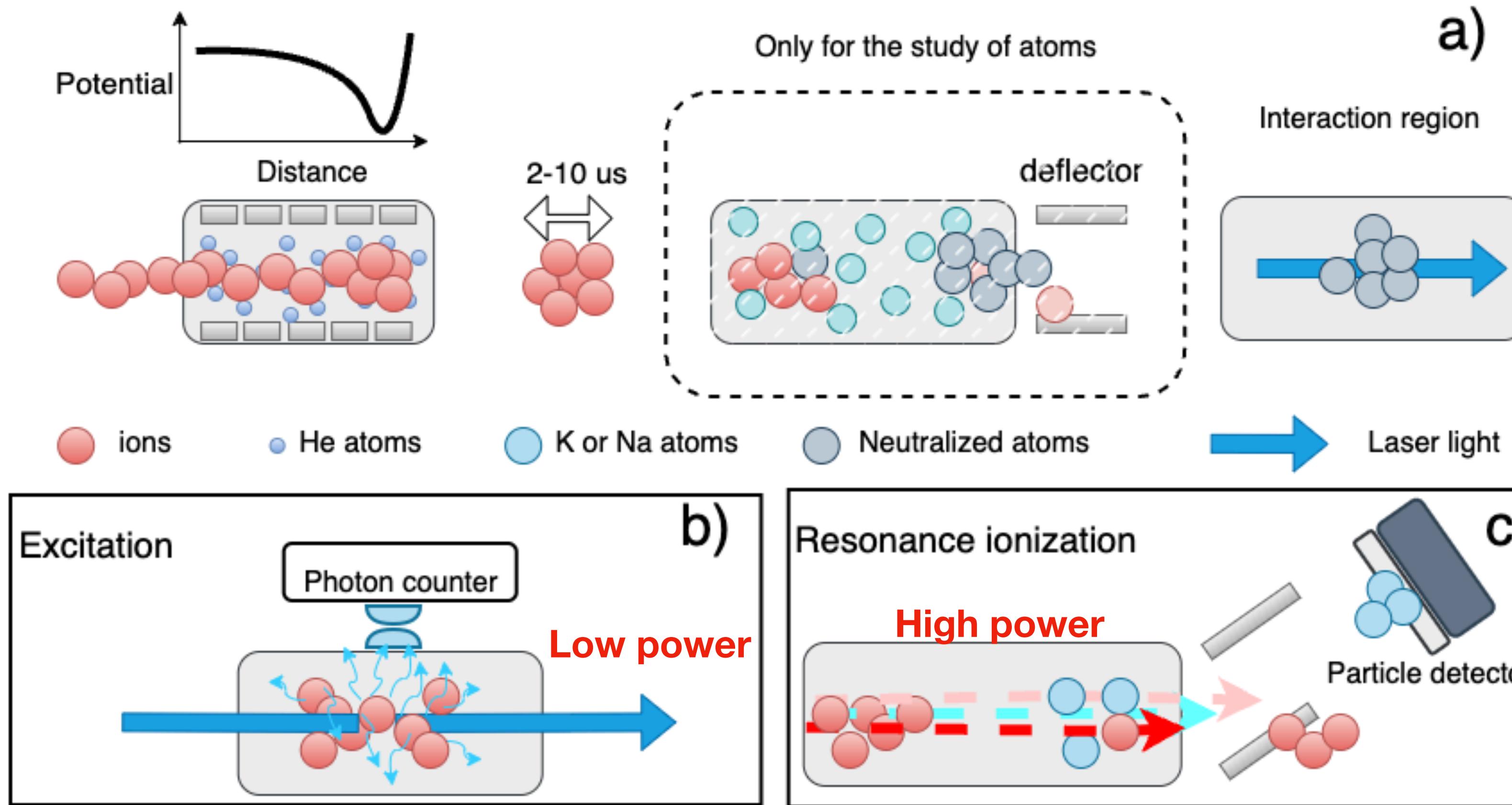
$$B = eQV_{zz}$$

$$\delta\nu^{AA'} = M \frac{m_{A'} - m_A}{m_A m_{A'}} + F \delta\langle r^2 \rangle^{AA'}$$

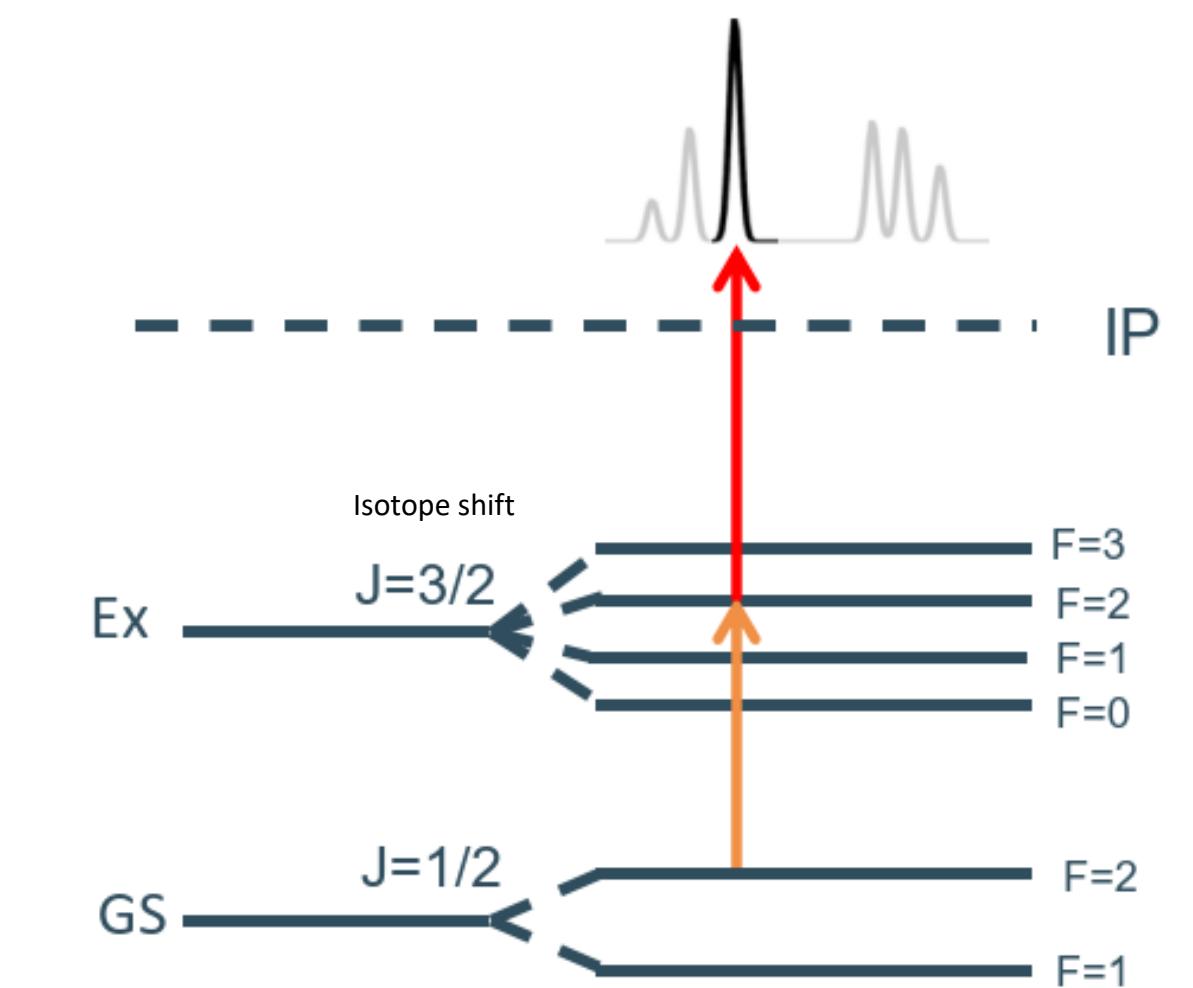
Laser spectroscopy



Laser spectroscopy

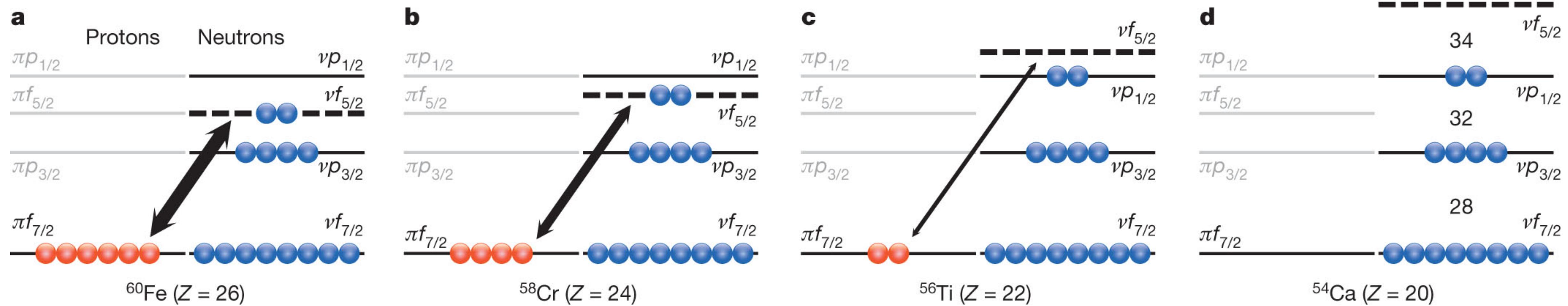


- Probing the hyperfine structure using narrowband laser
- Detect the photons following the de-excitation - CLS
- Detect the resonantly laser ionised ion - CRIS



Nuclear structure at $N=32$

Nuclear structure at $N=32$



Schematic illustration highlighting the attractive interaction between the proton $\pi f_{7/2}$ and neutron $\nu f_{5/2}$ single-particle orbitals for $N = 34$ isotones.

We investigated this in K ($Z=19$)

D Steffenbeck *et al.* *Nature* **502**, 207-210 (2013) doi:10.1038/nature12522

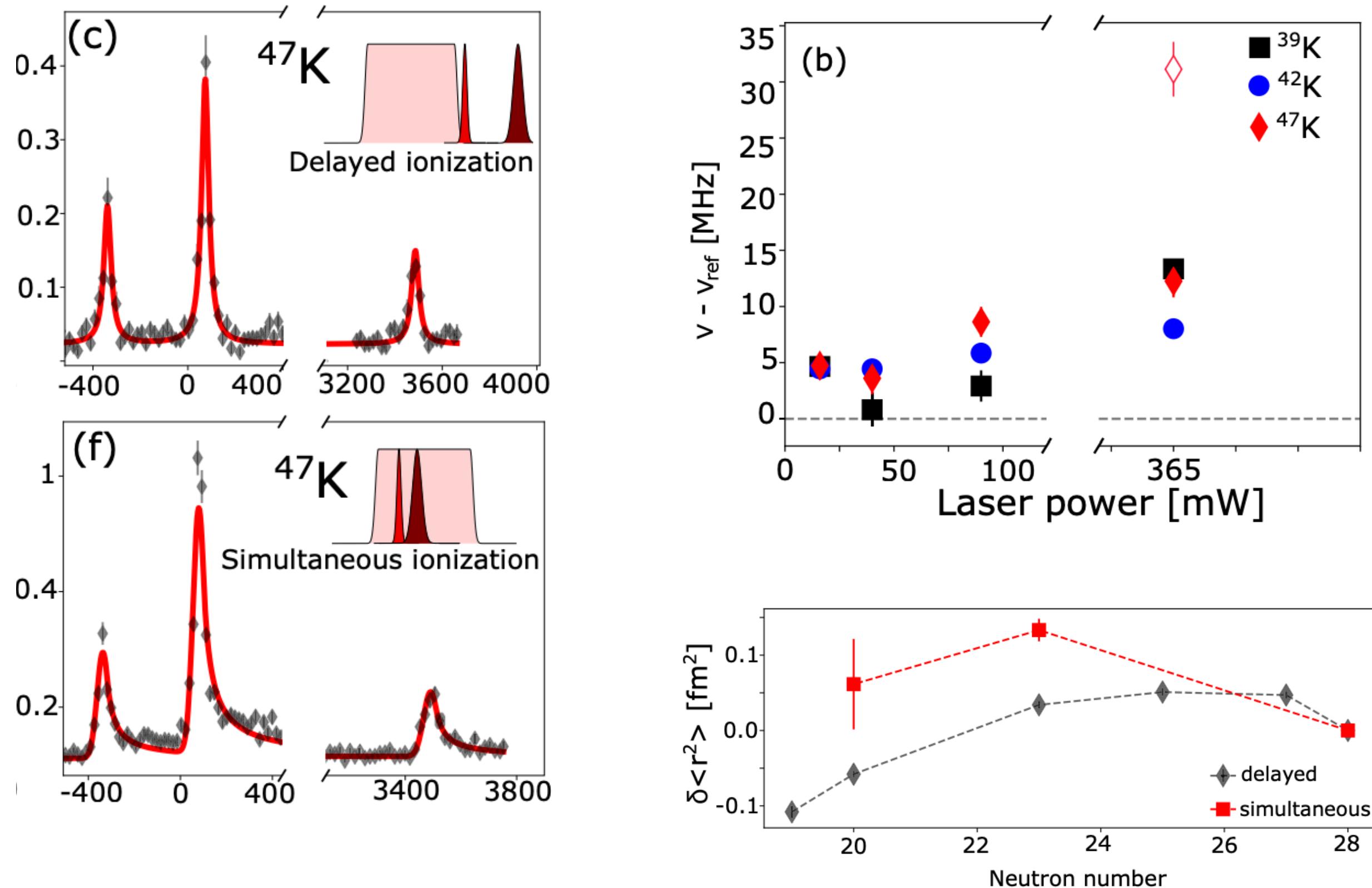
nature

Measurement of K ($Z=19$) isotopes across $N=32$

**CRIS of radioactive potassium isotopes
...after Fr, Ra, In, Cu and Ga**

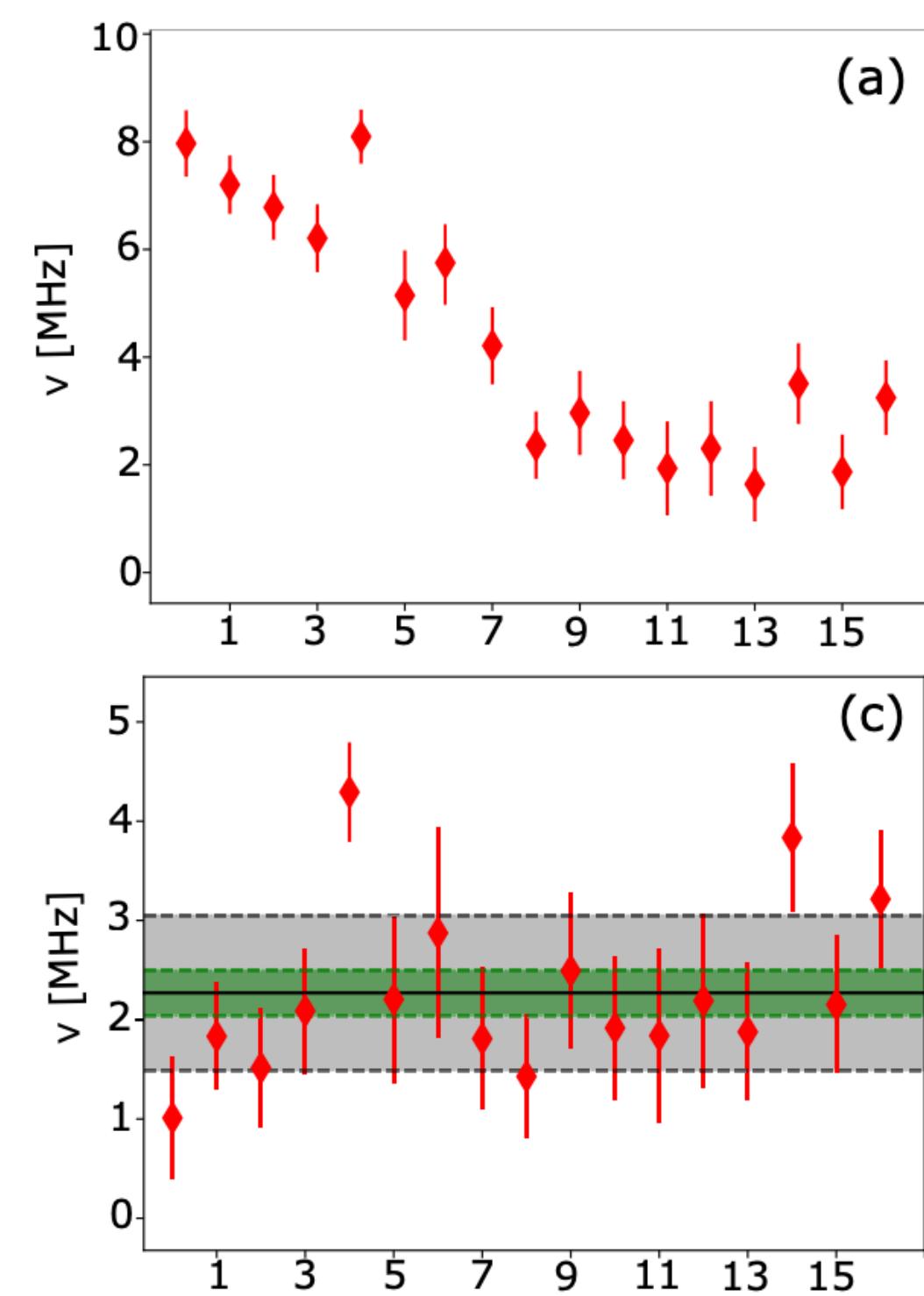
Hurdles on the way to measure ^{52}K

Investigate, improve and benchmark the precision and efficiency of the technique



The effect of high laser power, and timing of the laser pulses was carefully investigated.

