Evolution of ground state properties of Chromium isotopes from stability to the *N* = 40 Island of Inversion

Louis Lalanne

IPHC / CNRS

CRIS Collaboration meeting

31/01/2024

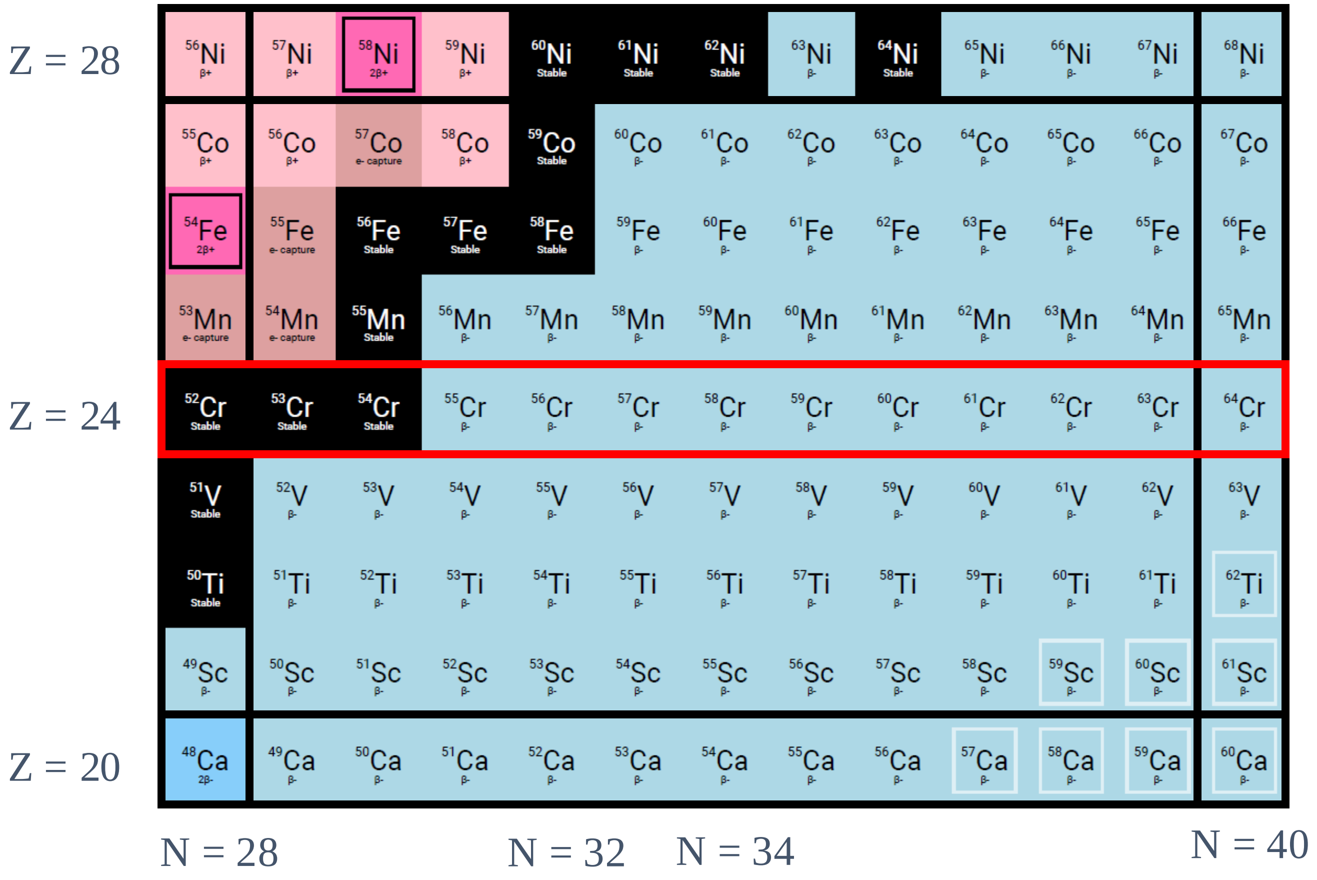
Introduction

Shell evolution between Ca and Ni:

- Sub-shell closure at N=32,34 around ^{52,54}Ca
- Sign for a weak sub-shell closure at N=40 in ^{68}Ni
- N=40 Island of Inversion (IoI) around ^{64}Cr

The Cr isotopes:

- Half filled $f_{7/2}$ → strongest *p-n* collectivity
- Mass : gradual increase of collectivity and deformation from N=34 onward (1)
- Competing nuclear shapes in ^{62}Cr (2)
- ^{64}Cr predicted center of the N=40 Island of Inv. (3)
- No firm assignment of g.s. spins
- No radii or moments known outside stability

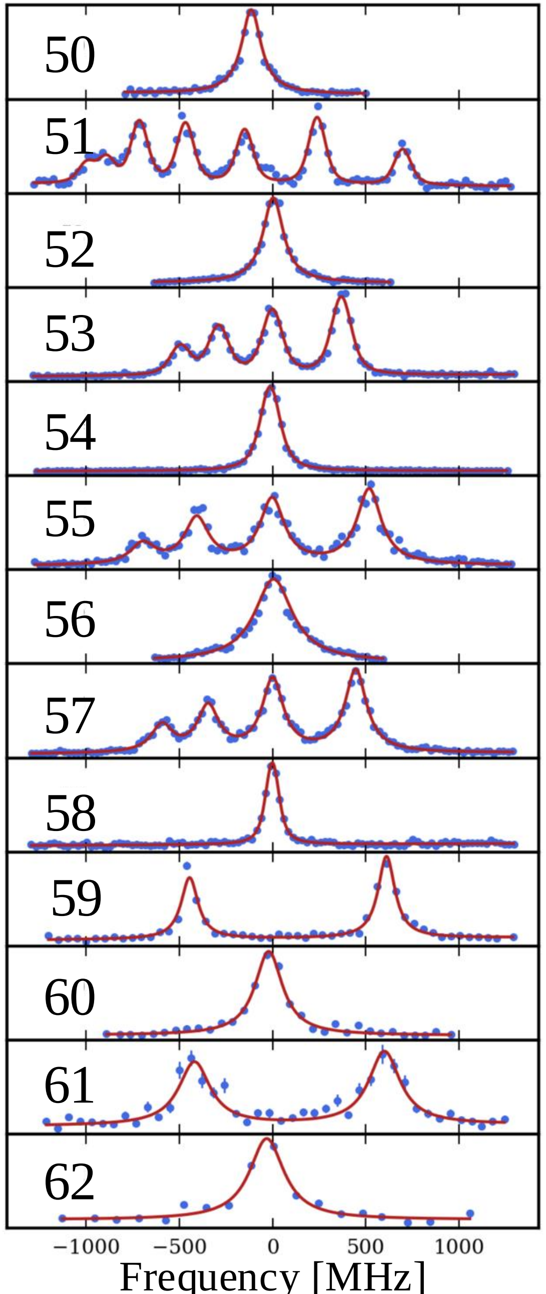


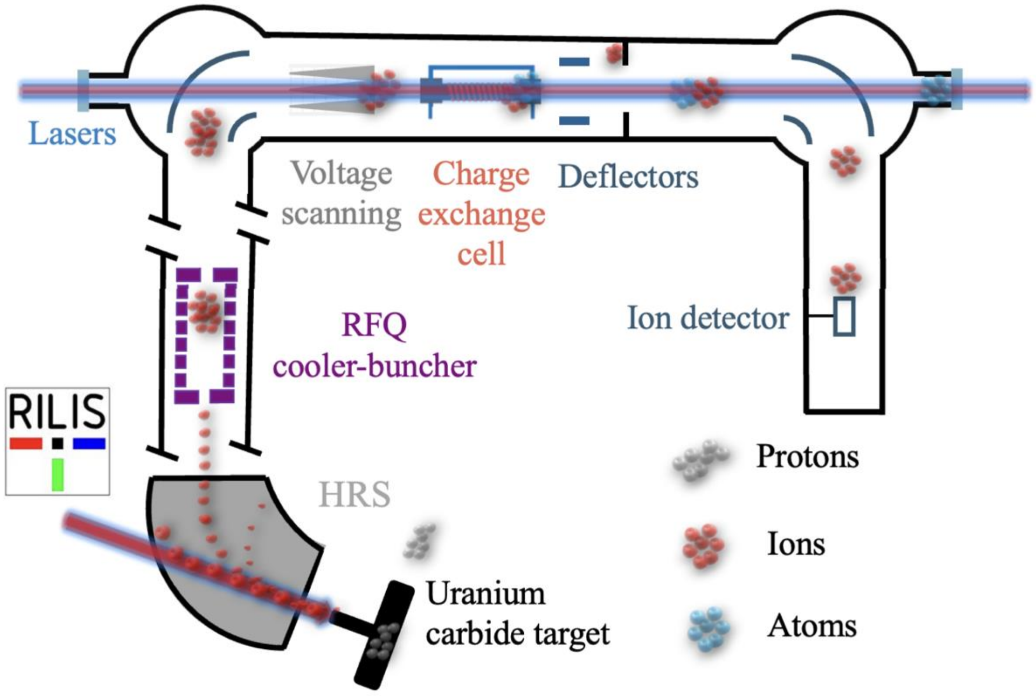
Goals:

- ➢ First measurement of electromagnetic g.s. properties of neutron rich Cr outside stability
- ➢ Better understand the structure of the odd-*A* Cr ground states
- ➢ Investigate the structural changes along the chain and the formation of the N=40 IoI

(1) M. Mougeot *et al.*, PRL **120**, 232501 (2018)
(2) A. Gade et al., Nature Physics **21**, 37-42 (2025)
(3) S. Lenzi et al., PRC **82**, 054301 (2010)

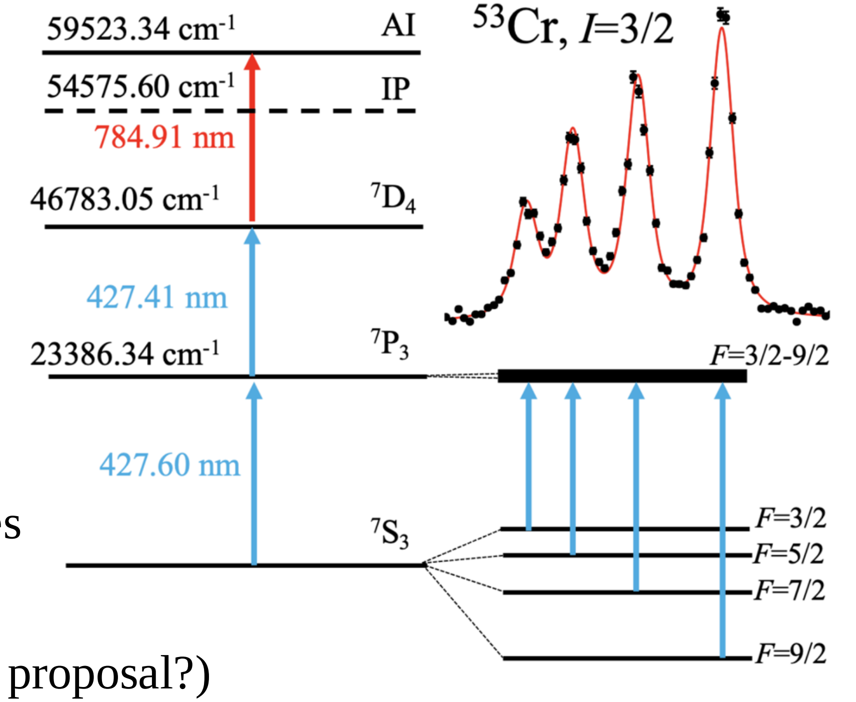
The Cr experiment





Cr Experiment, 7 days, Jully 2023:

