Nuclear structure studies in the Ca region with collinear laser spectroscopy

The cases of Ar (Z=18) and V (Z=23)

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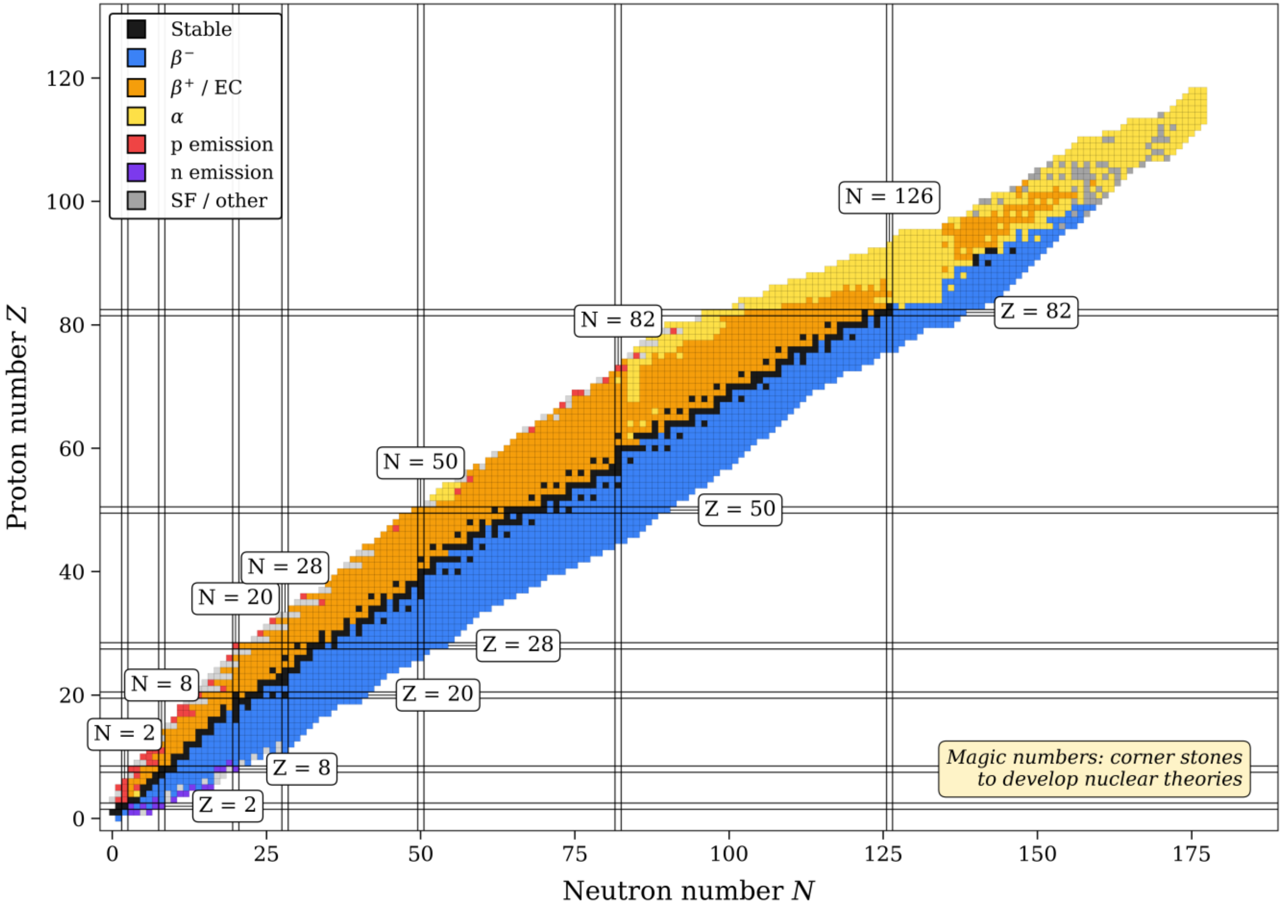
KU Leuven, Instituut voor Kern- en Stralingsfysica