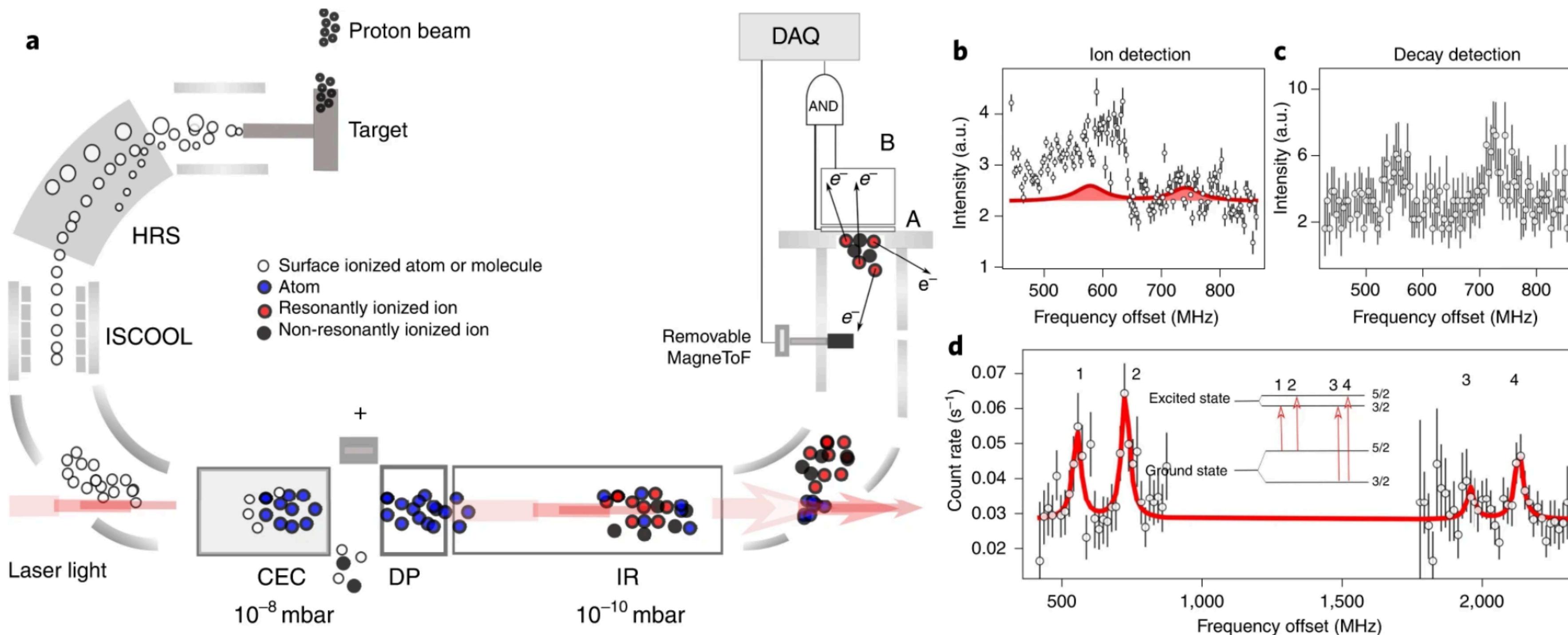
A procedure was developed for correcting the wavelength meter drifts and improve the precision of the technique.



Use of high-energy laser pulses leads to line-shape distortions. Delayed ionization removes this, but affects the efficiency.

Á. Koszorús et al., Phys. Rev. C **100**, 034304 – 2019

CRIS with decay detection



- 350 ion/s production rate for ^{52}K
- 10^6 ion/s isobaric contamination
- Changing proton current

CRIS combined with beta decay detection

Successful measurement of the hyperfine structure of $^{50-52}\text{K}$ with this technique.

Charge radii of neutron-rich potassium compared to theory

NNLO_{sat} fitted to properties of selected nuclei up to $A=25$

NNLO_{go} new interaction from chiral-effective field theory:

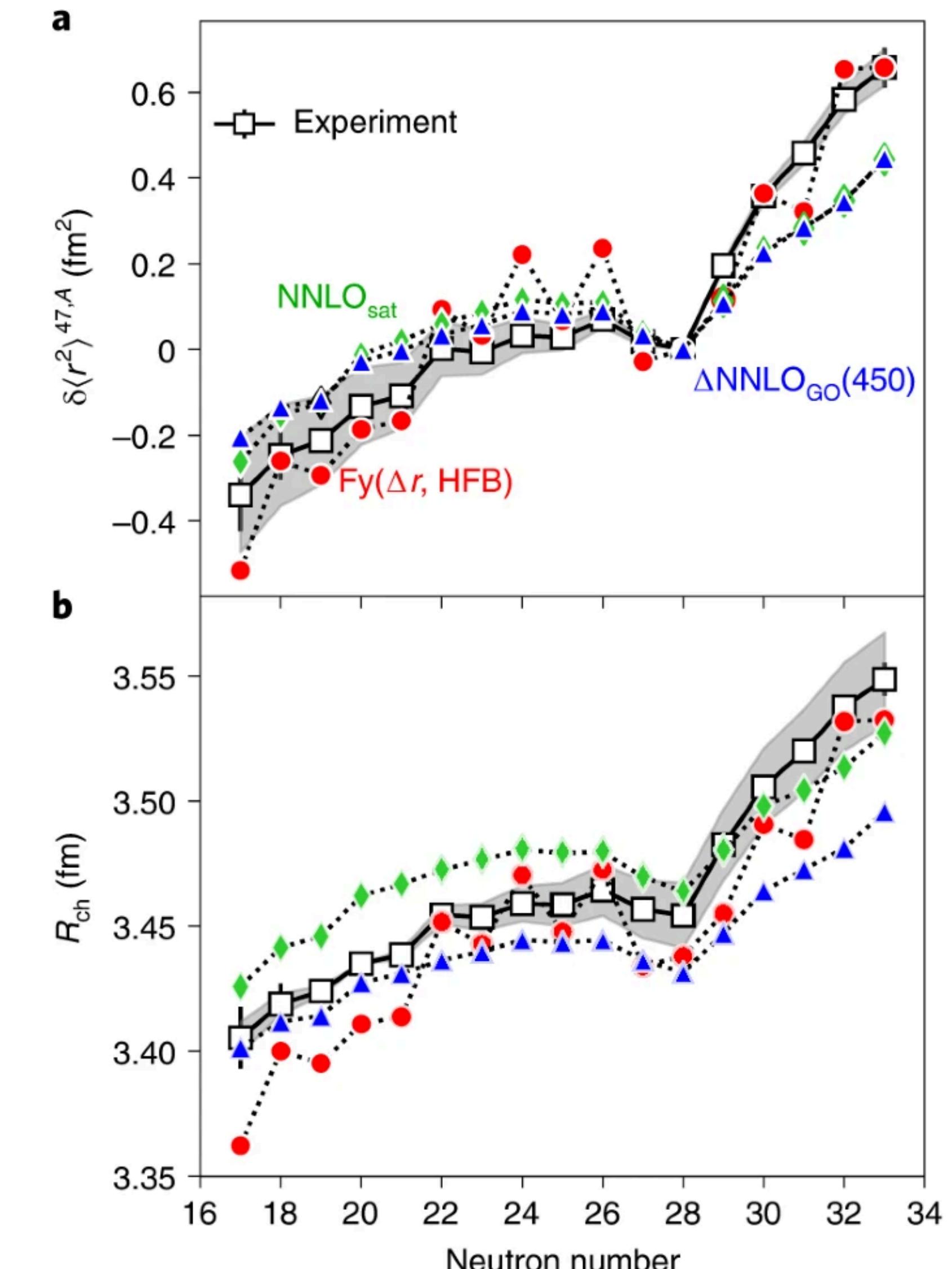
- Explicitly includes the $\Delta(1232)^1$ isobars
- fitted to the properties of $A \leq 4$ and **nuclear matter properties** (the saturation energy and density, and the symmetry energy of nuclear matter)

Fayans DFT (Δr , HFB) successful for Cu ($Z=29$), Cd ($Z=48$), Sn ($Z=50$), Ca ($Z=20$) and K ($Z=19$)

Two ab initio interactions - same results

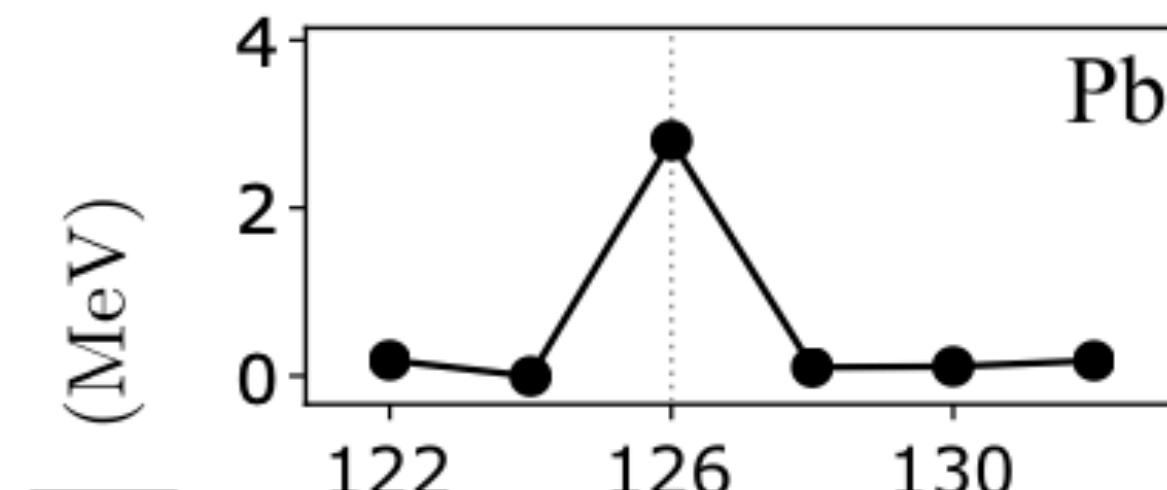
Missing many-body correlations?

[1] A Ekström, G Hagen, TD Morris, T Papenbrock, PD Schwartz
Physical Review C 97 (2), 024332

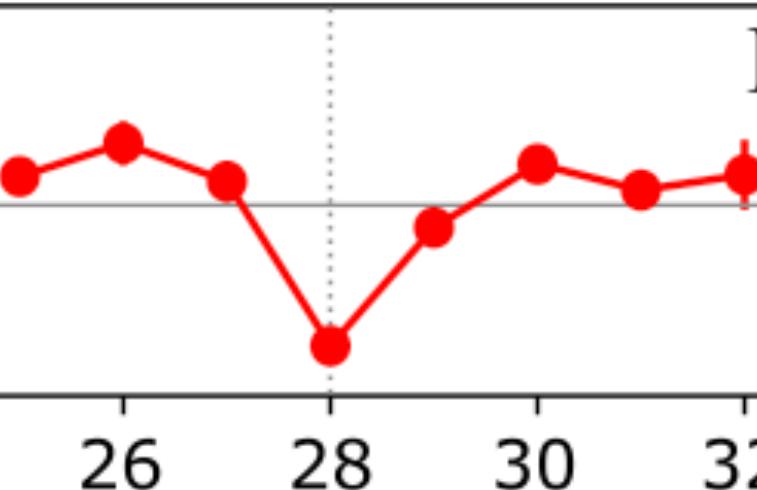
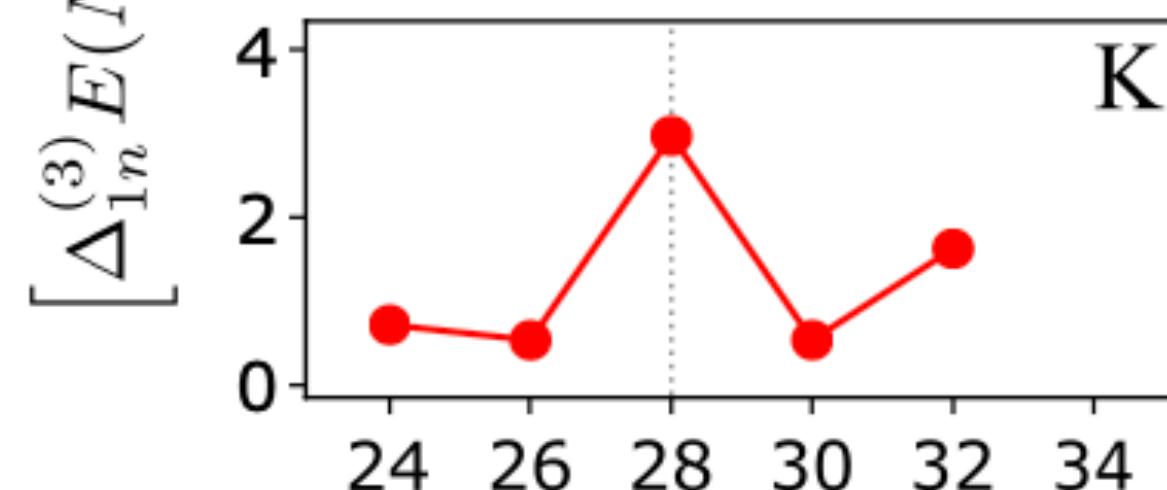
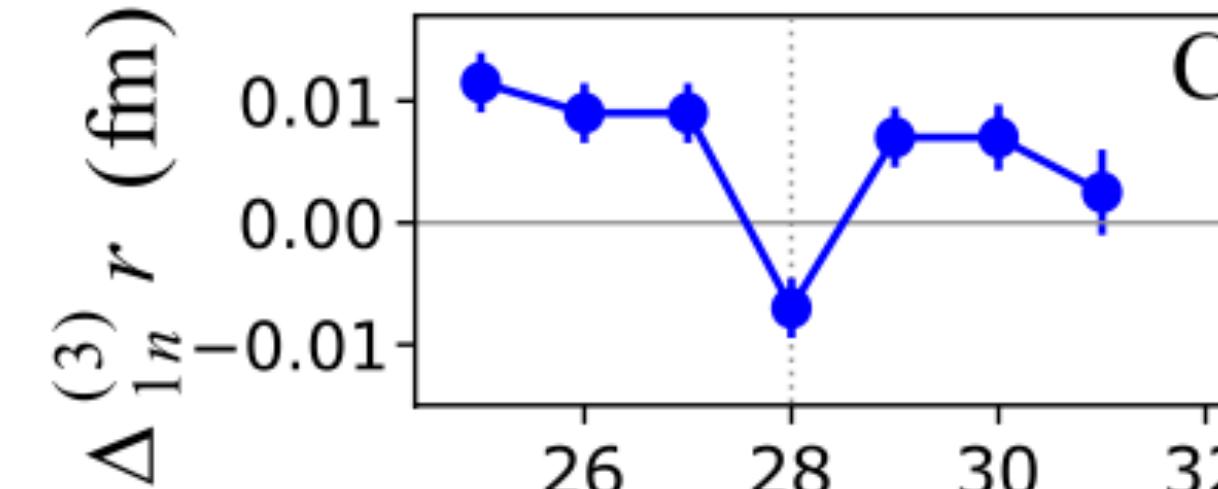
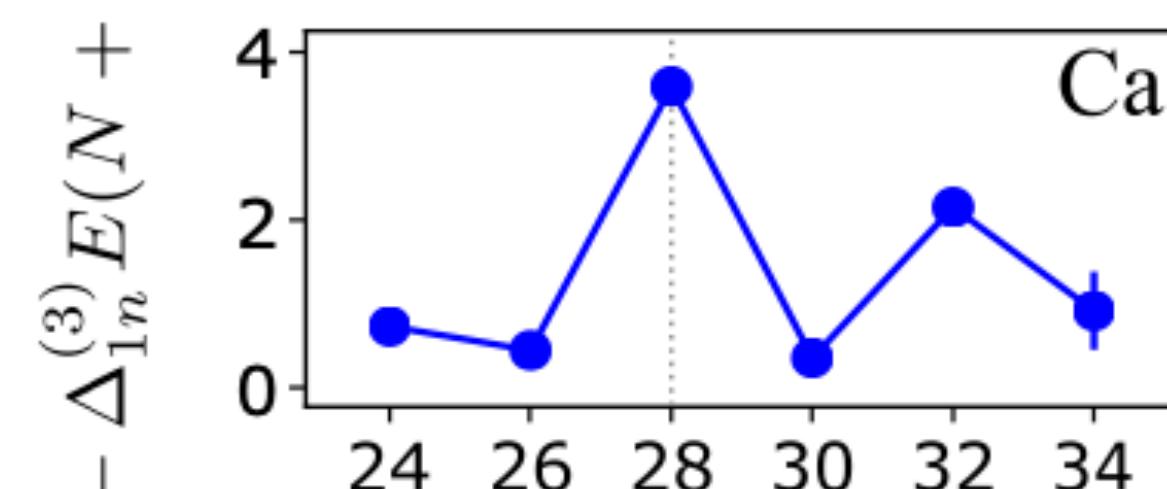
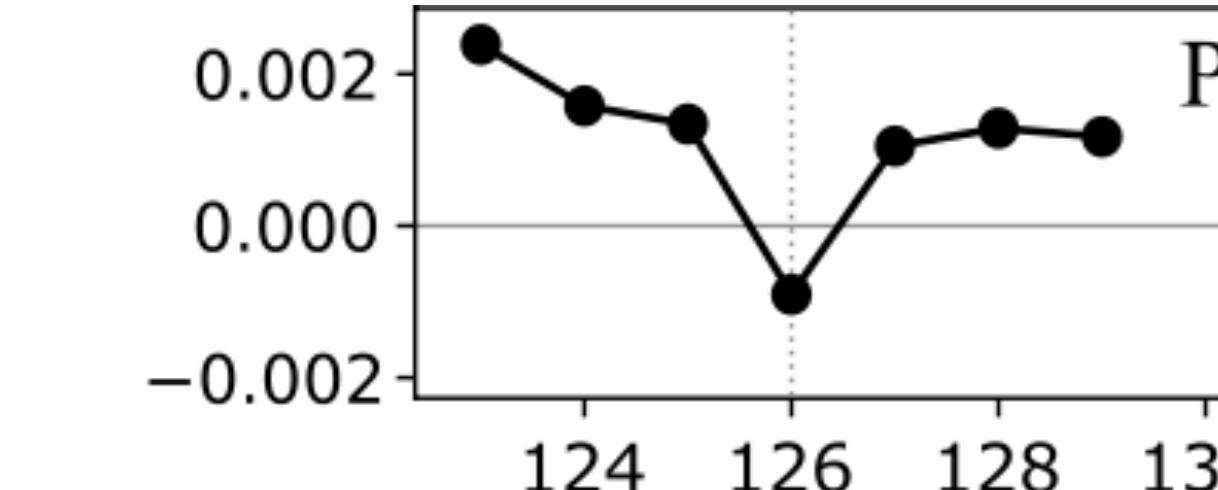