- $^{50-63}$Cr beams @ ISOLDE
- UC target + RILIS
- MT + DSS
- no sensitivity to Q



- RILIS scheme development nov. 2022:

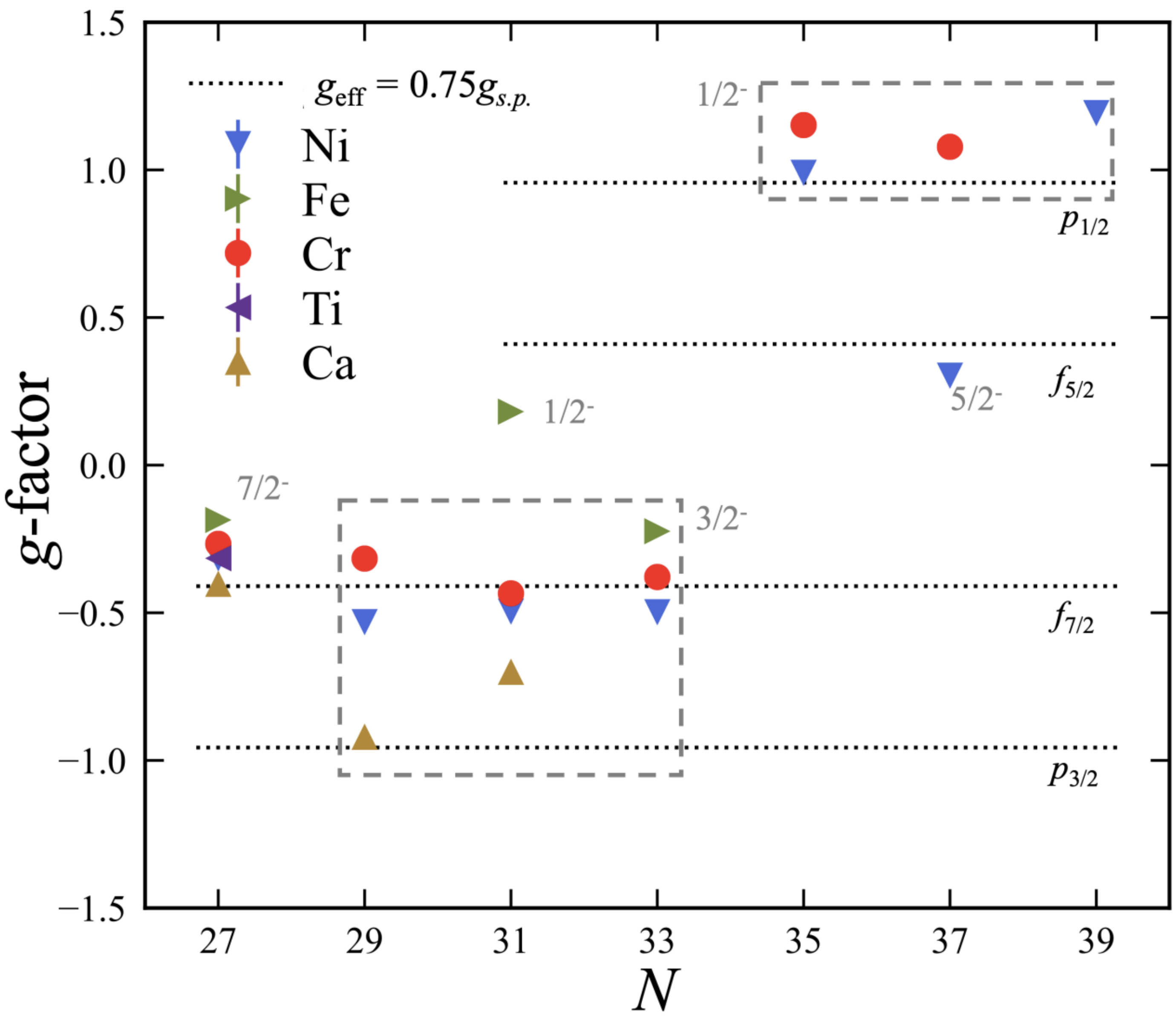
→ Very efficient and selective blue-blue-red, Ti:Sa only scheme, using AI

- Suffered from very large isobaric stable molecules

^{61,62,63}Cr ~ 3000, 600, few 10th of pps

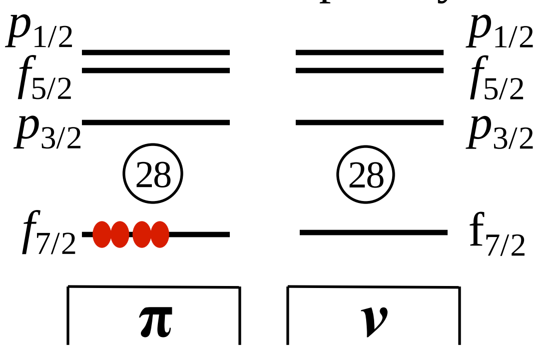
- ^{63}Cr observed but nothing can be extracted (futur proposal?)

2nd Paper: Spin and moments of neutron rich Cr isotopes



g-factor : $g = \frac{\mu}{I\mu_N}$

→ Sensitive to orbitals occupied by valence nucleons



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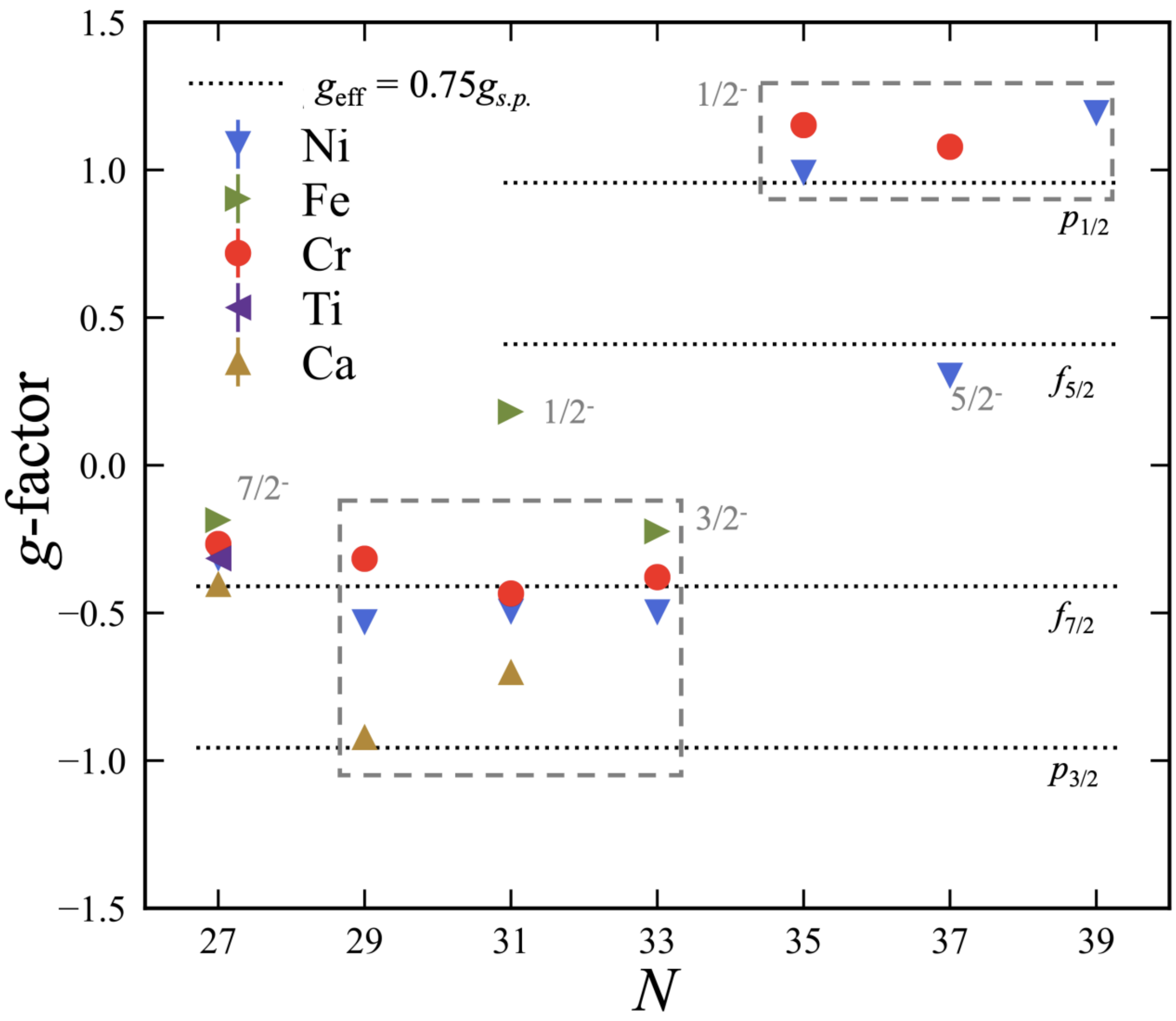

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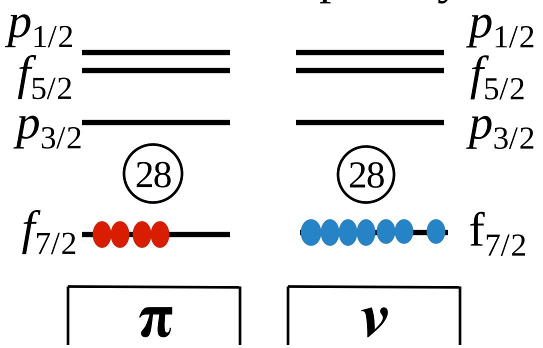
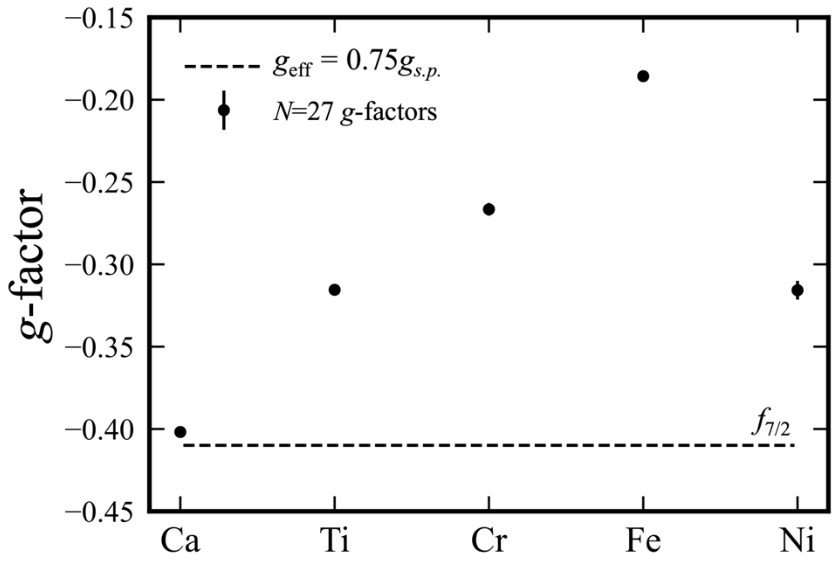