Zakopane Conference on Nuclear Physics 2026

The Ca region — a laboratory for shell evolution

N = 28 shell closure on both sides of a doubly-magic core

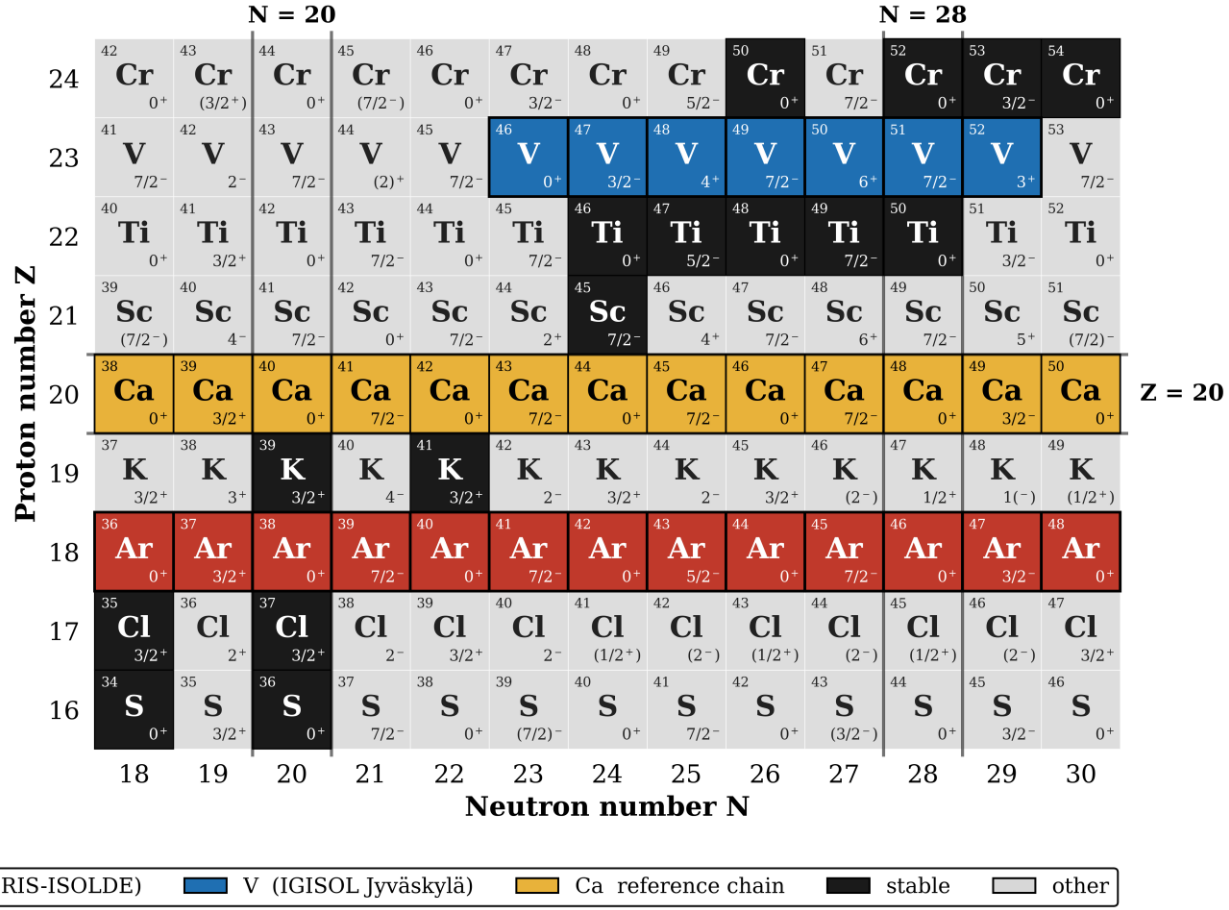


Ar chain (this work, CRIS-ISOLDE) · V chain (IGISOL, in analysis)

The Ca region — a laboratory for shell evolution

N = 28 shell closure on both sides of a doubly-magic core

- **Ca (Z = 20)** hosts two doubly-magic nuclei: **^{40}Ca (N = 20)** and **^{48}Ca (N = 28)**
- Rich testbed for **shell-model, ab-initio and DFT** benchmarked on the Ca chain (Garcia Ruiz 2016)
- Open question: how do **proton-holes (Ar)** and **proton-particles (V)** reshape the neutron shell structure?
- Signatures: **magnetic moments μ** → single-particle content; **quadrupole Q_s** → deformation; **$\delta\langle r^2\rangle$** → charge distribution
- Complementary ISOLDE + IGISOL laser-spectroscopy programme covers **both sides of Z = 20**



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Collinear laser spectroscopy

The hyperfine fingerprint delivers μ, Q_s and $\delta\langle r^2\rangle$ model-independently