Charge radii of neutron-rich potassium

Binding energies



Charge radii



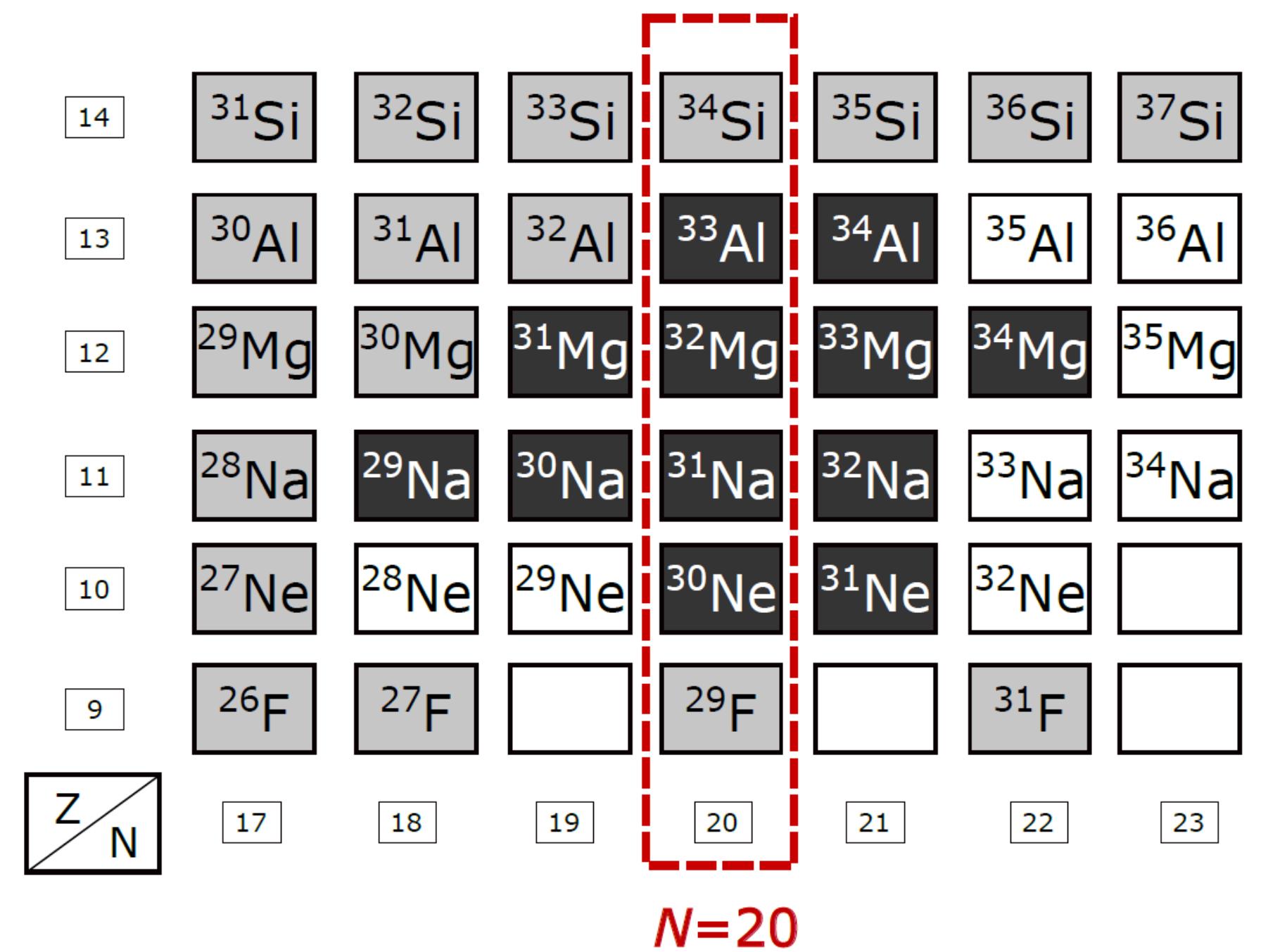
Three-point filter for the binding energies and the radii.

Typical example of magicity at $N=126$ and $N=28$.

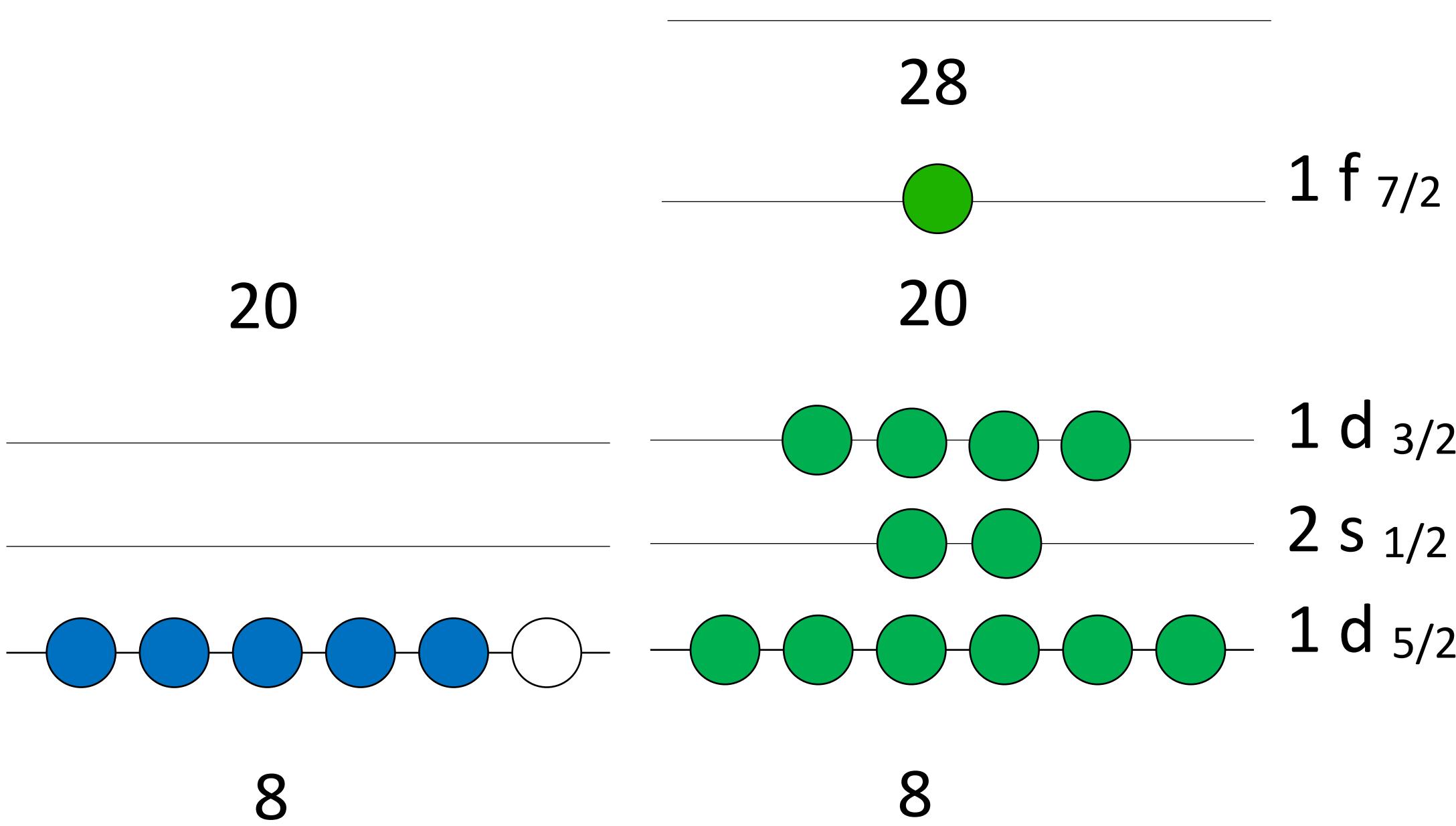
Both the binding energies and the measured radii across $N=32$ are consistent with a sub-shell closure at $N=32$.

Short excursion to the island of inversion at $N=20$

Charge radii on the edge of the island of inversion

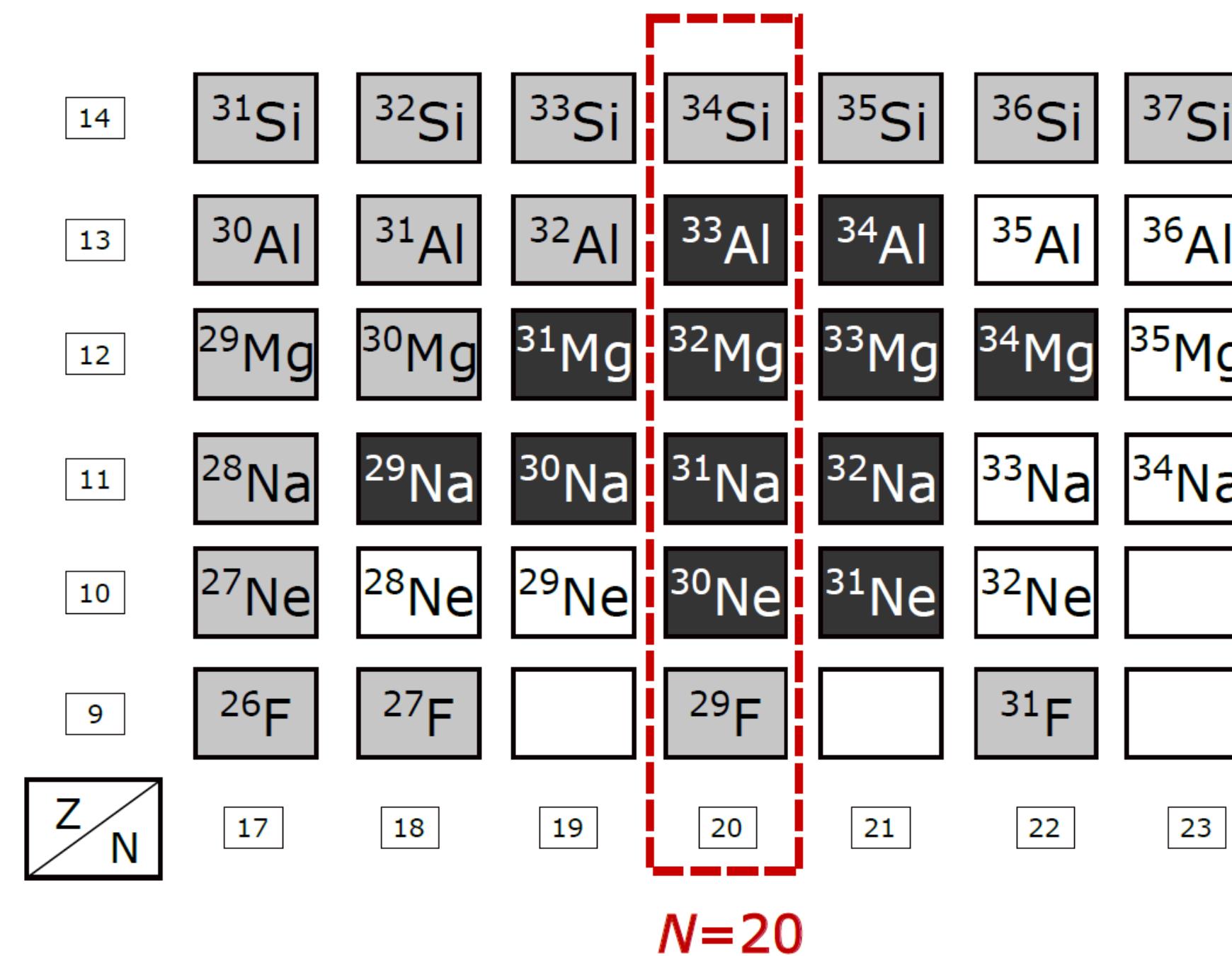


Aluminium chain wedged between Mg (inside the island of inversion) and Si (which is outside).