- ^{51}Cr (N=27) → ν $f_{7/2}$ configuration



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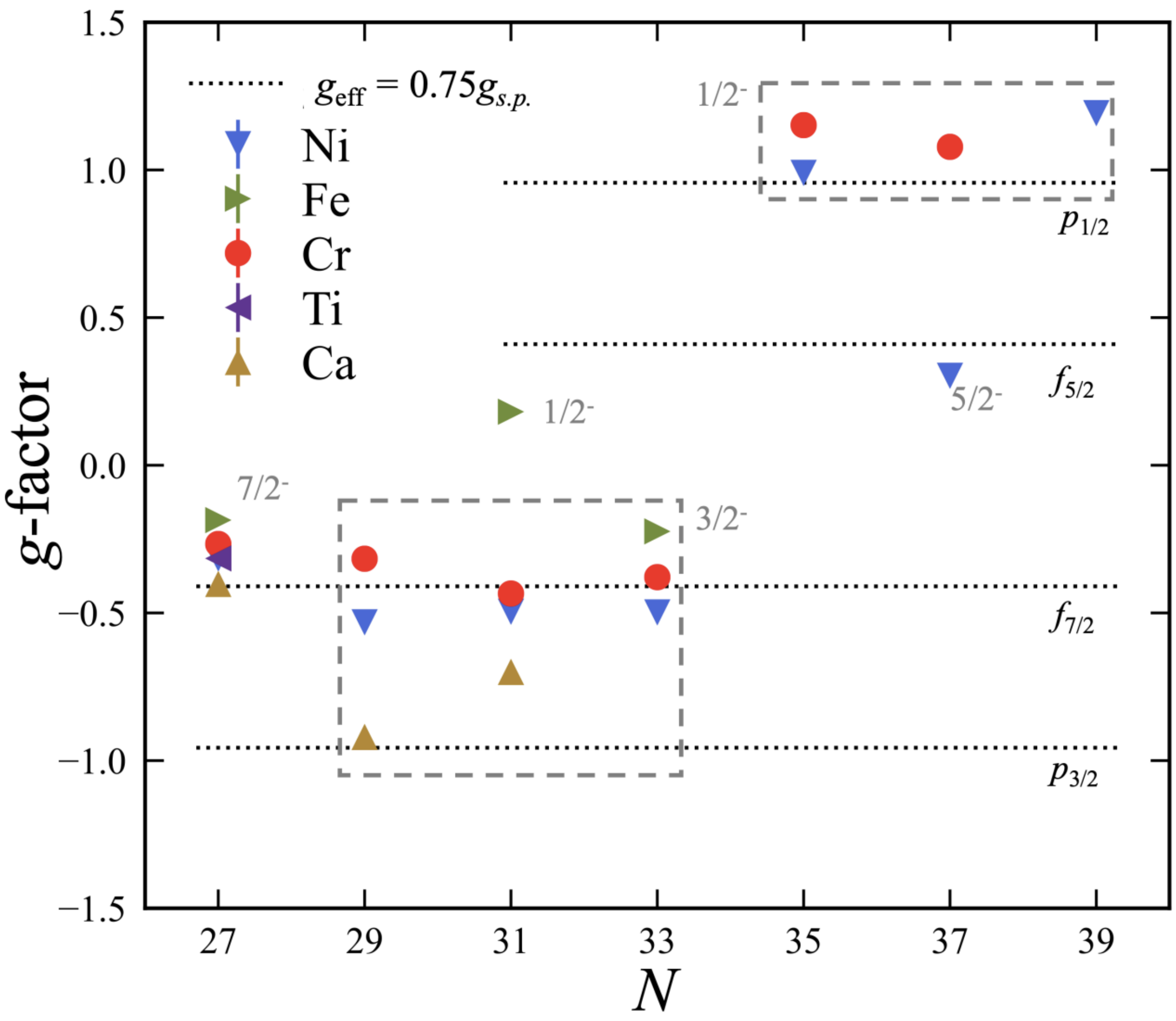

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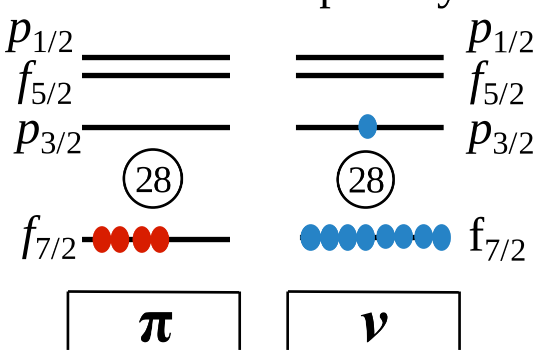

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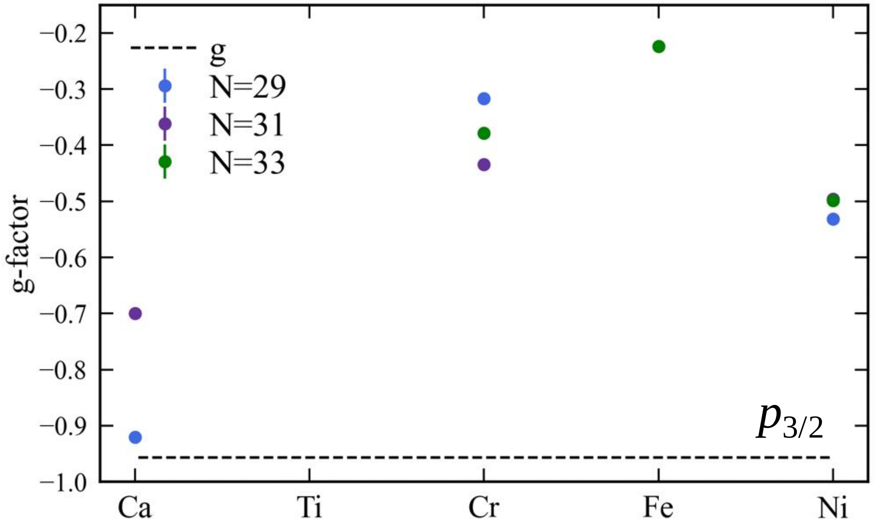

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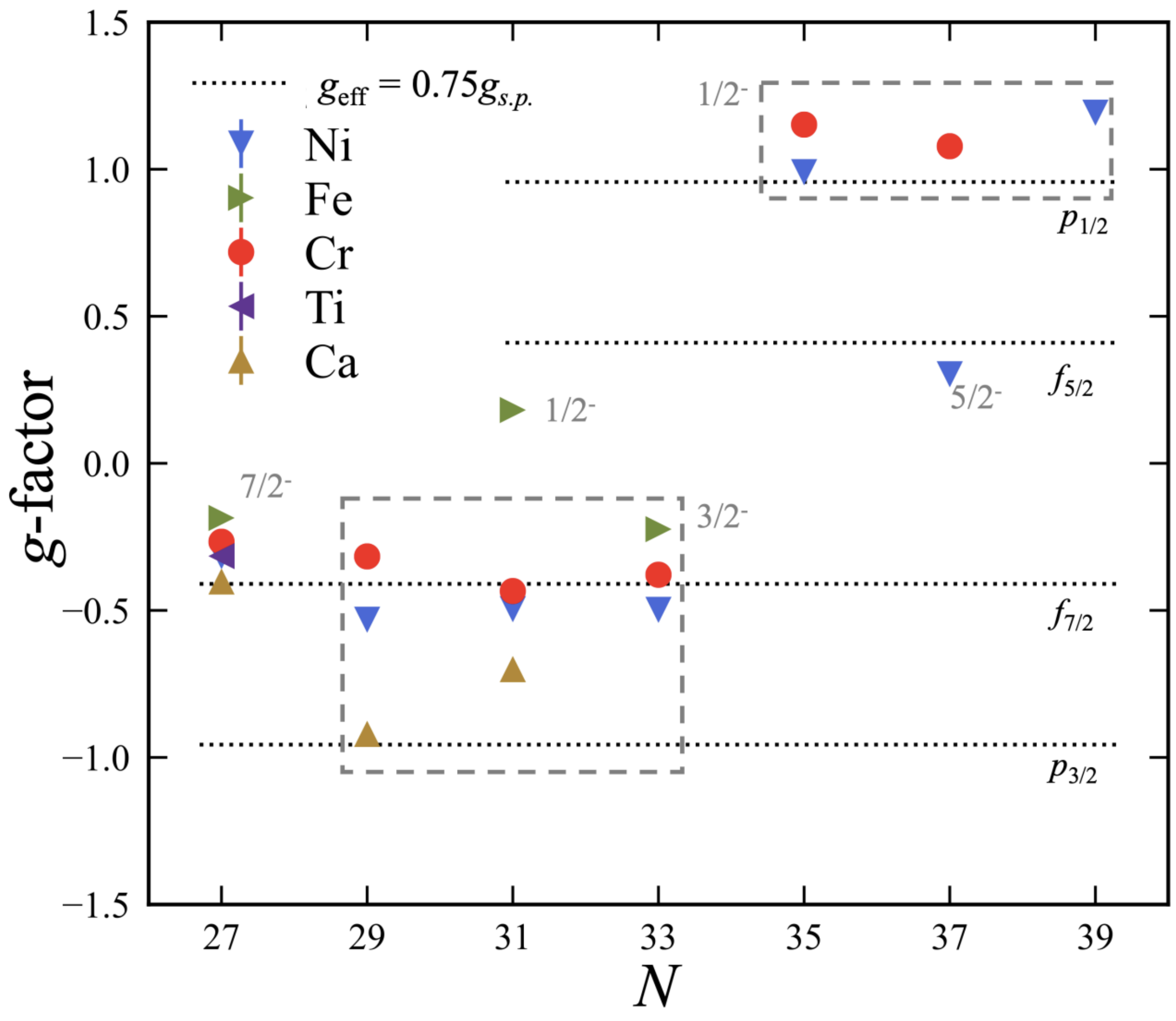

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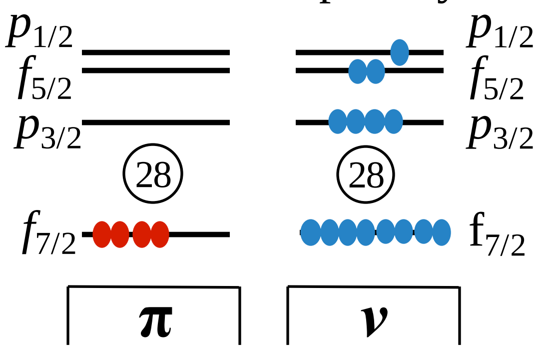
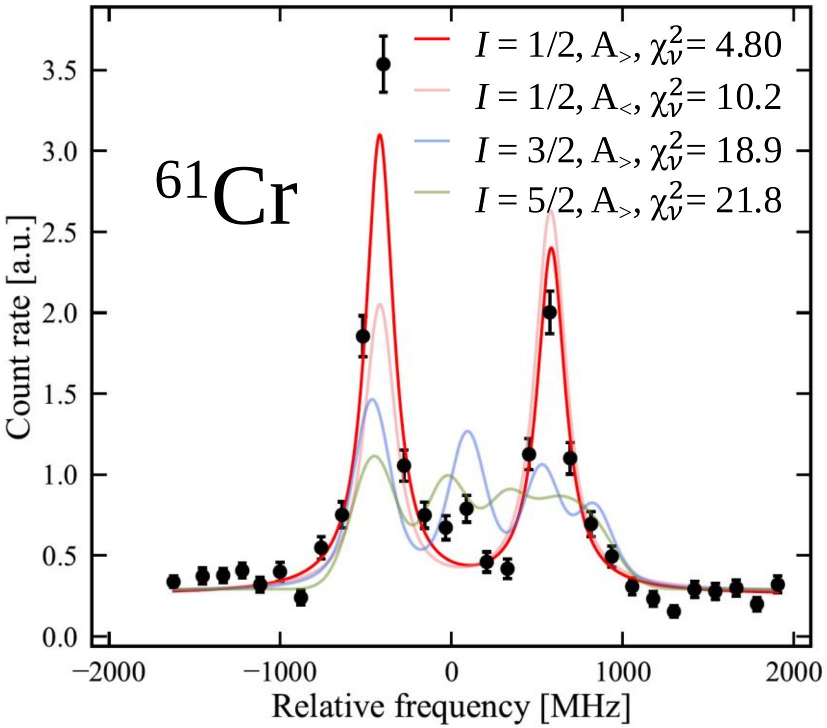
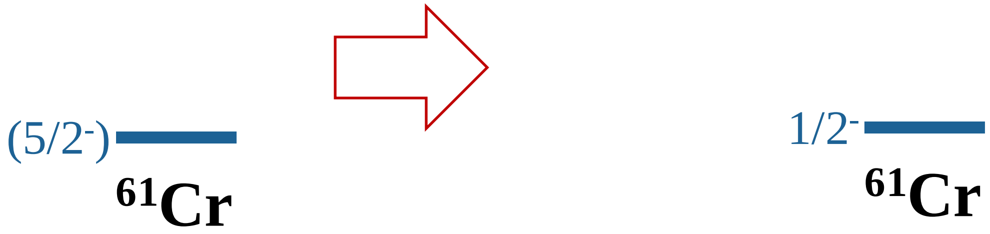


- ^{51}Cr (N=27) → ν $f_{7/2}$ configuration
- ^{53,55,57}Cr (N=29, 31, 33) → ν $p_{3/2}$ configuration
- ^{59,61}Cr (N=35, 37) → ν $p_{1/2}$ configuration
  - No strong deviation from eff. s.p. value
  - N=37 config. moving from ν $f_{5/2}$ in Ni (Z=28) to ν $p_{1/2}$ in Cr (Z=24) due to deformation

Status of the paper :
- Writing almost finalized
- To be submitted to PRC or EPJA

1st Paper: ^{61}Cr as a doorway to the N=40 IoI





Spin ^{61}Cr found to be 1/2 , disagrees with 5/2 assignment from literature

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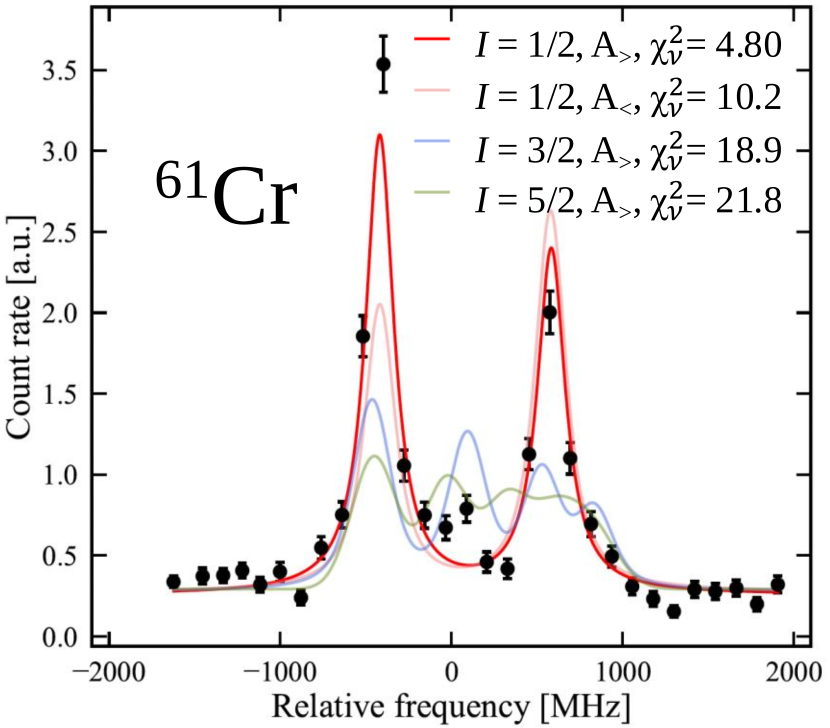

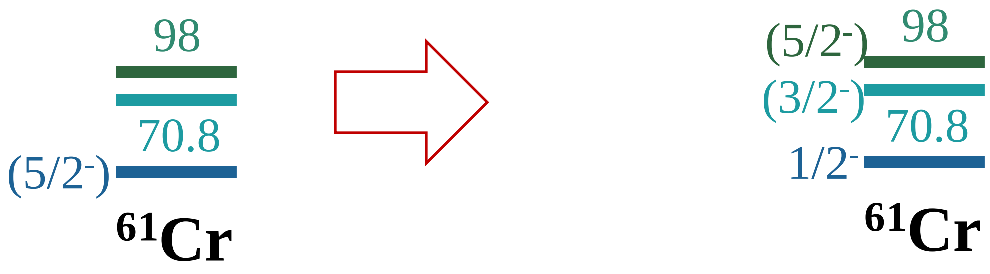

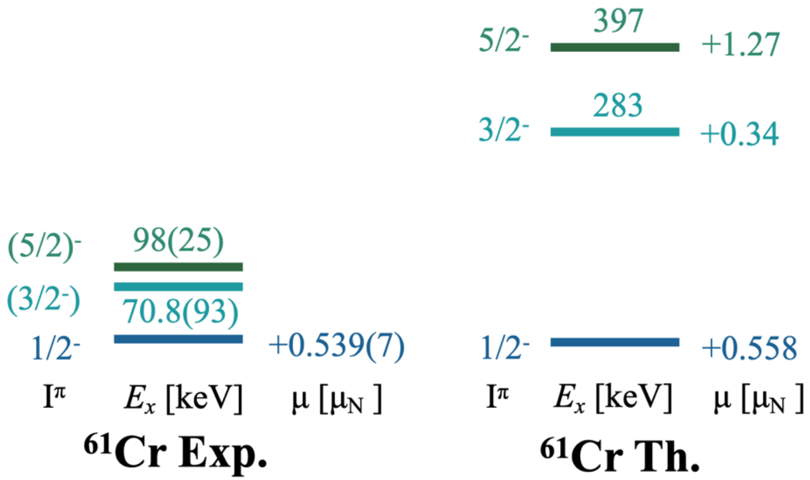

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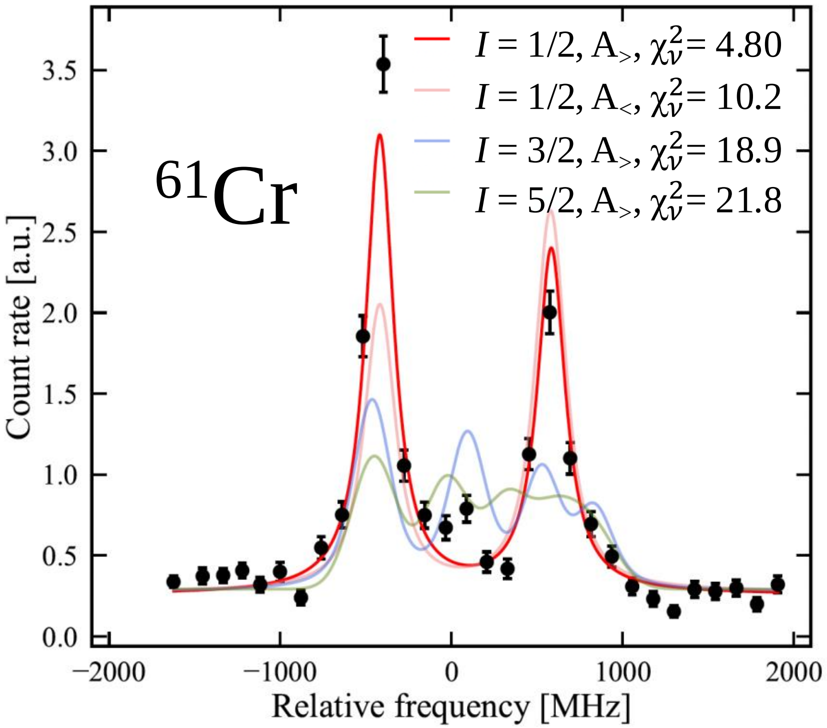