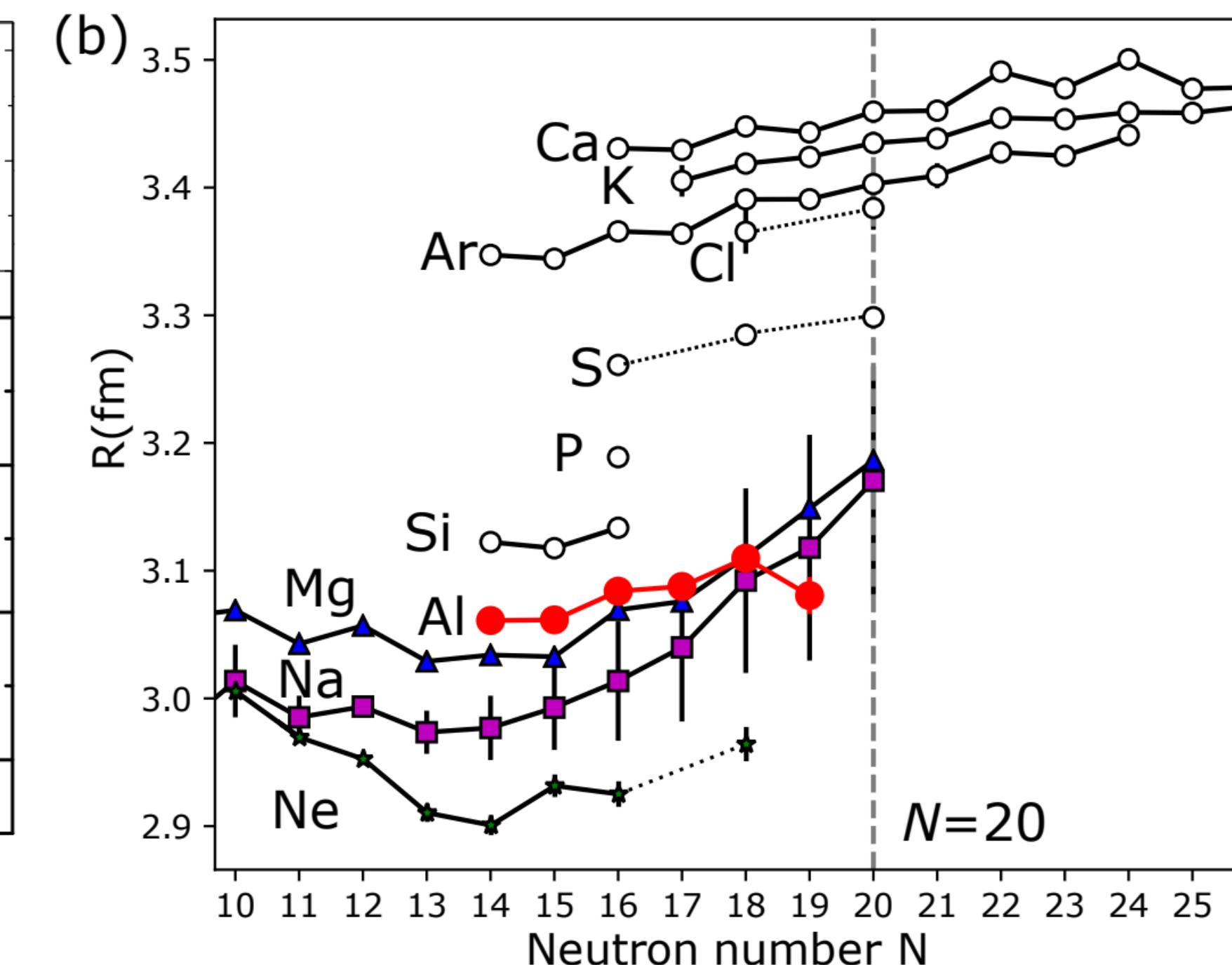
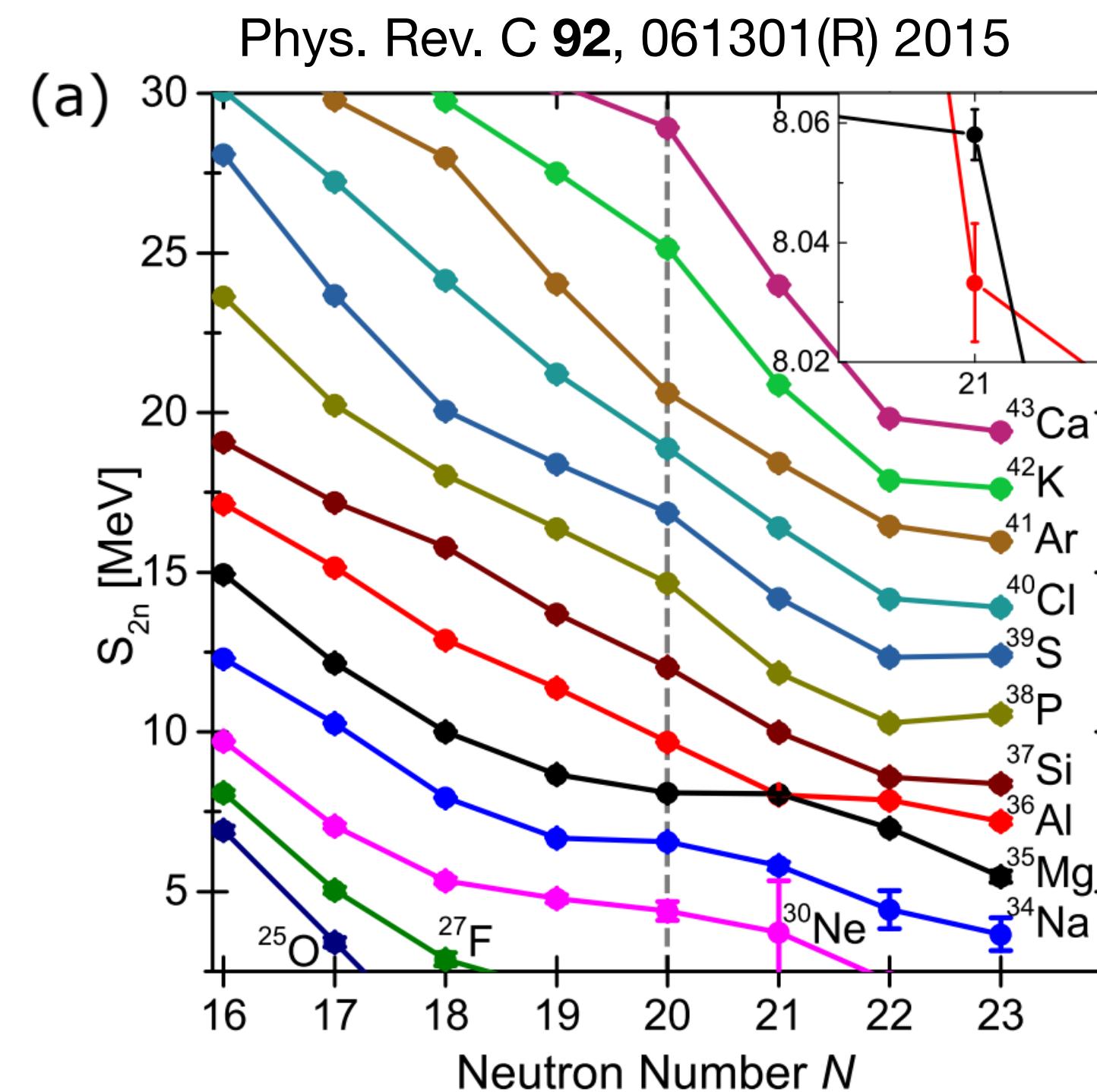


Naive picture of the structure of $^{33,34}\text{Al}$

Charge radii on the edge of the island of inversion



Aluminium chain wedged between Mg (inside the island of inversion) and Si (which is outside).

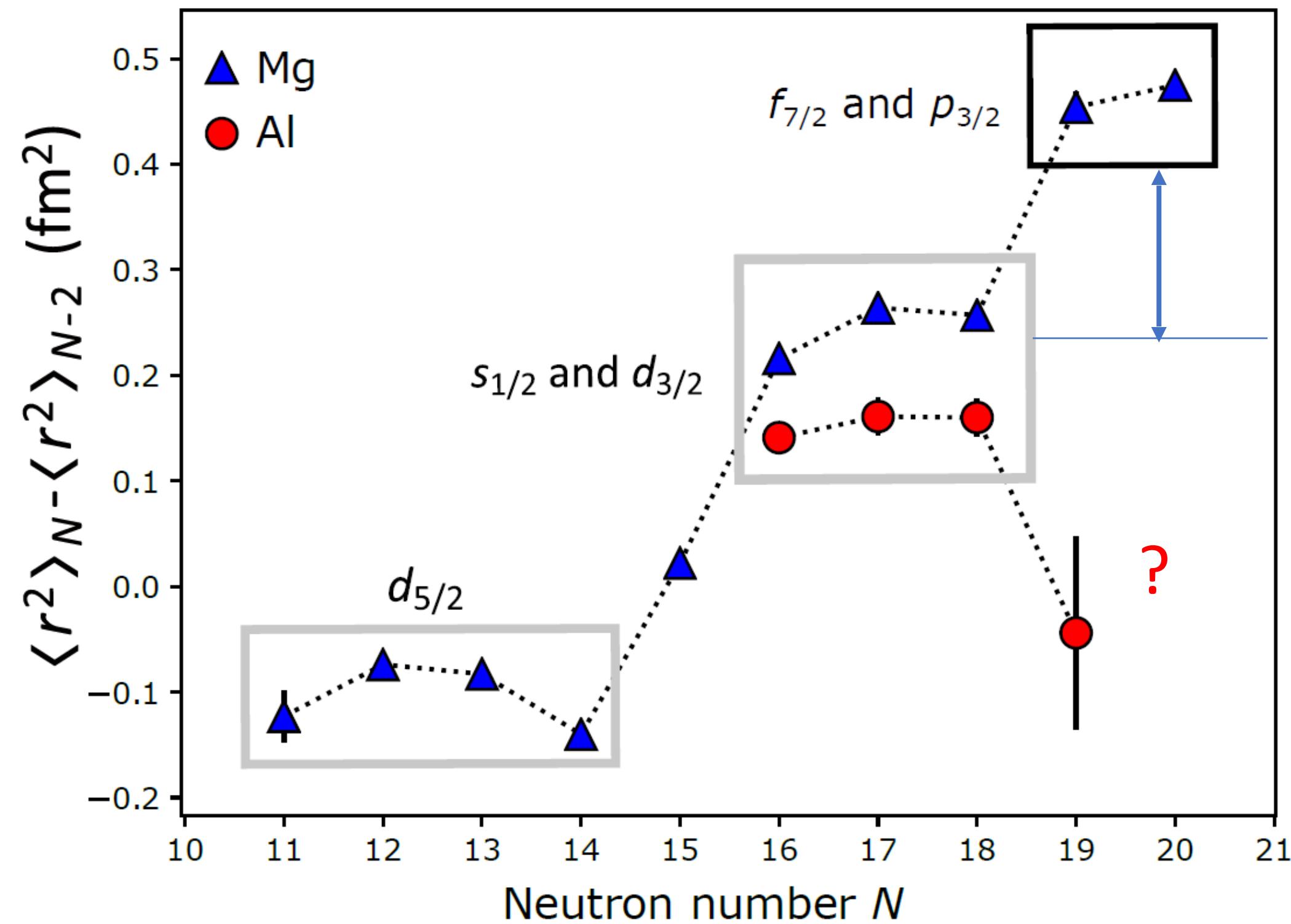


Clear signature of the lol in the binding energies.
No radius measurement beyond $N=20$ until Ar ($Z=18$).

[1] D.T. Yordanov et al. Phys. Rev. Lett. 108, 042504

[2] H. Heylen et al. Phys. Rev. C 103, 014318

Charge radii on the edge of the island of inversion



- The charge radii are sensitive to structural changes in the island of inversion and shell closures.
- A striking correspondence is found between the nuclear charge radius and the neutron shell structure [1].
- The onset of deformation is clear at $N=19$ in the Mg chain [1].
- The radius of ^{32}Al is unexpectedly small [2].

[1] D.T. Yordanov et al. Phys. Rev. Lett. 108, 042504

[2] H. Heylen et al. Phys. Rev. C 103, 014318

Charge radii on the edge of the island of inversion

- Experiment at CRIS this year.
- Technical difficulties prevented the precision measurements.
- Promising preliminary results.
- Production rates of ^{33}Al and ^{34}Al 450 and 150 cps respectively
- **Only a few hours of measurement resulted in reasonable spectra.**

The charge radii seem to show strong signature of the island of inversion.

More precise measurements are coming next year!

- New experiment focusing on $^{33,34}\text{Al}$ and possibly ^{35}Al as well.

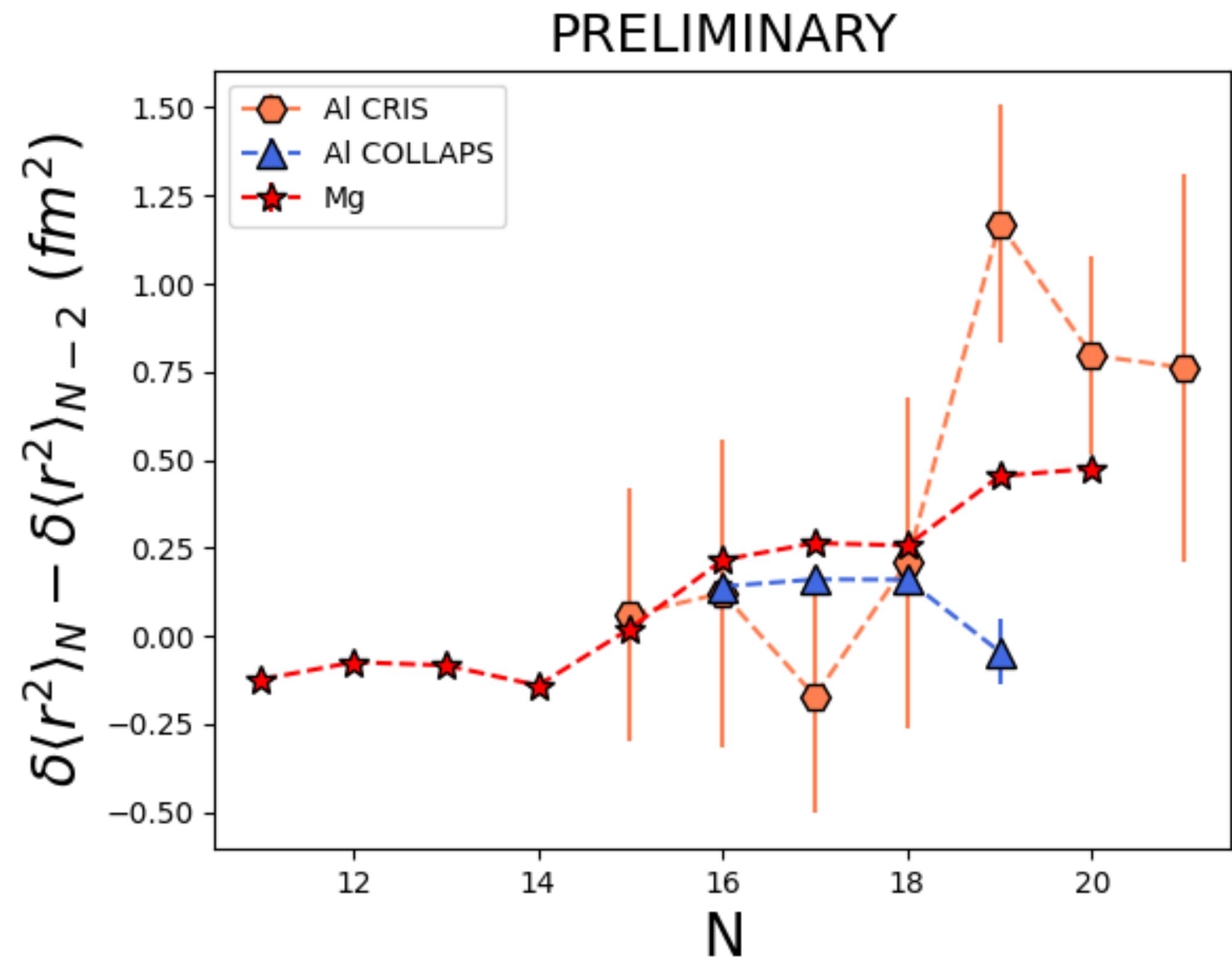
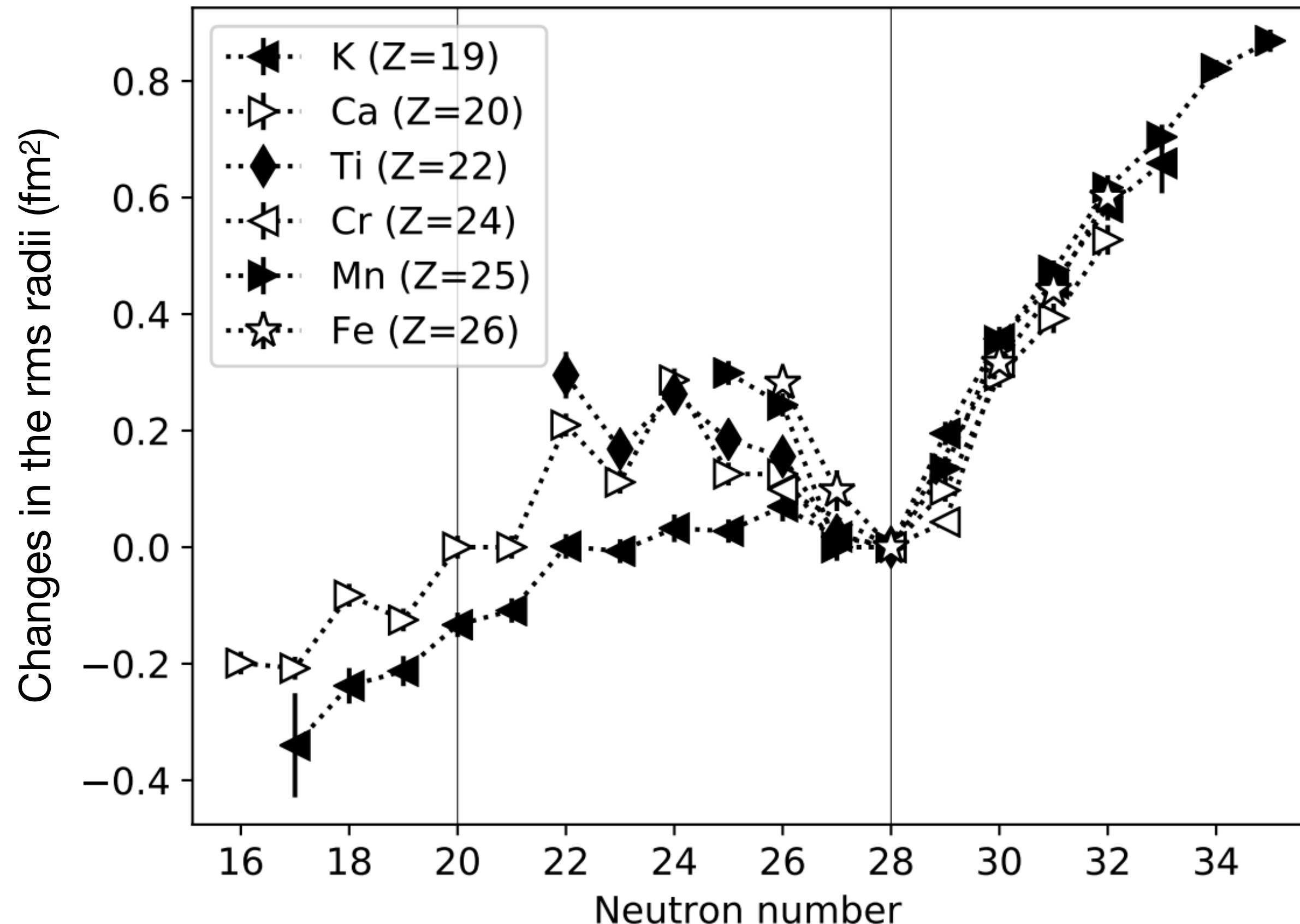