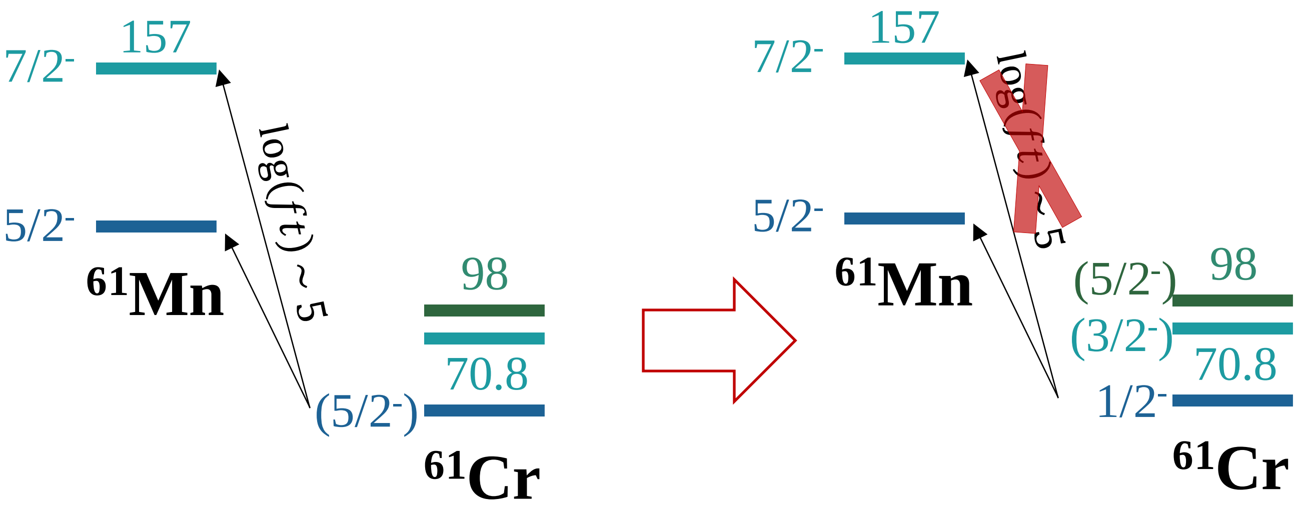

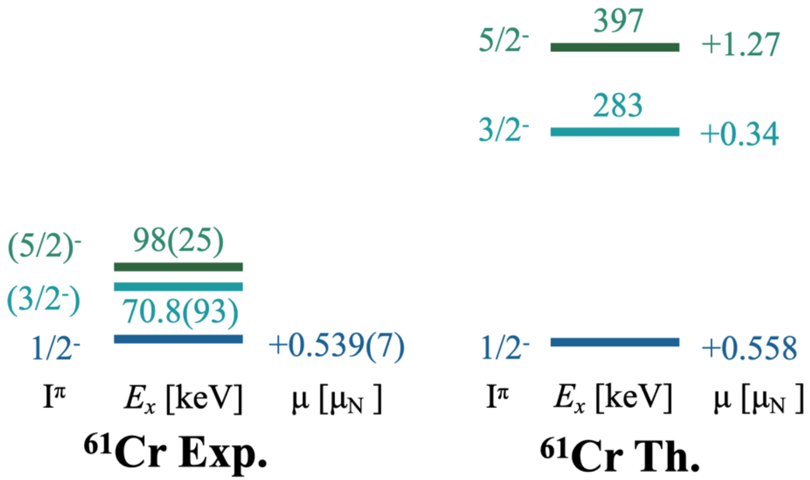

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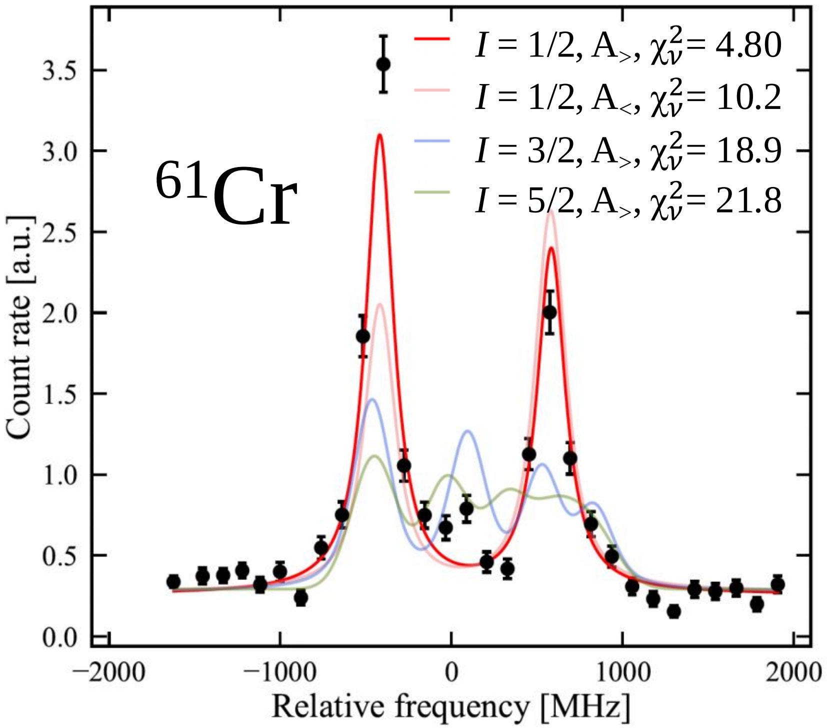

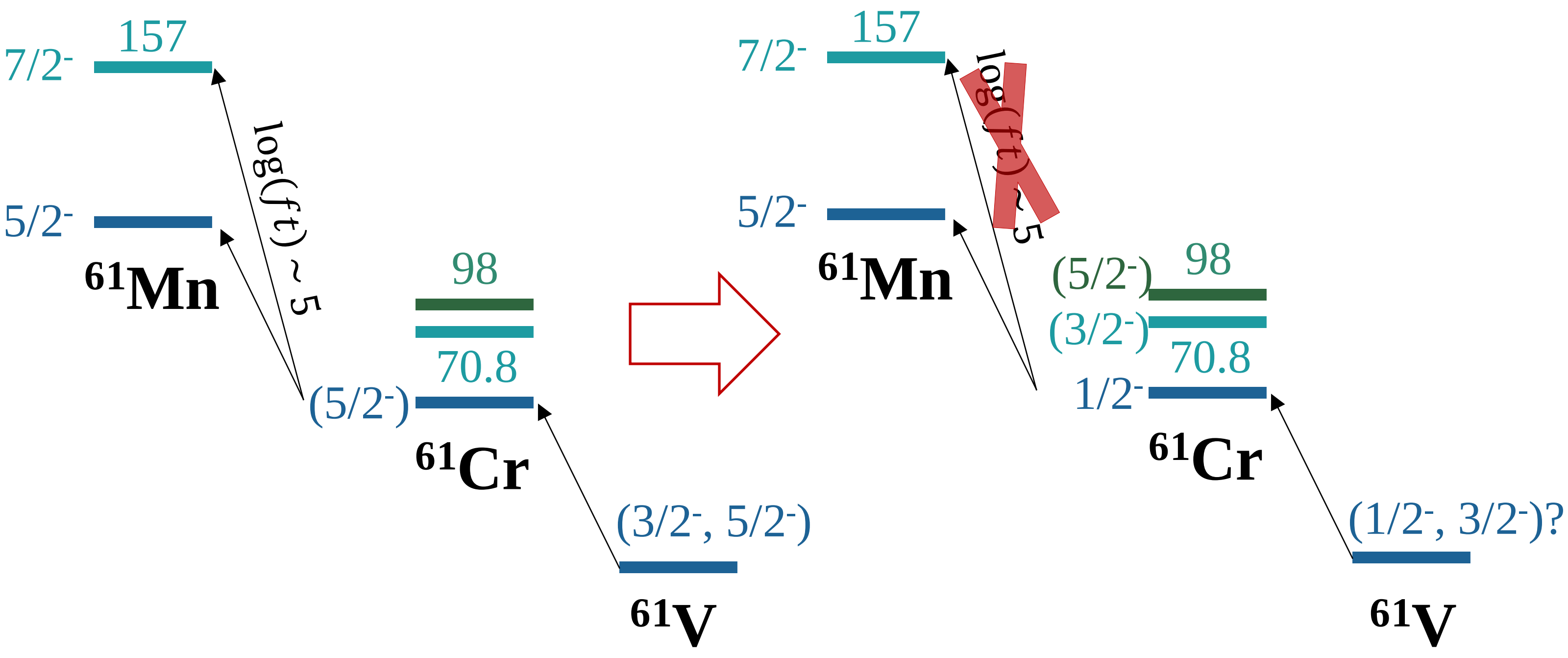

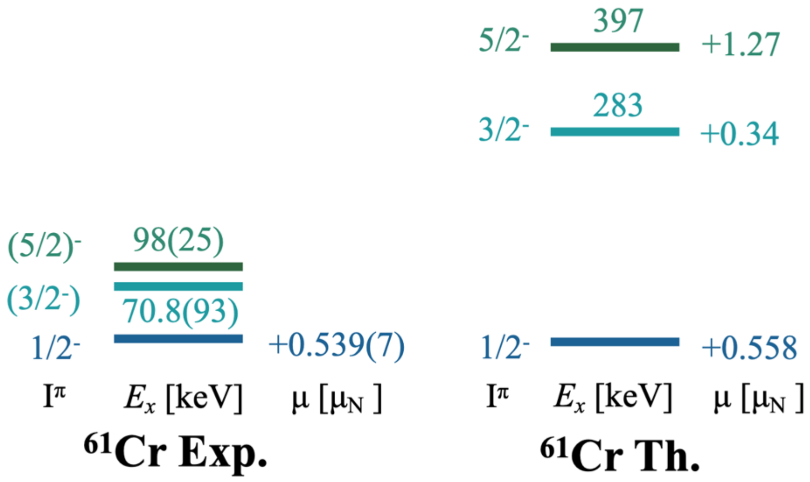

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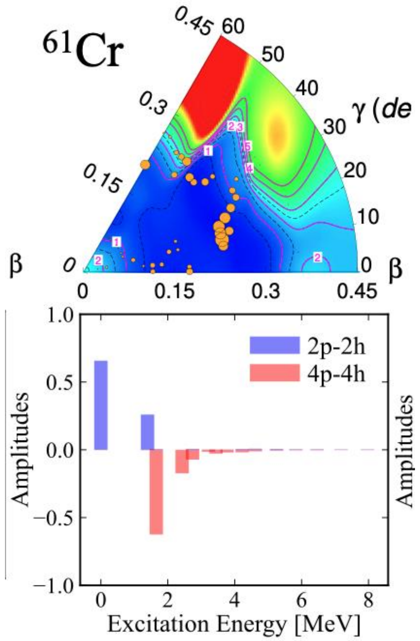
- Spin-parity assignment of first two ^{61}Cr excited state from multipol.
- Over estimation beta feeding in ^{61}Mn
- Constrain ^{61}V g.s. spin
- Call for additional decay data on ^{61}V and ^{61}Cr

1st Paper: ^{61}Cr as a doorway to the N=40 IoI

Magnetic dipole moment:

$\mu_{\text{SM, BM1 bare operator}}(^{61}\text{Cr}) = +0.558\ \mu_N$

$\mu_{\text{exp}}(^{61}\text{Cr}) = +0.539(7)\ \mu_N$



Occupations:

^{61}Cr	$f_{7/2}$	$p_{3/2}$	$f_{5/2}$	$p_{1/2}$	$g_{9/2}$	$d_{5/2}$
p	3.33	0.29	0.33	0.04		
n	8.0	3.78	2.49	1.07	1.46	0.19

Shell Model and DNO calculations at IPHC (F. Nowacki and D.D. Dao) :

- ✓ Reproduces magnetic moment within experimental error bars
- ✓ Reproduces $1/2^-$ g.s. spin-parity
  - ➢ 2p-2h neutron intruder configuration with lonely $p_{1/2}$ neutron
  - ➢ Triaxiality of ^{61}Cr ground state

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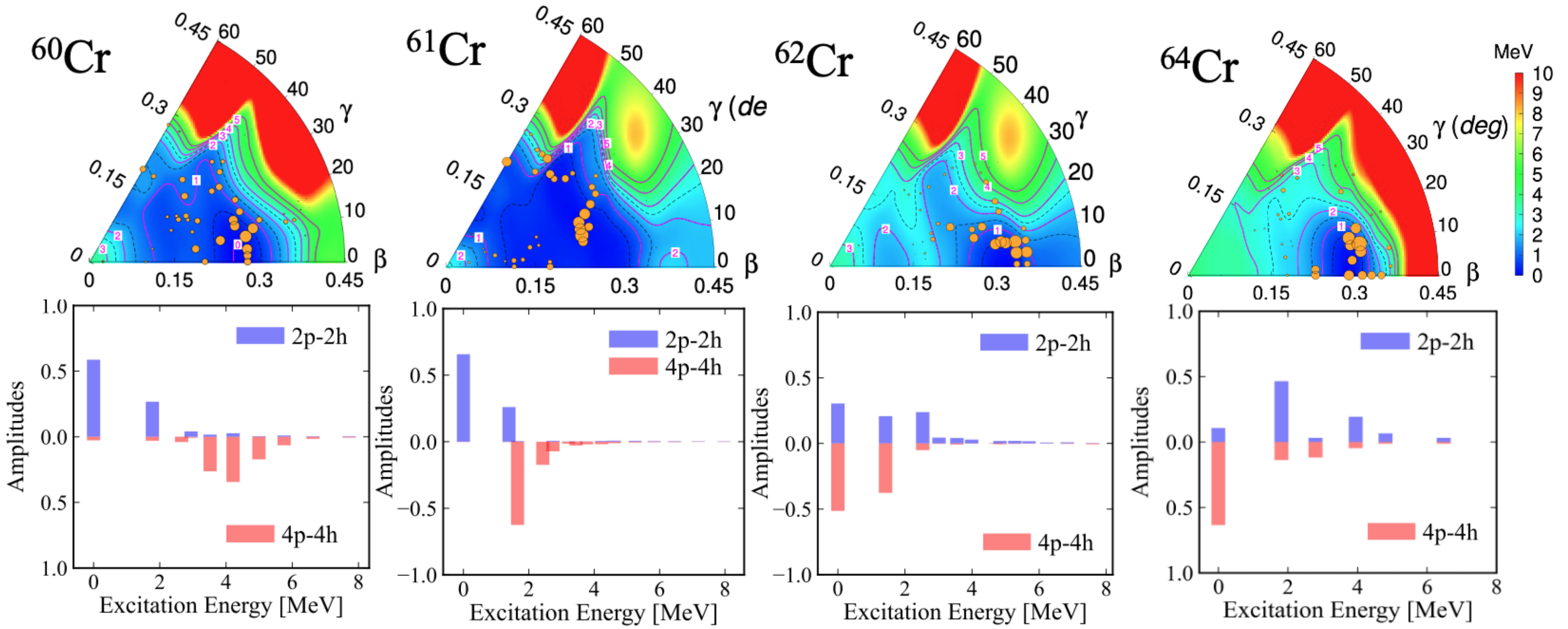

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    - ➢ 2p-2h neutron intruder configuration with lonely $p_{1/2}$ neutron
    - ➢ Triaxiality of ^{61}Cr ground state
    - ➢ ^{61}Cr makes the transition between the 2p-2h and the 4p-4h regime of the N=40 IoI

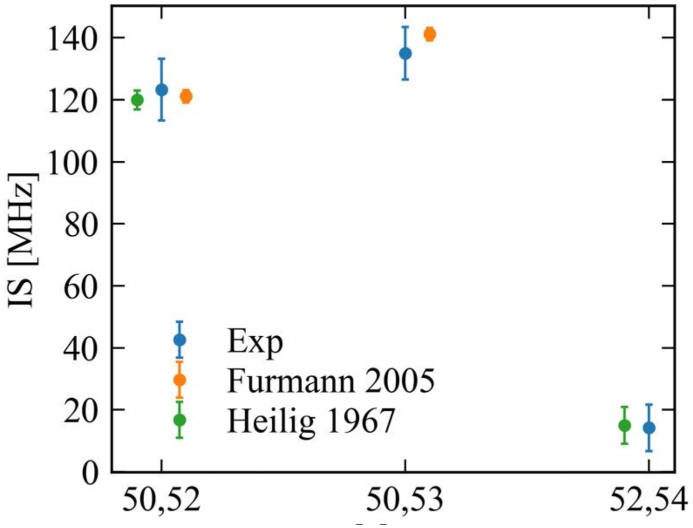
Quantum phase transition at the entrance of the N=40 IoI

Status of the paper :

- Submitted to PRL
- Not accepted first round, second submission under preparation

arXiv:2409.07324

3rd Paper: Charge radii of Cr isotopes



$$\delta\nu_i^{A,A'} = \frac{A - A'}{AA'} M_i + F_i \ \delta\langle r^2\rangle^{AA'}$$

- F and M determined from King plot using model independent absolute radii values [(1)] (muonic+e^- scat.) and average of lit. + CRIS IS

(1) J. W. Lightbody et al., PRC 27, 1 (1983)

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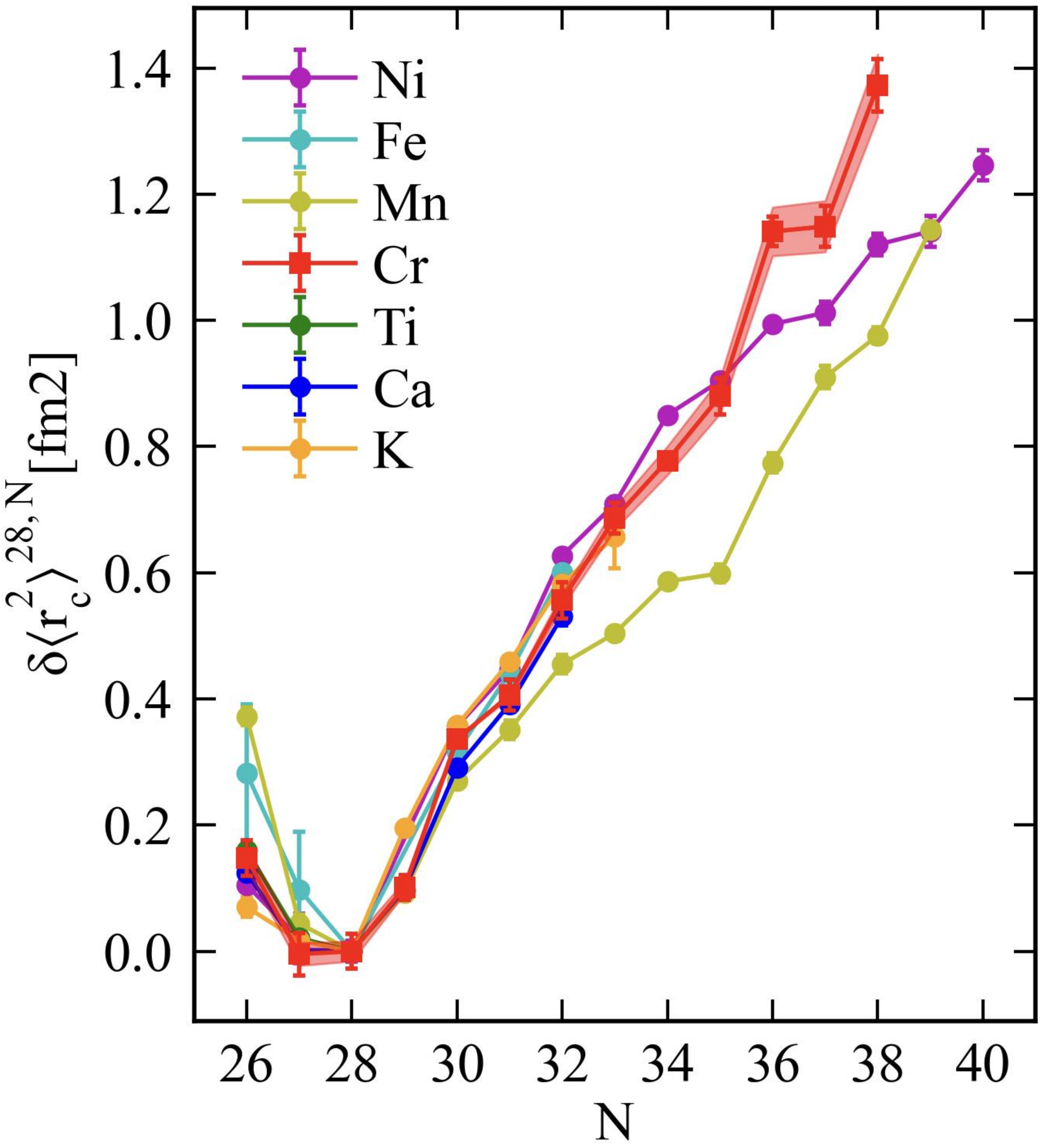

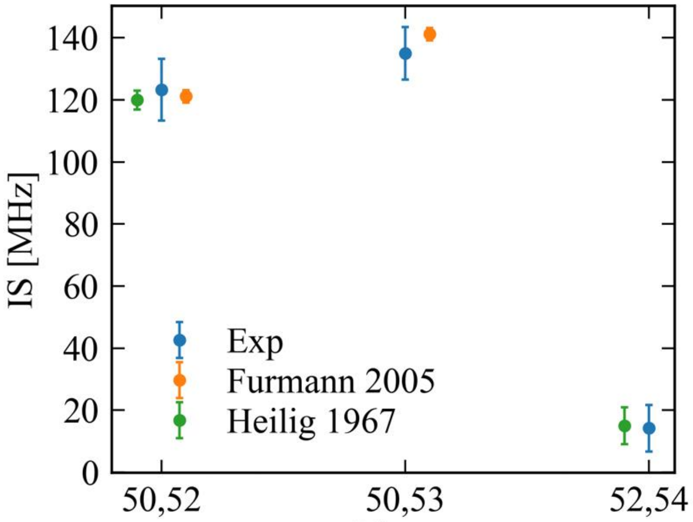

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- F and M determined from King plot using model independent absolute radii values (1) (muonic+e- scat.) and average of lit. + CRIS IS

- Strong kink observed at N=28, in good agreement with literature
- Steep increase of the Cr charge radii between N=28 and N=32 following closely the Ca trend
  → Z independent behaviour
- Clear change of slope at N=34 between deformed Cr, and spherical Ni. Also seen in Mg
- Strong odd-even staggering of the Cr radii for N>34

(1) J. W. Lightbody et al., PRC 27, 1 (1983)