Figure made by Jordan R. Reilly (The University of Manchester)

Proton-rich landscape between $Z=20$ and $Z=28$

Collinear laser spectroscopy at IISOL

Proton-rich landscape between Z=20 and Z=28



Radii are sensitive to the structural changes in this region.

- Different slope
- Different **odd-even** staggering
- ⁴⁰Ca+alpha structure in ⁴⁴Ti
- **Self-conjugate nuclei**

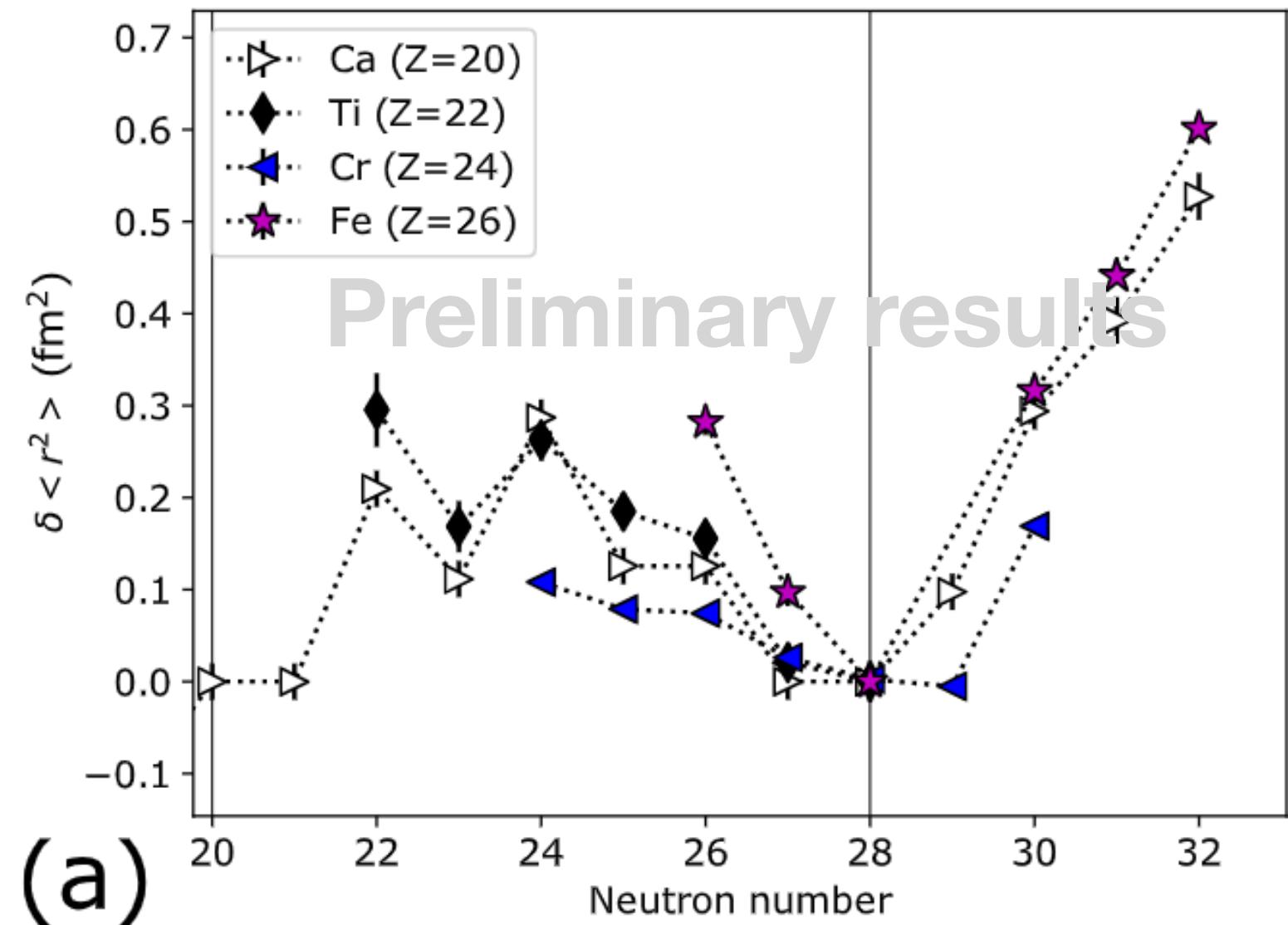
No Z-dependence above N=28

No measured data for radioactive V (Z=23), Cr (Z=24), Co (Z=27)
Limited data for Fe (Z=26)

**Difficult beams to produce
Complex atomic structure**

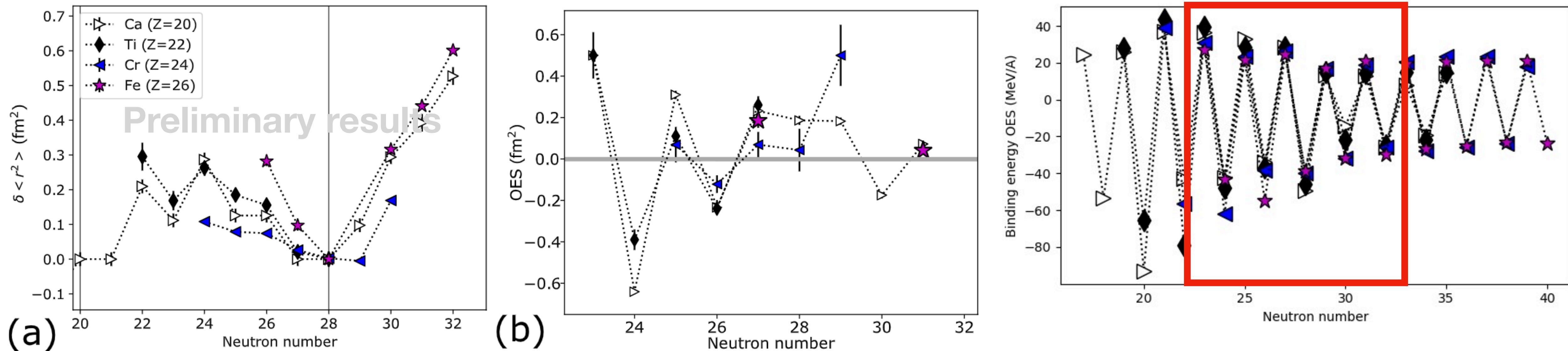
IGISOL (JYU) is the perfect place to explore the region!

Preliminary result of the Cr ($Z=24$) measurements



Charge radii seem to be smaller than the trends in the region suggest.

Preliminary result of the Cr ($Z=24$) measurements

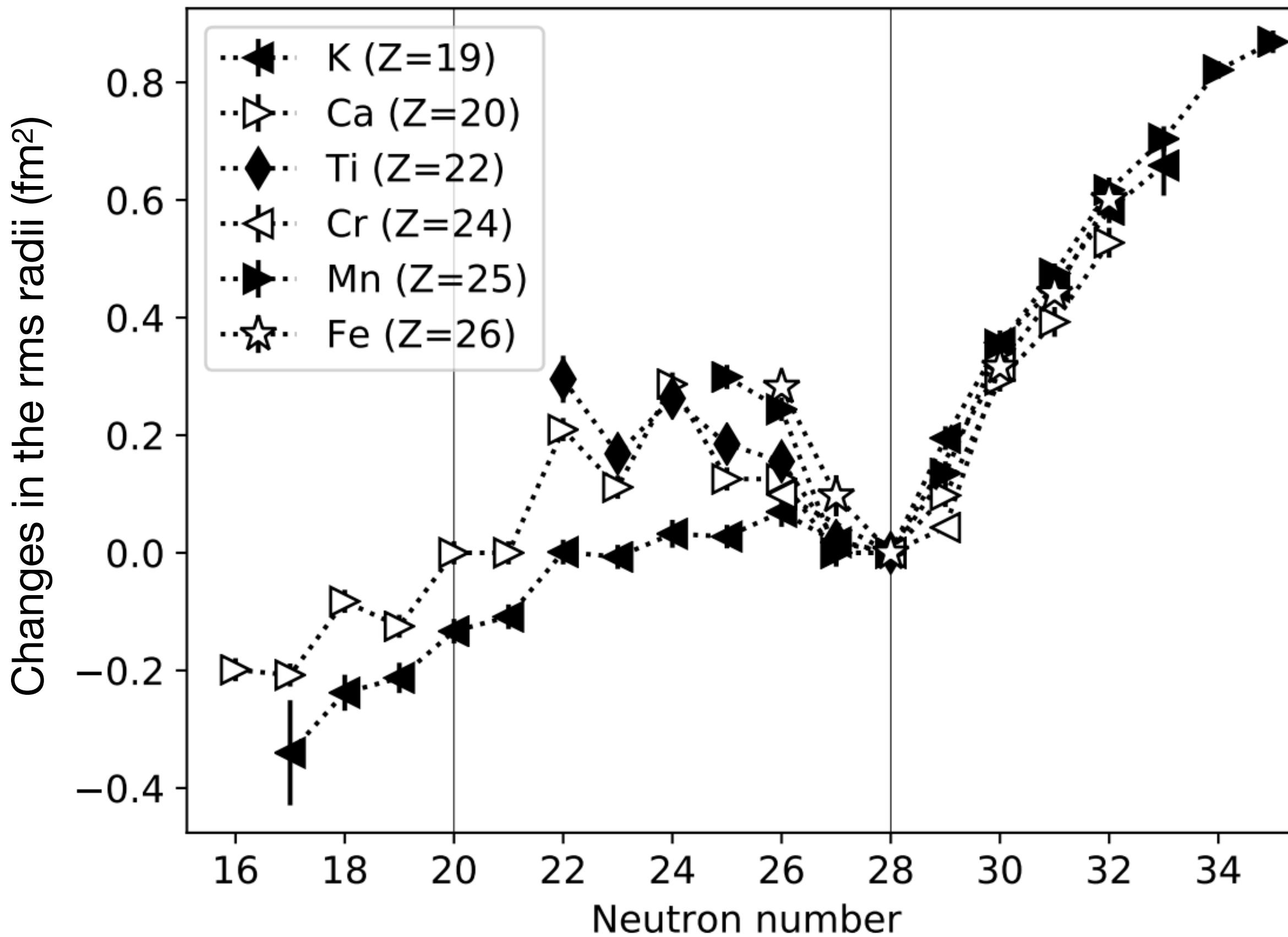


Charge radii seem to be smaller than the trends in the region suggest.

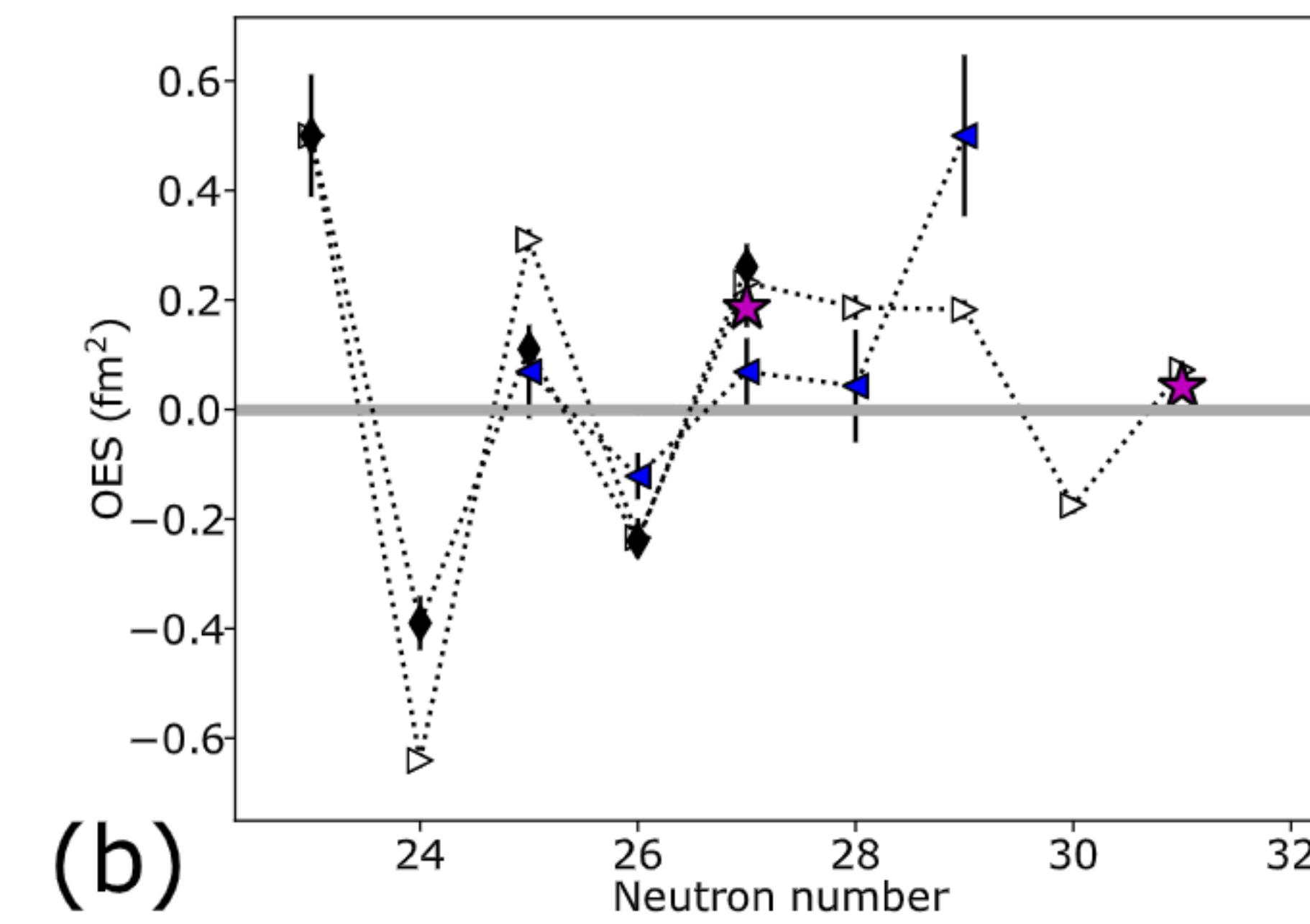
- **OES** is smaller than in Ca and Ti.
- For Fe there is not enough data arrive to a conclusion.

The OES of the bidding energies is not sensitive to the structural changes which greatly affect the radii.

Collinear laser spectroscopy of Co ($Z=27$) and Fe ($Z=26$)



- Charge radii and OES of radioactive Co isotopes
- Odd-even staggering in the Fe chain



(b)

Collinear laser spectroscopy of Co and Fe

- $^{54}\text{g,mCo}$ and $^{58}\text{g,mCo}$

Isospin symmetry and isomer shifts in the vicinity of the $N=Z=28 \rightarrow$ Á. Koszorús et al.
Physics Letters B 819 136439 (2021)

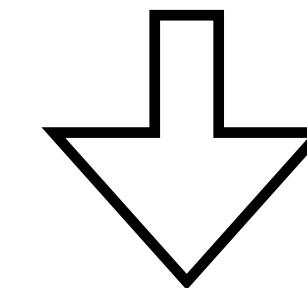
- Study of the nuclear deformation and the (purity of) configuration by extracting the nuclear moments
- $^{53}\text{g,mFe}$ at IGISOL - mirror nucleus of $^{53}\text{g,mCo}$ isotope with the proton-emitting isomer

Ground and isomeric state information for $^{54}_{27}\text{Co}$

E(level) (MeV)	Jπ	Mass Excess (keV)	T _{1/2}	Decay Modes
0.0	0+	-48010.1 4	193 ms 7	$\varepsilon = 100.00\%$
0.1971	7+	-47813.0 4	1.48 m 2	$\varepsilon = 100.00\%$

Ground and isomeric state information for $^{53}_{26}\text{Fe}$

E(level) (MeV)	Jπ	Mass Excess (keV)	T _{1/2}	Decay Modes
0.0	7/2-	-50947.5 17	8.51 m 2	$\varepsilon = 100.00\%$
3.0404	19/2-	-47907.1 17	2.54 m 2	IT = 100.00%

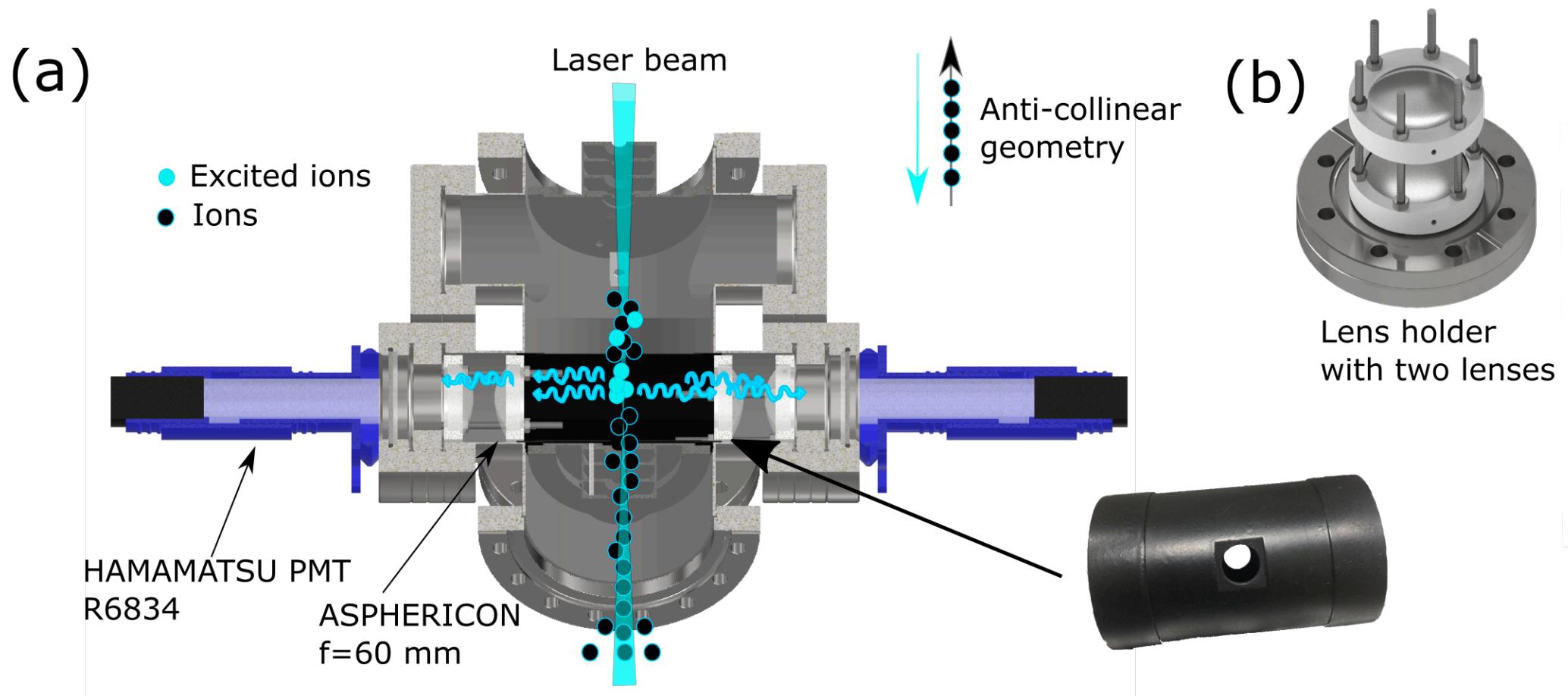


Ground and isomeric state information for $^{53}_{27}\text{Co}$

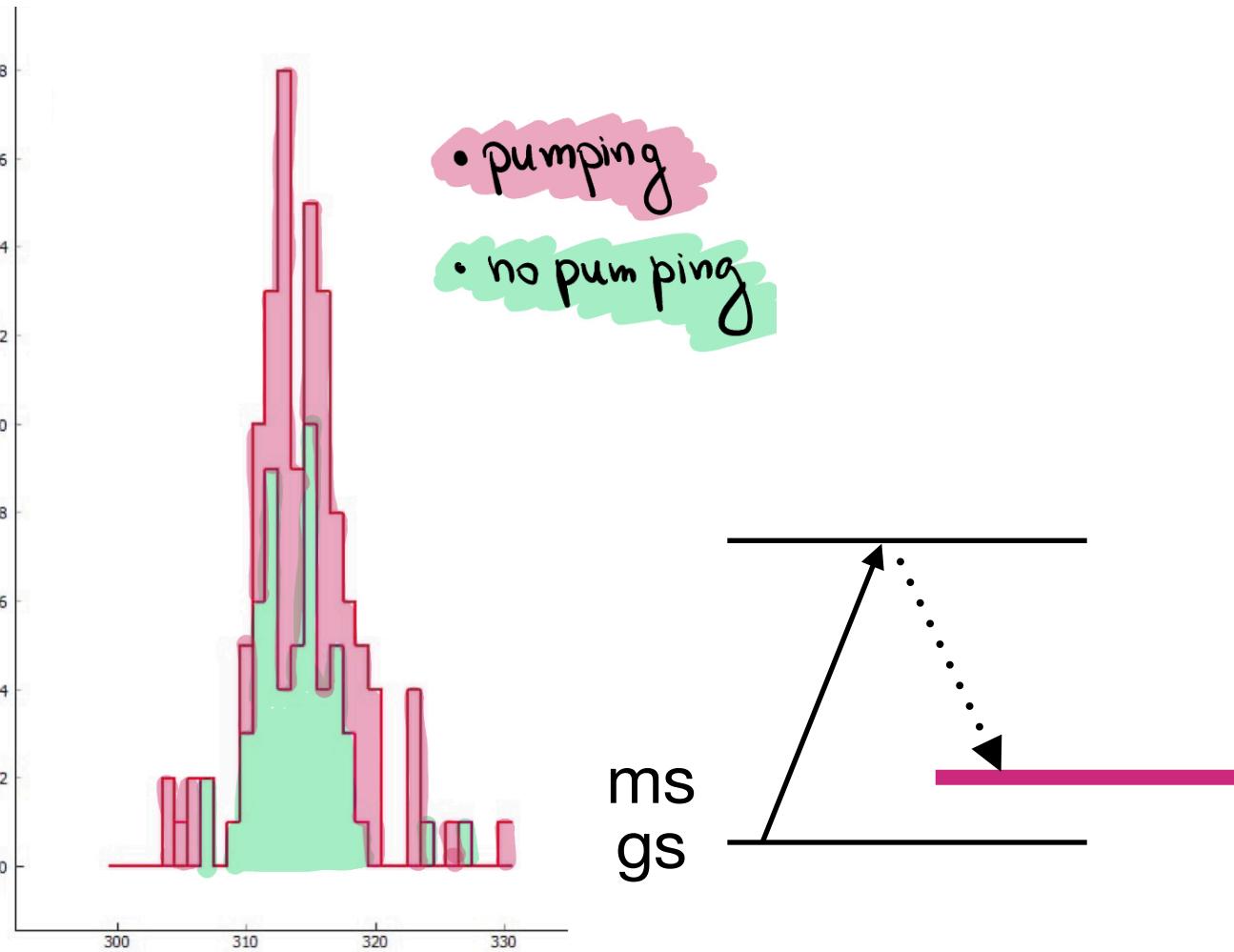
E(level) (MeV)	Jπ	Mass Excess (keV)	T _{1/2}	Decay Modes
0.0	(7/2-)	-42659.4 17	240 ms 20	$\varepsilon = 100.00\%$
3.1970	(19/2-)	-39462.4 17	247 ms 12	$\varepsilon \approx 98.50\%$ $p \approx 1.50\%$

Collinear laser spectroscopy of $^{54,55,57-59}\text{Co}$ and $^{53-58}\text{Fe}$

- Complicated atomic structure: development of an efficient way to study Co and Fe
- New, flexible light collection region for improved efficiency and wider spectral range
- Excellent signal to background in the new system
- Optical pumping in the cooler for Co doubled the efficiency