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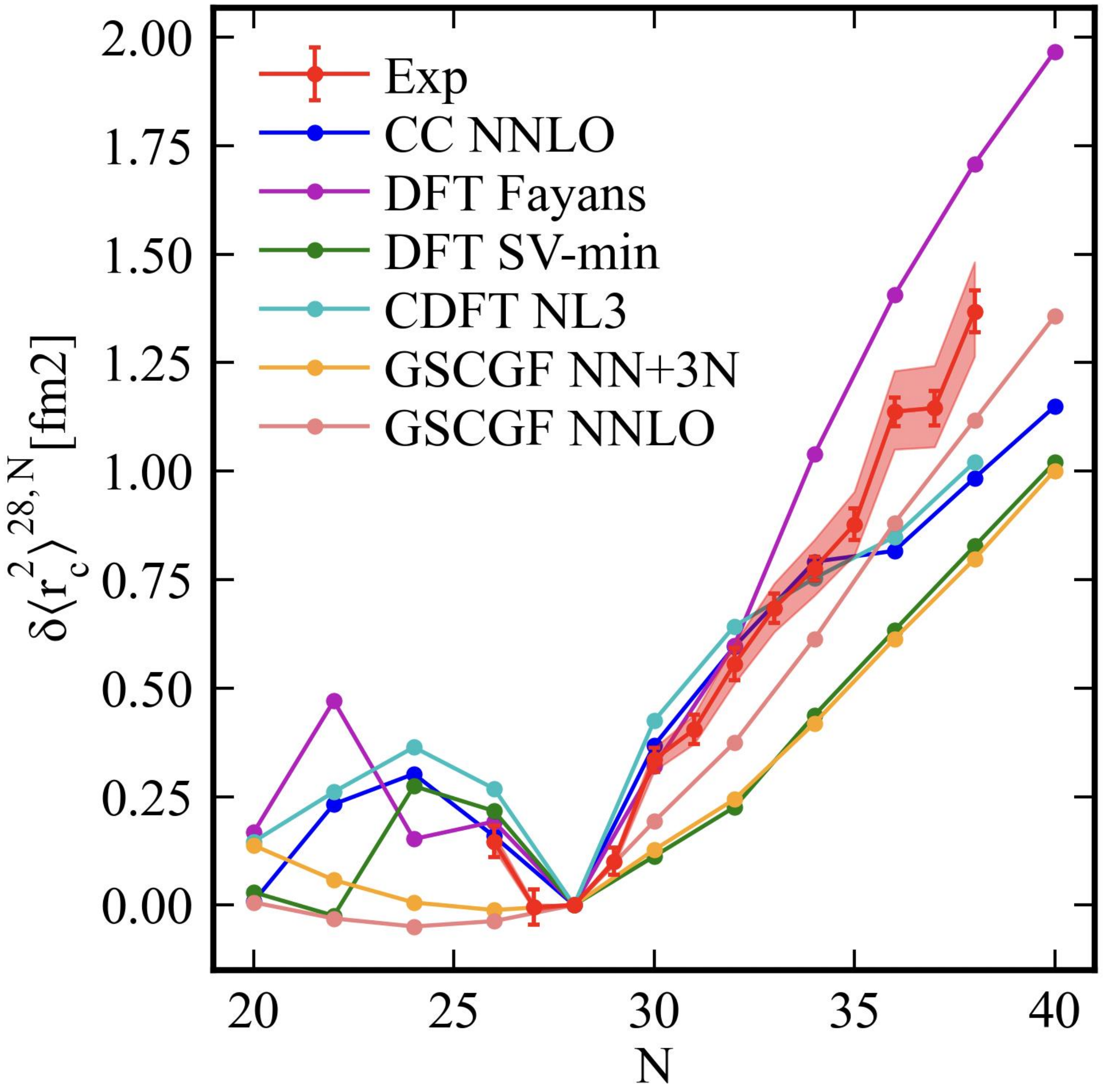


- Not a single theory on the market can describe the evolution of the radii approaching the IoI

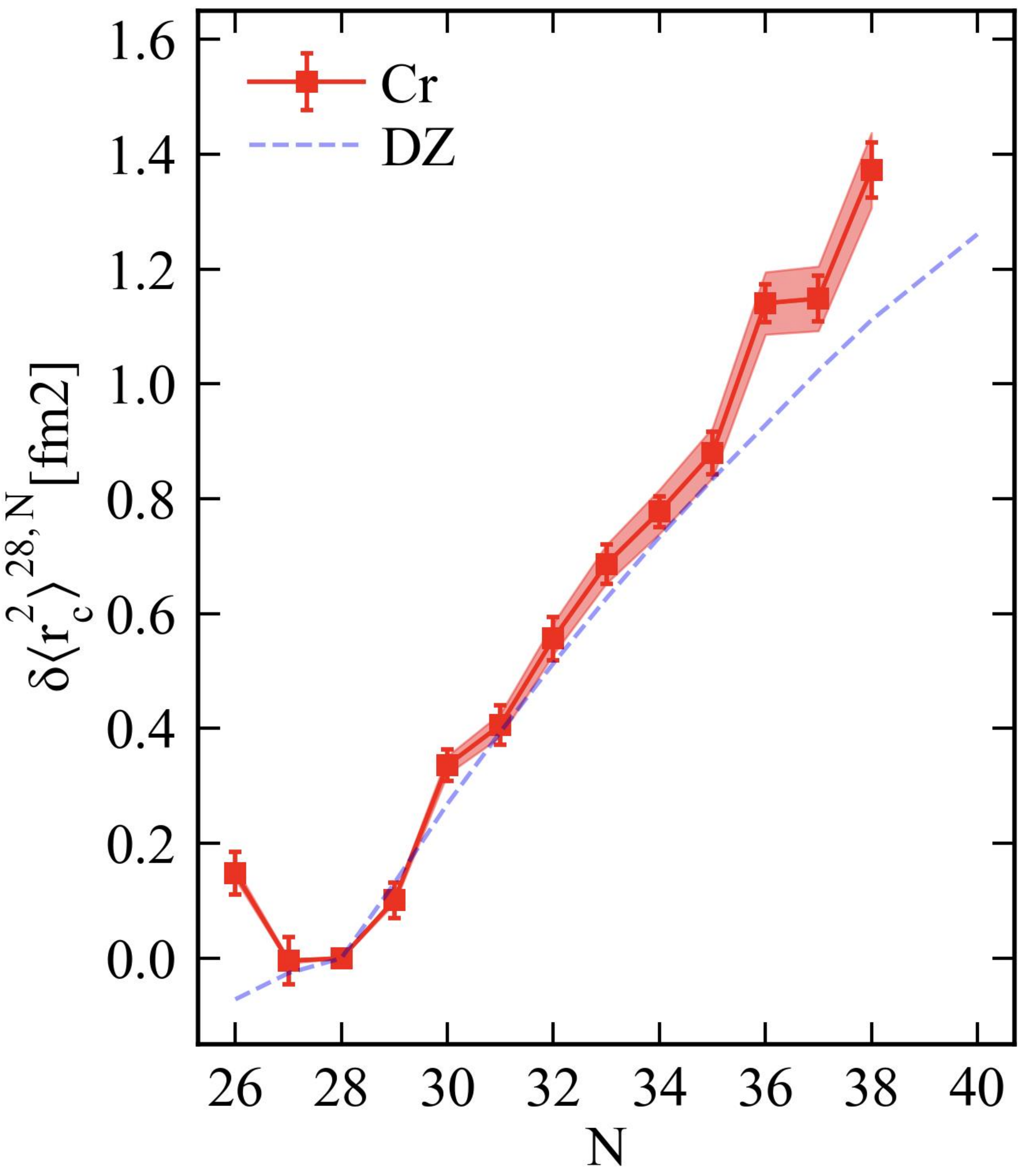
(1) M. Kortelainen, Z. Sun, G. Hagen, W. Nazarewicz, T. Papenbrock, and P.G Reinhard , Phys. Rev. C **105**, L021303 2022
(2) U. C. Perera, A. V. Afanasjev, and P. Ring, Phys. Rev. C **104**, 064313 2021
(3) V. Somà, C. Barbieri, T. Duguet & P. Navrátil, EPJA 57, 135 (2021)

3rd Paper: Charge radii of Cr isotopes

DZ : $$\rho_\pi^{sc} = \rho_\pi + \mathcal{D}, \quad \mathcal{D} = \lambda S_\pi S_\nu + \mu Q_\pi Q_\nu .$$

$$\sqrt{\langle r_\pi^2 \rangle} \approx \rho_\pi = A^{1/3}\left(\rho_0 - \frac{\zeta}{2}\frac{t}{A^\sigma} - \frac{\upsilon}{2}\left(\frac{t}{A}\right)^2 \right) e^{(g/A)}$$

Phenomenological macroscopic formula from :
J. Duflo, A.P. Zucker, Phys. Rev. C 66 (2002) 051304(R)



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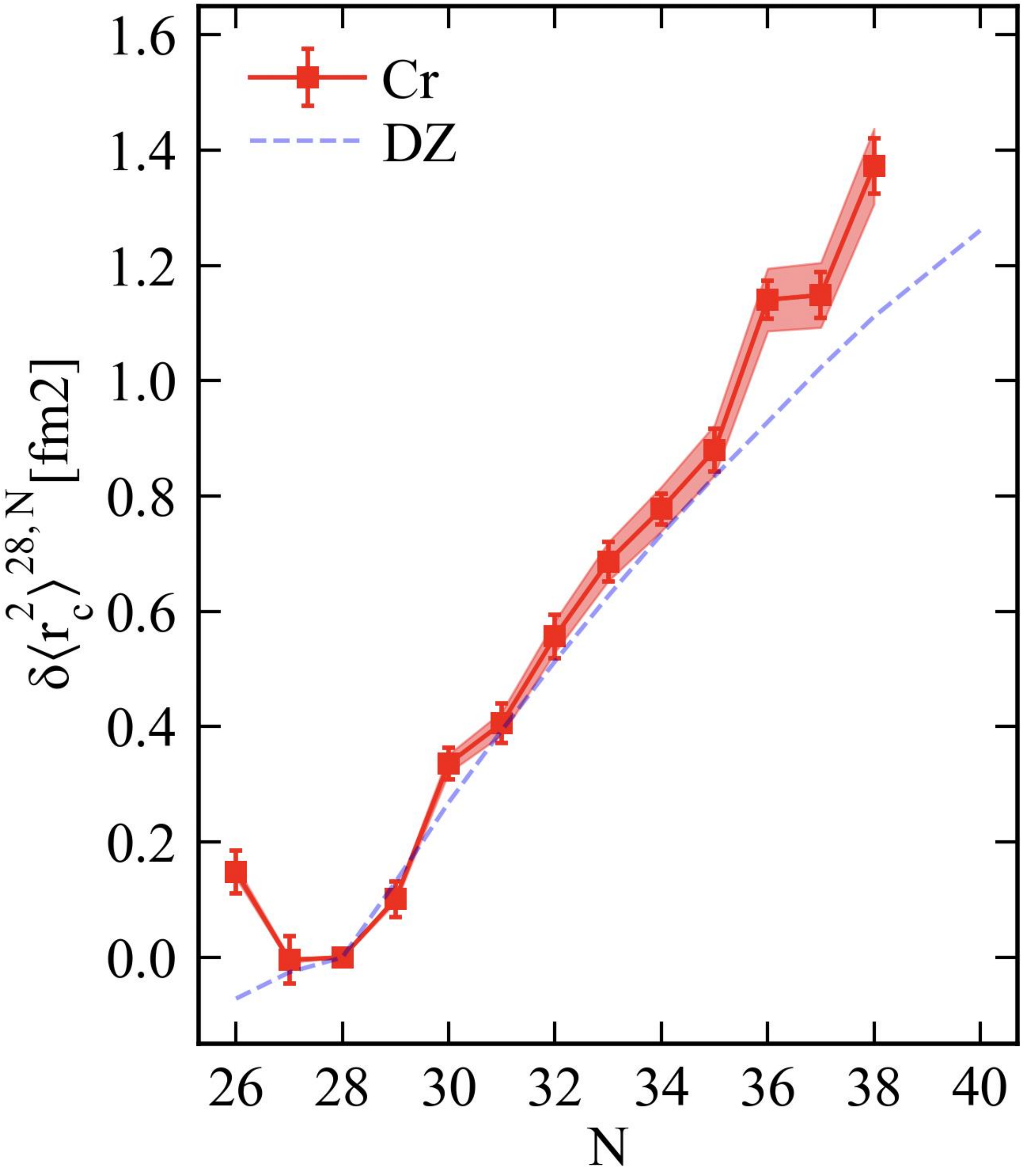
SM :

DZ + *coeff* * π *p* orbitals occupancies



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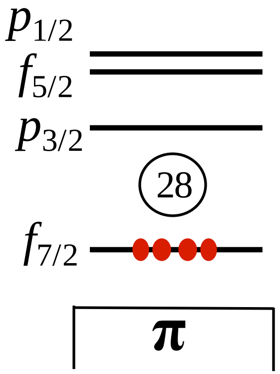

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SM :

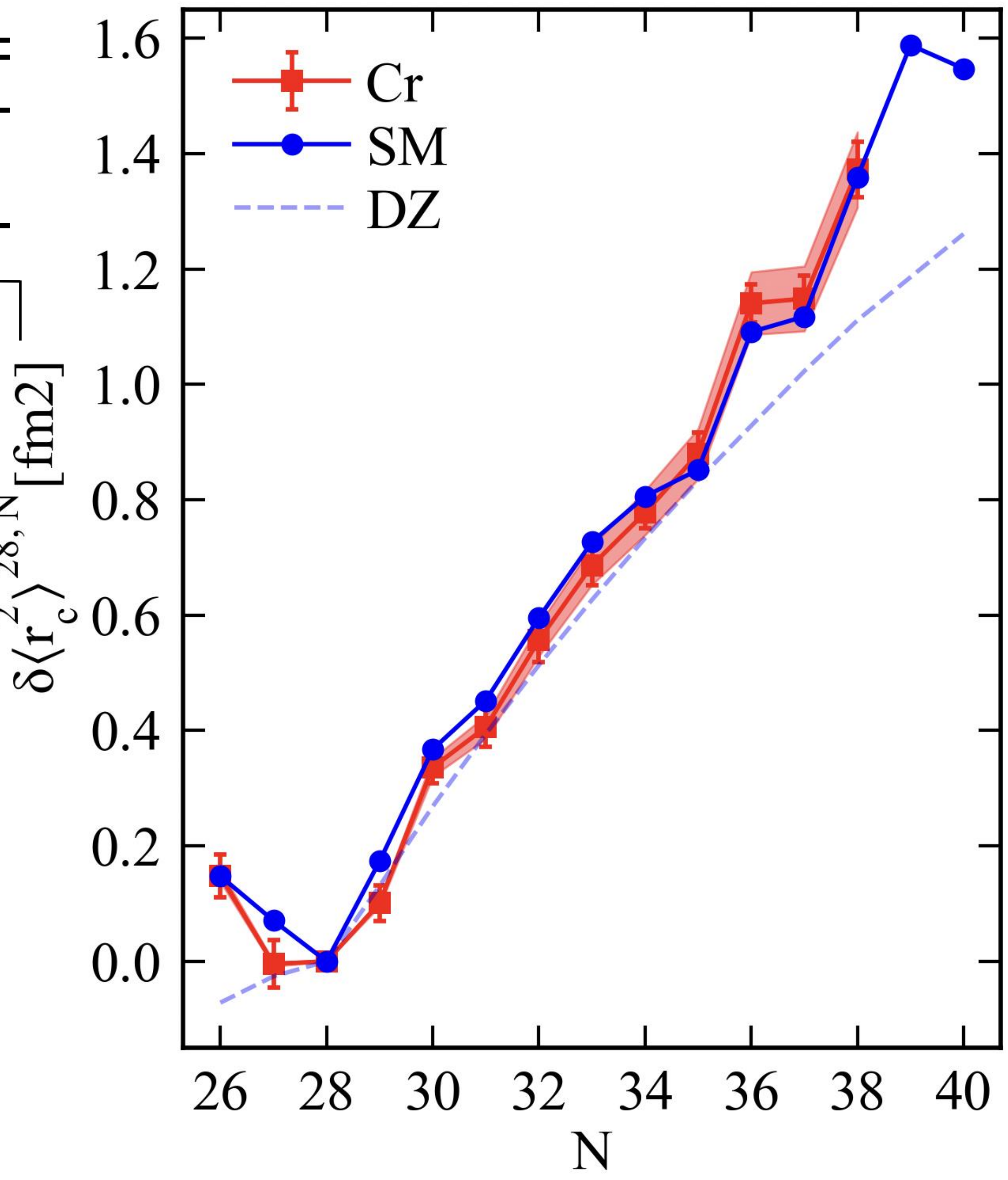
DZ + *coeff* * π *p* orbitals occupancies

→ Just add one parameter, proportional to the proton *p* orbits occupancies reproduce exp. data very well

→ Deviation from DZ at N ≥ 36, where deformation arise

Interpretation :

- stronger deformation → stronger quadrupole correlation → stronger mixing between $\Delta l = 2$ protons *f* and *p* orbits.
- Small mixing difference due to deformation are seen in the charge radii. Related to the halo character of the *p* orbits probed by *coeff*



Status of the paper :

- Interpretation still ongoing; to be submitted to Nature

Conclusion

- ^{61}Cr as a Doorway to the N=40 Island Of Inversion
  → Moment and spin of ^{61}Cr, implication on decay data
  → Quantum Phase Transition identified at the entrance of the N=40 IoI
  → Submitted to PRL, not accepted first round, to be resubmitted

- Spin and moment of neutron rich Cr isotopes
  → First moment and spin measurement of odd-A neutron rich Cr isotopes
  → Evolution of configuration mixing in the Ca-Ni region
  → Calculations to be performed, writing almost finished, to be submitted to PRC or EPJA

- Charge radii of Cr isotopes entering the N=40 IoI : the ultimate probe of the wavefunction
  → Signature of rising deformation entering the N=40 Island of Inversion
  → First microscopic interpretation of radii within IoI with SM calculations, evidence for halo proton *p* orbits
  → Interpretation to be finalized, writing to be started. Submission to Nature/Nature Physics by the end of the year

The collaboration

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[3] *Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France*
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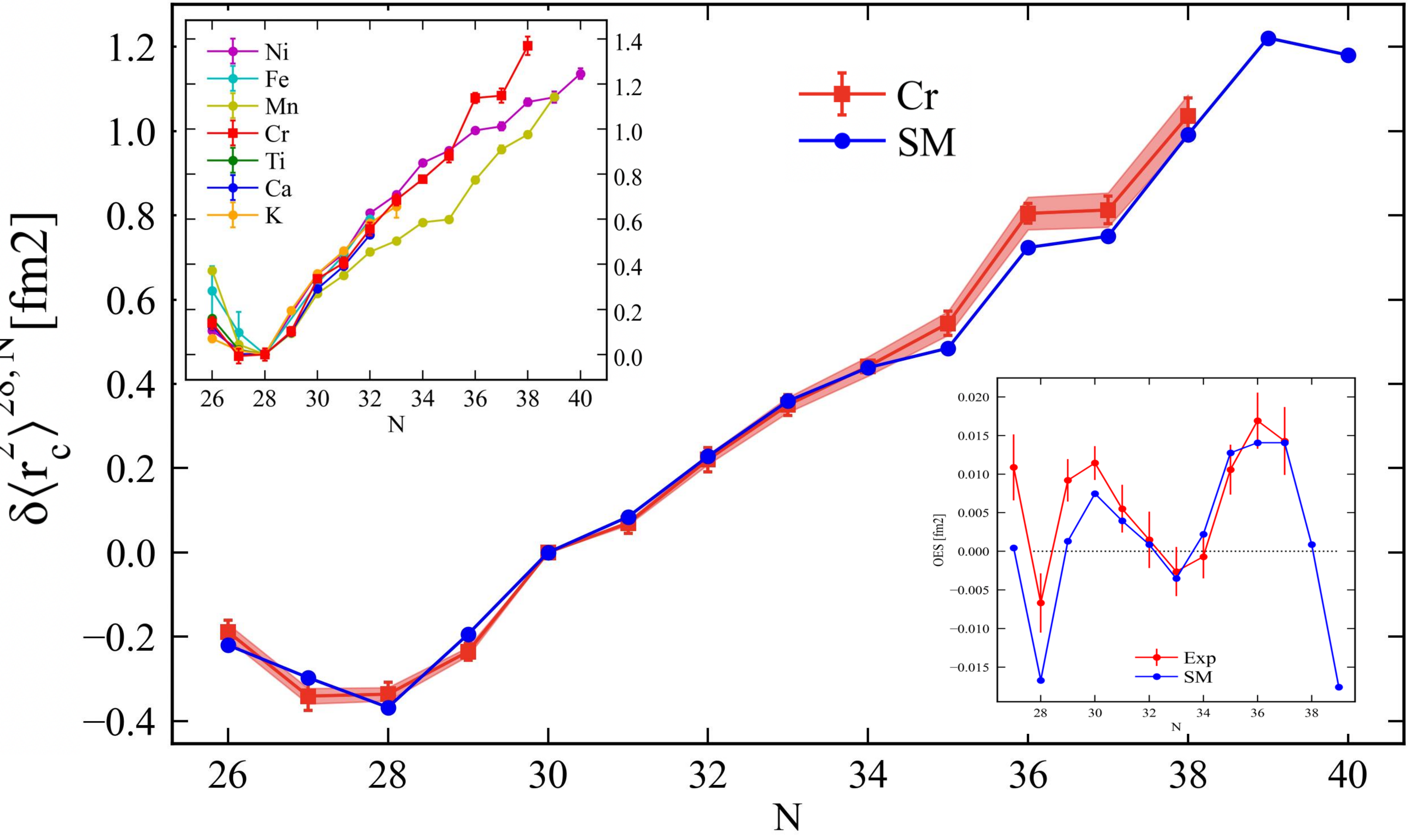
[6] *Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[7] *Department of Physics, University of Gothenburg, SE-412 96 Gothenburg, Sweden*

THANK YOU FOR YOUR ATTENTION



δ⟨r_c^2⟩^{28,N} [fm2]
N
Cr
SM
Ni
Fe
Mn
Cr
Ti
Ca
K
OES [fm2]
Exp
SM