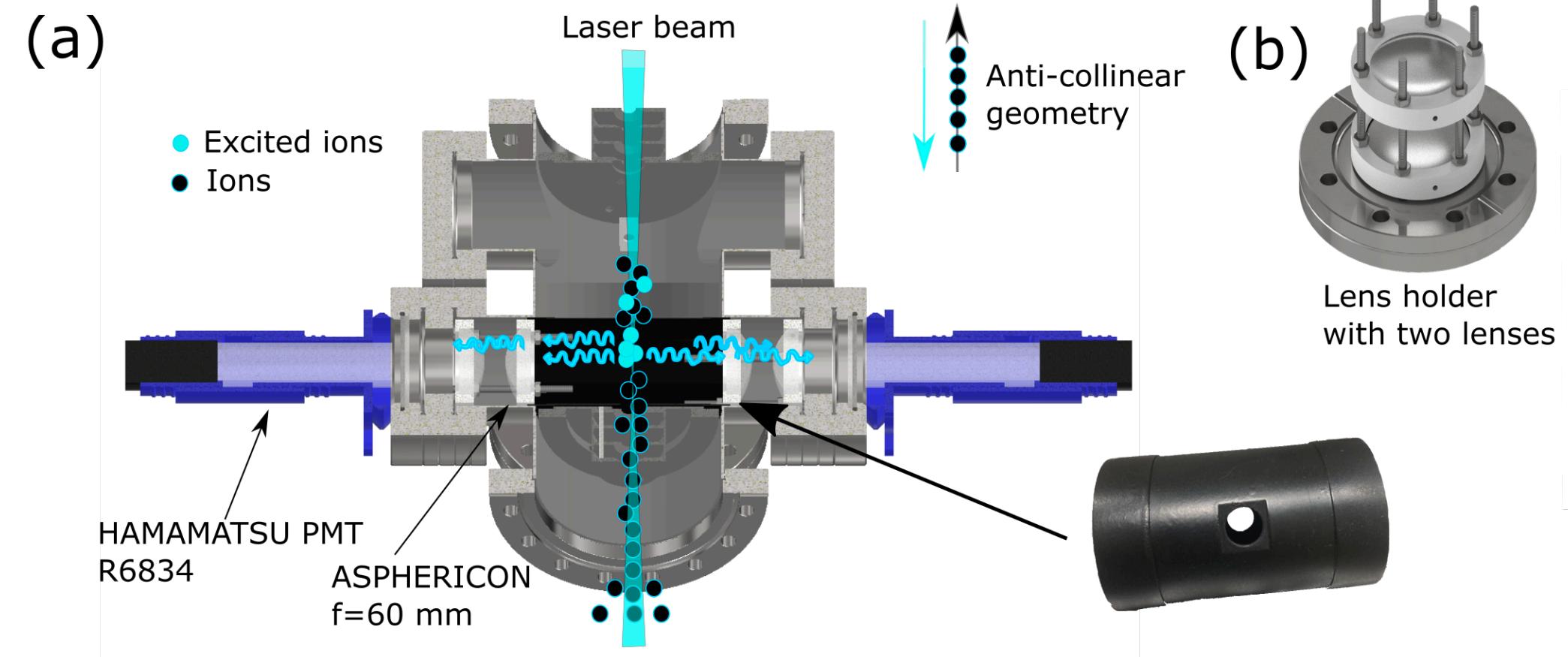


Á. Koszorús et al. in preparation

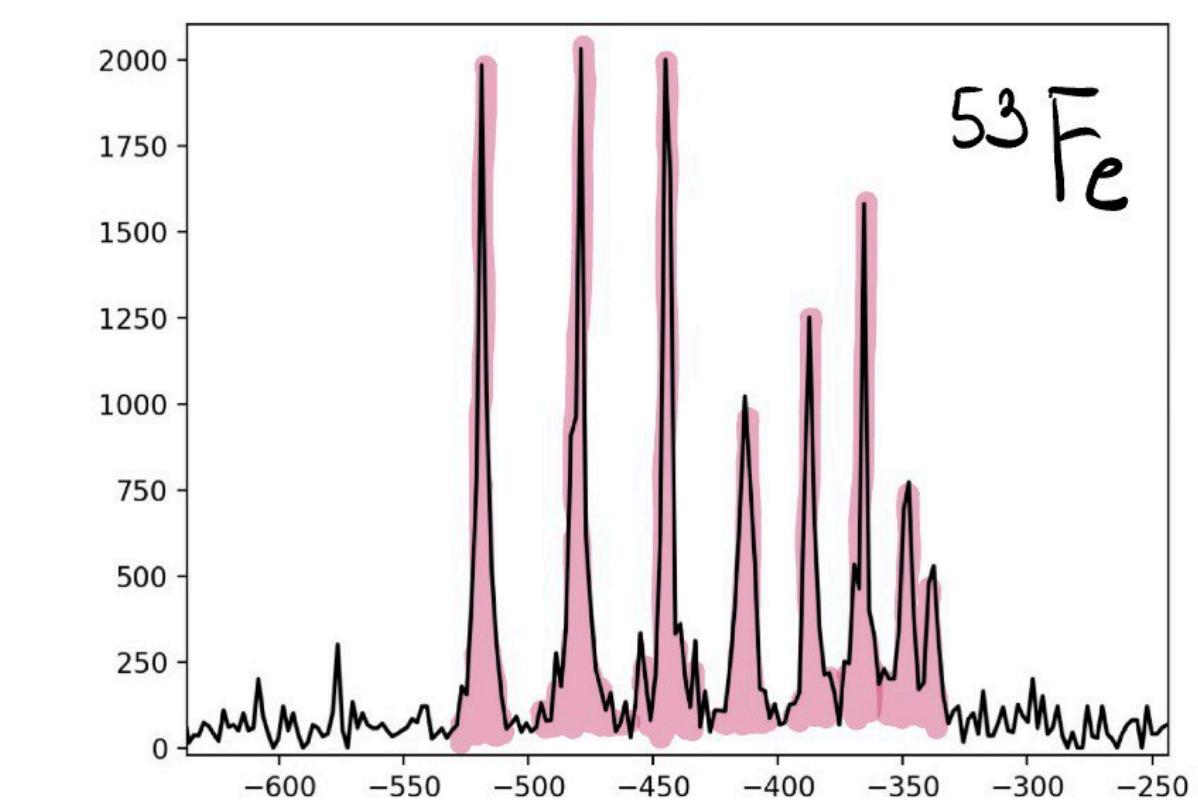
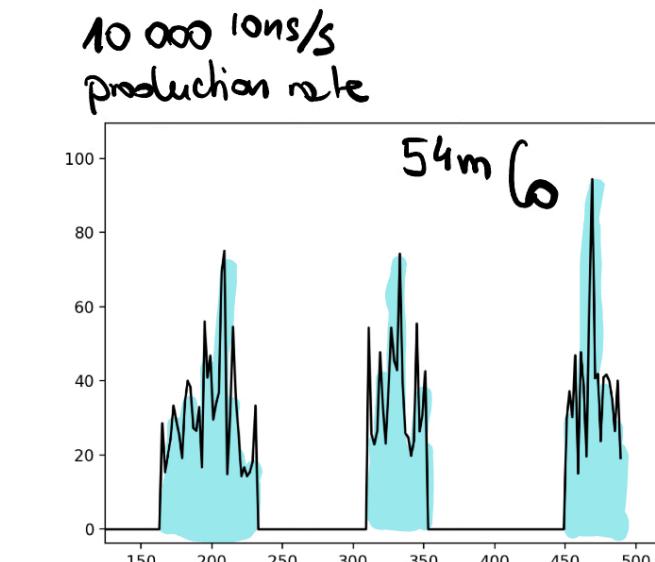
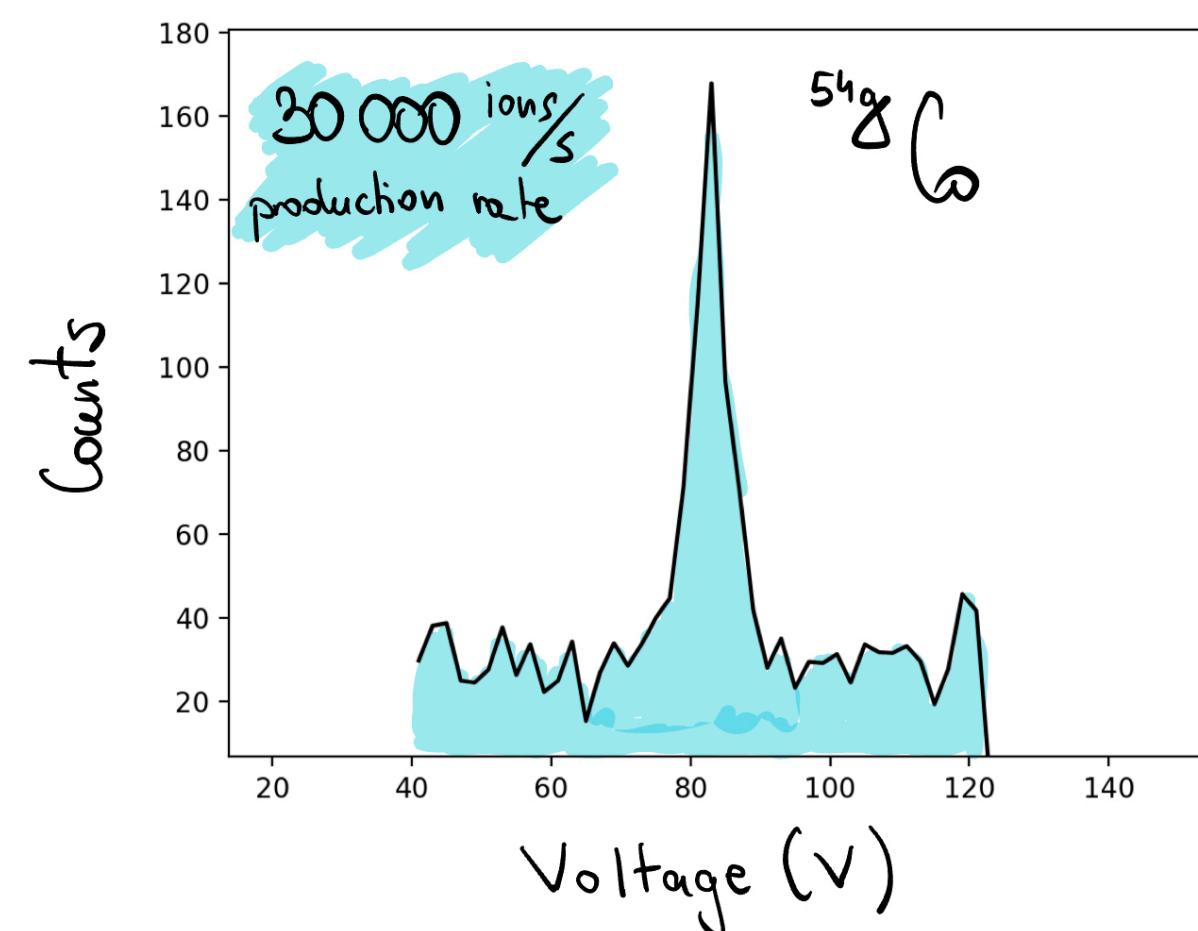
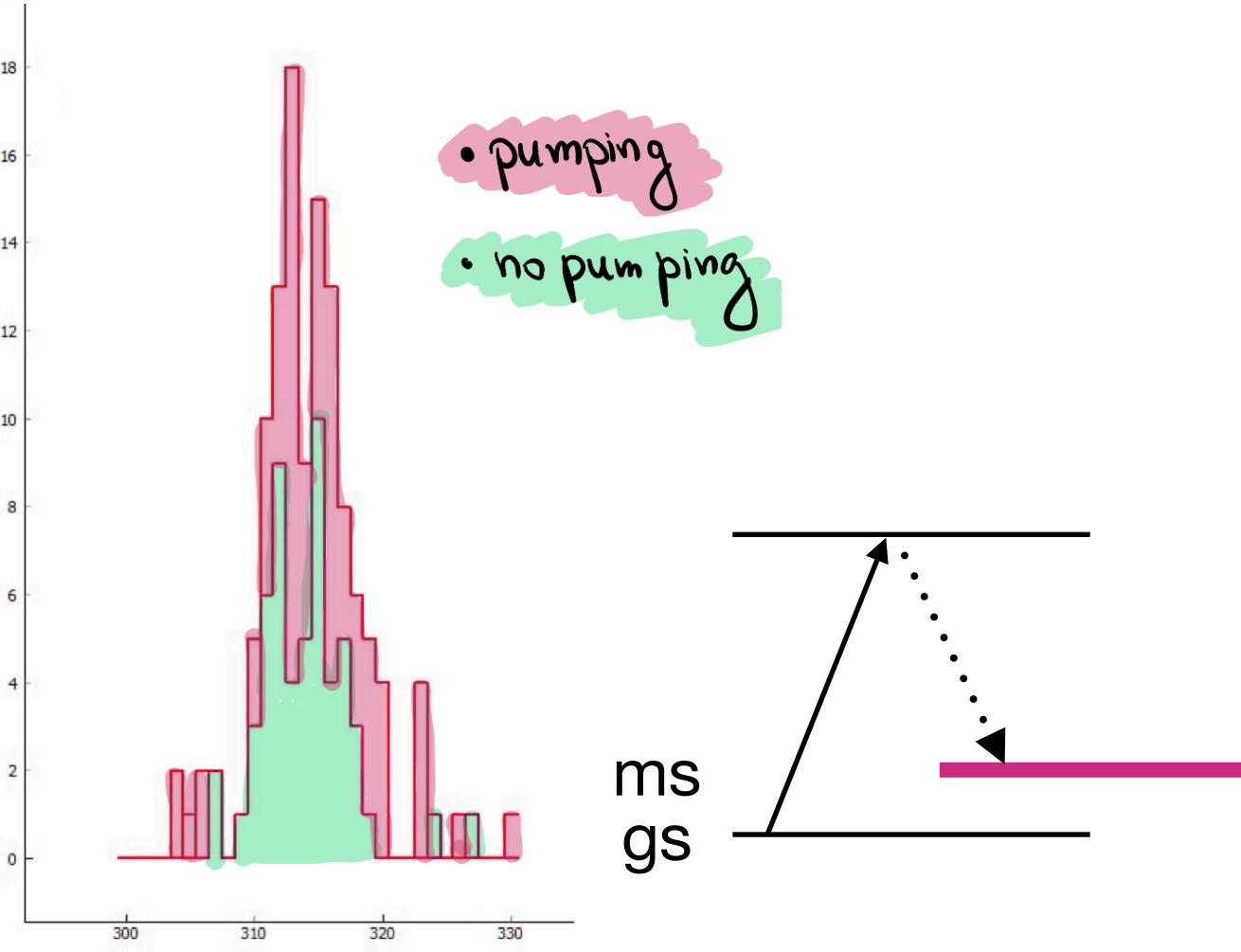


Collinear laser spectroscopy of $^{54,55,57-59}\text{Co}$ and $^{53-58}\text{Fe}$

- Complicated atomic structure: development of an efficient way to study Co and Fe
- New, flexible light collection region for improved efficiency and wider spectral range
- Excellent signal to background in the new system
- Optical pumping in the cooler for Co doubled the efficiency



Á. Koszorús et al. in preparation



And what is ahead ...



New ISOL facility in Belgium ISOL@MYRRHA

Operating parameters of ISOL@MYRRHA:

- 100-MeV protons
- 250 Hz pulse-repetition rate
- Up to max 0.5 mA beam current on ISOL target
- Up to 25 kW in-target power deposition

- Ideal place for precision measurements which normally require weeks of beamtime
- Laser(-RF) spectroscopy setup
- Delivery of polarised ion beams
- Traps for ion beam preparation
- There enough space to implement new experiments taking advantage of the unique aspects of this facility!

Summary

Charge radius of K isotopes across $N=32$ - CRIS + decay detection

No signature of the shell closure in the radii

State-of-the-art coupled cluster calculation underestimate the size of neutron rich isotopes

Charge radii of Al isotopes across $N=20$

Preliminary results suggests a jump in the radii, similarly to Mg in the island of inversion

New light collection region at IGRISOL for the study of Fe ($Z=26$) and Co ($Z=27$)

Cr results deviate from the expected trend

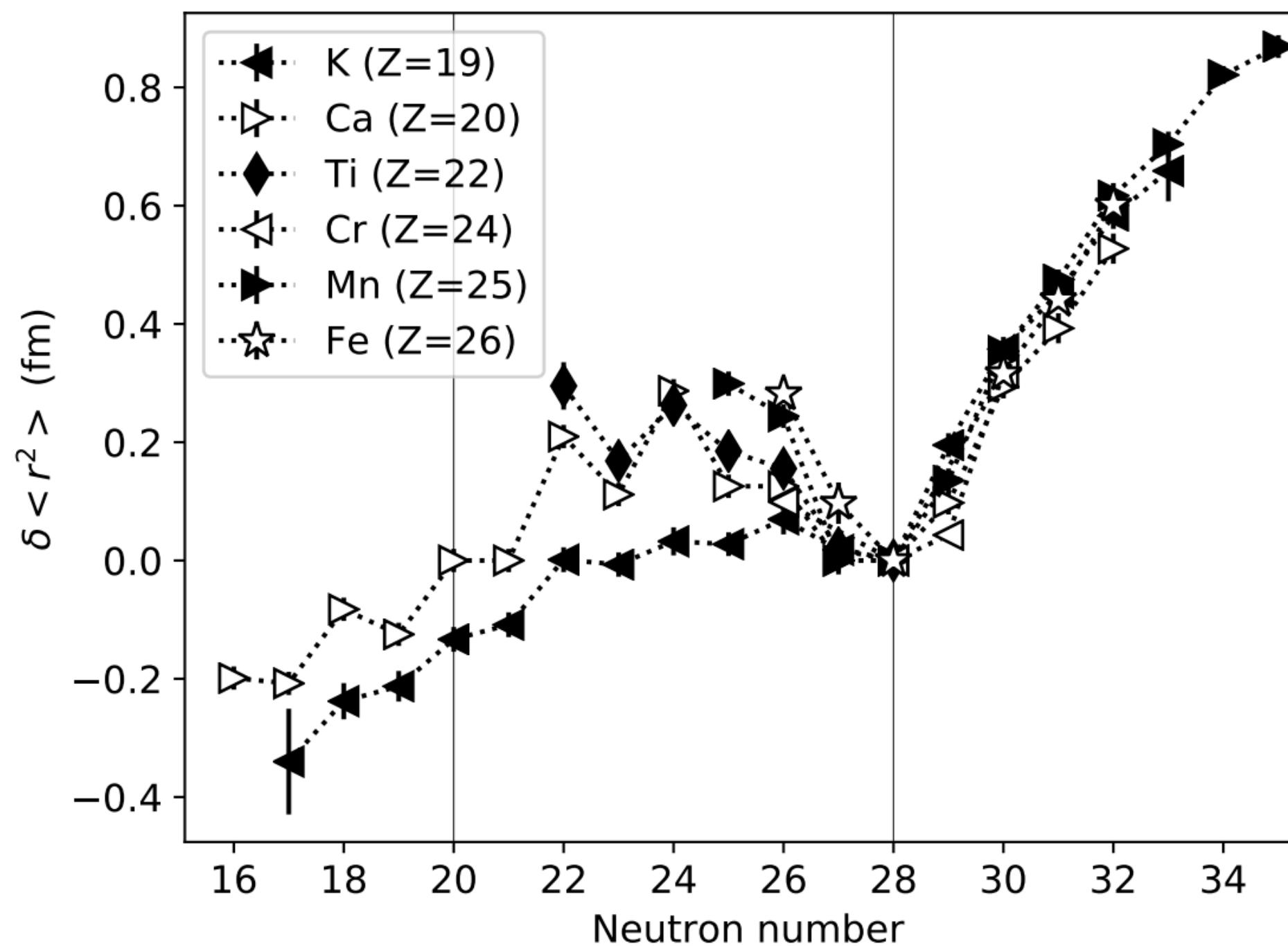
First laser spectroscopy on radioactive Co performed

Thank you for your attention

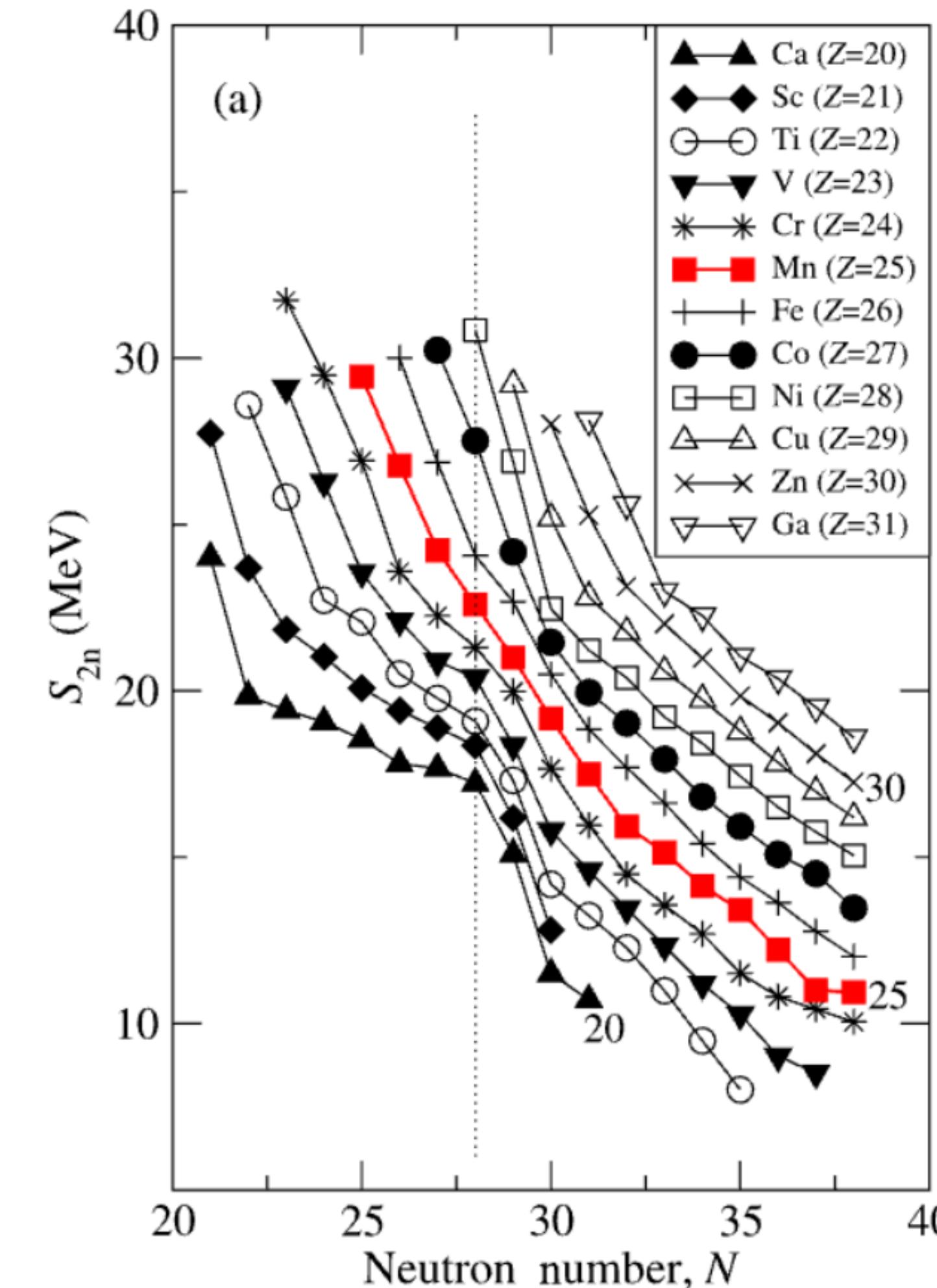
Also thanks to **Gerda Neyens, Bradley Cheal, Iain Moore, Paul Campbell, Ruben de Groote, Kieran Flanagan, X.F. Yang, old and new members of the CRIS Collaboration, ISOLDE and IGISOL; W. Nazarewicz, P.-G. Reinhard, Gaute Hagen, A. Ekström, C. Forssén, M. Kortelainen, T. Papenbrock, B. Sahoo, and many others** who supported our work

Evolution of the signatures of (sub)shell closures

(Relevant for this presentation)



- Changes in the mean-squared charge radii:
- No sign of shell closure at $N=20$
- Clear signature of shell closure at $N=28$, remains the same from $Z=20$ until $Z=28$

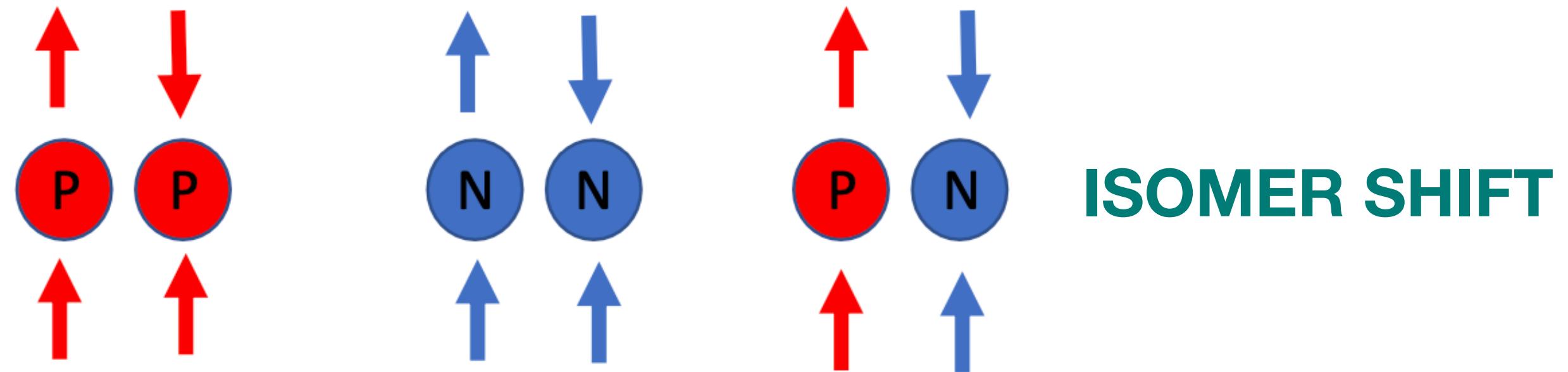


Unlike the radii, a clear evolution is seen in the S_{2n} - No sign of the shell structure at $N=28$ in Mn.

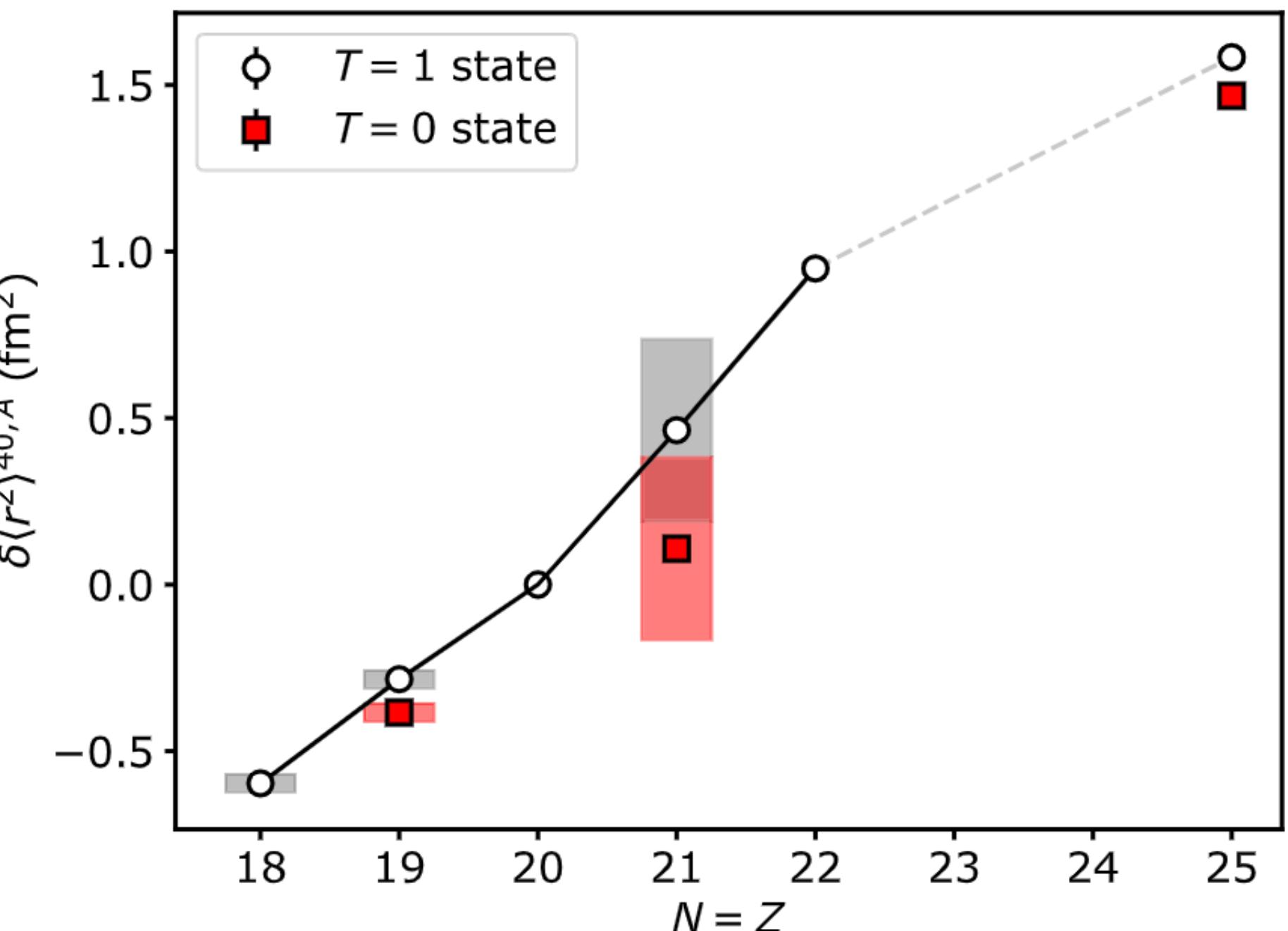
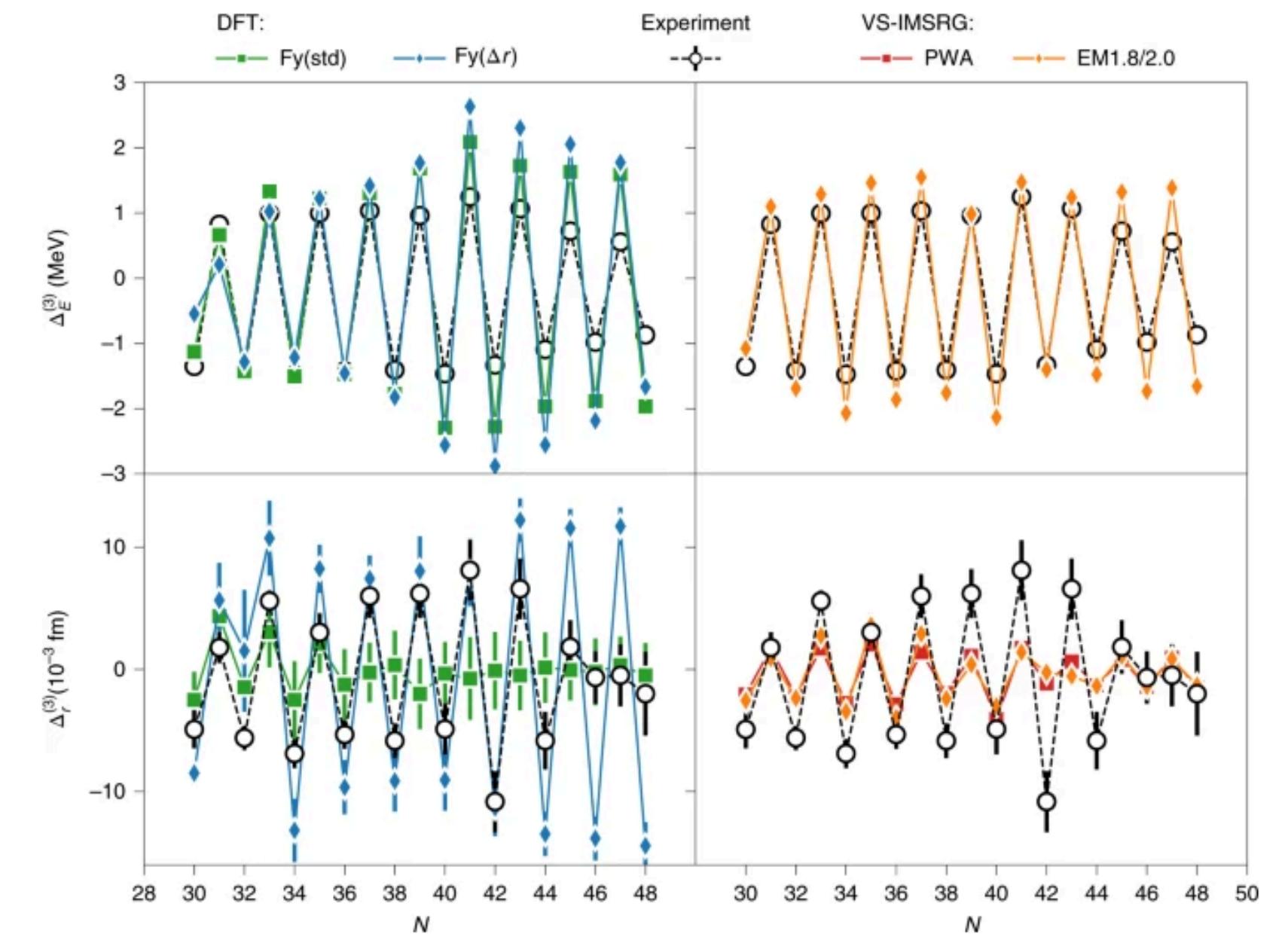
Recent development in theoretical calculation allow for these two observable to be discussed alongside each other.

Reproducing and predicting both at the same time remains a challenge.

The self-conjugate ^{42}Sc

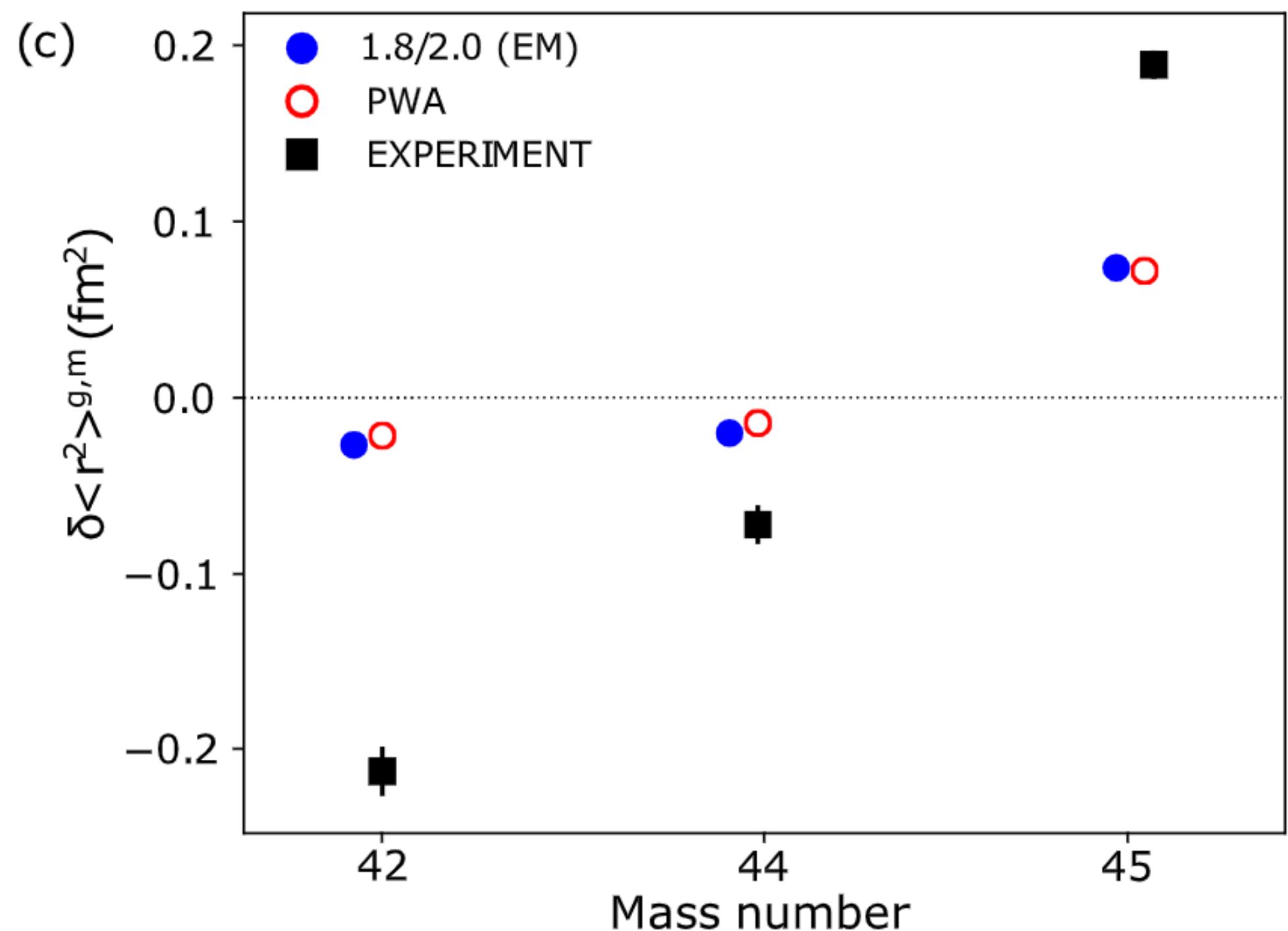


- Only 1 case has been studied before, ^{38}K $d_{3/2}$
(Phys. Rev. Lett. 113, 052502, 2014)
- The isomer shift of the $T=0$ and $T=1$ states in self conjugate nuclei was understood based on a simple picture of proton-neutron pairing, similar mechanism as for the odd even staggering.
- **Theory worked remarkably well for ^{38}K**
- $T=1, I=0$ state always larger \rightarrow works for ^{42}Sc as well!
- VS-IMSRG calculations accurately described the odd-even staggering in Cu – **Does it work for isomer shifts?**



The self-conjugate ^{42}Sc

- Very simple system: 1 proton and 1 neutron outside the ^{40}Ca core
- Other Sc isotopes have a more complicated structure
- Moments predicted by naive back of the envelope calculations
- The isomer shift in ^{42}Sc challenges this simple picture.
- Shell model underestimates it by more than a factor two
- VS-IMSRG underestimates the value by almost an order of magnitude
- Soon new data for the self-conjugate $^{26g,m}\text{Al}$ - relevant for determination for V_{UD} (collaboration between COLLAPS and IGISOL)
- Isomer shift of $^{54g,m}\text{Co}$



Á. Koszorús et al. Physics Letters B 819 136439 (2021).

Co (and Fe)

- Only 1 charge radius is known
- 1 proton hole in the Ni core
- Isomers, and the self-conjugate ^{54}Co
- **Proton emitter isomer in ^{53}Co**

Charge radius and moments never measured for such a system

- **Complex atomic (ionic) properties**
- Most suitable transitions in the ions are in the 220 nm – 240 nm range or around 206 nm
- Ground state is not sensitive to the charge radii
- **Offline test are needed using the stable Co isotope**
- A new light collection region is needed!