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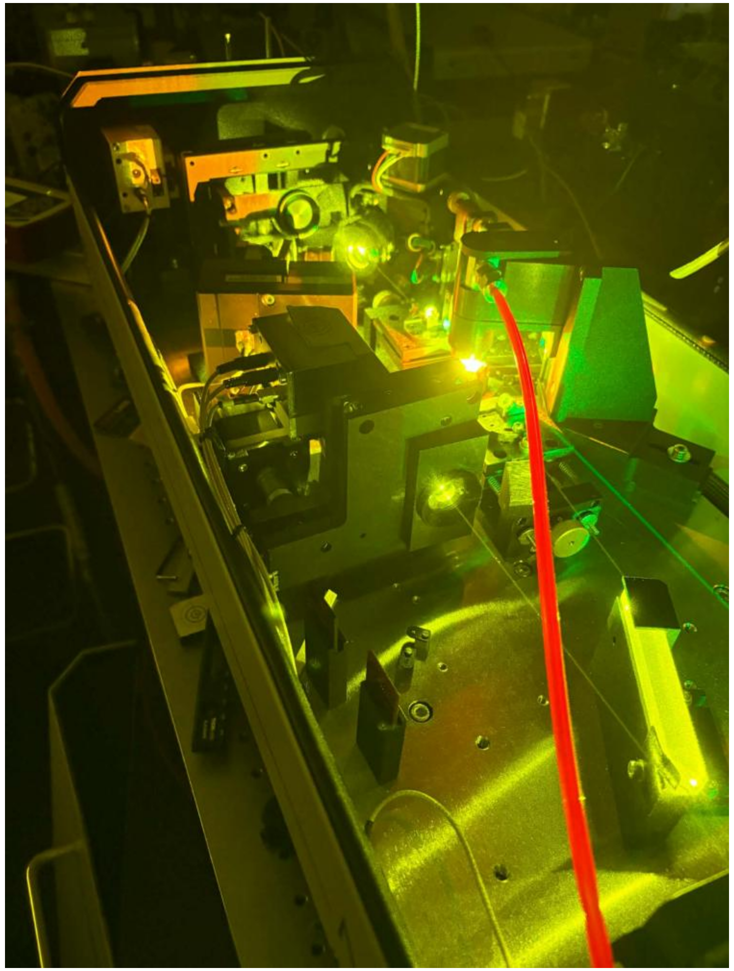

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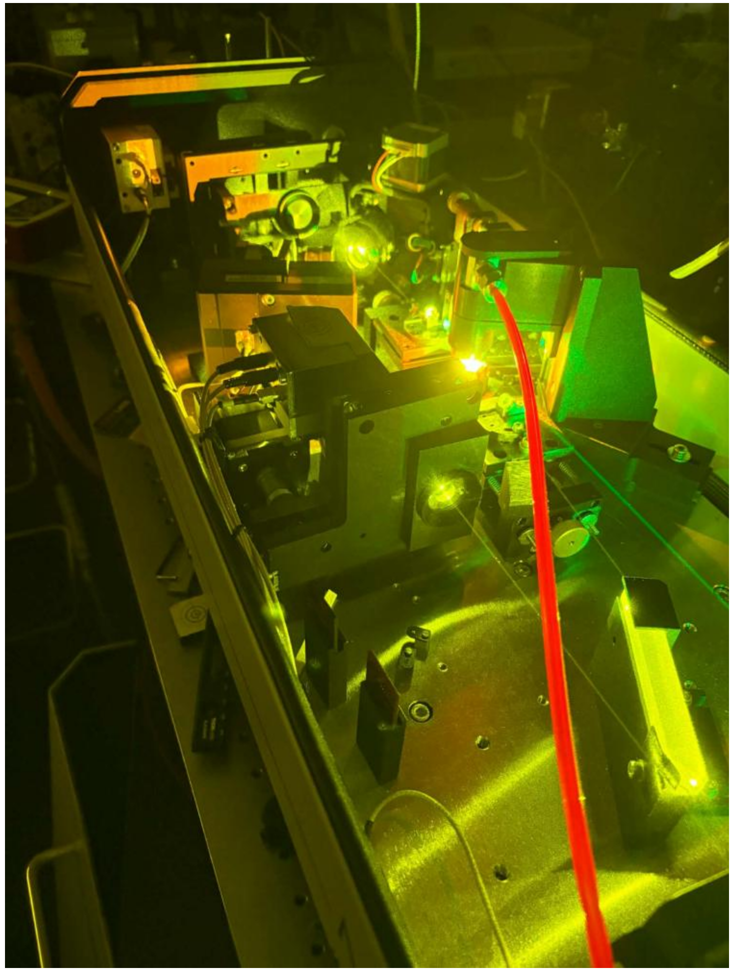
CRIS @ ISOLDE → Ar isotopes

- Production via protons on thich target.
- Step-wise resonance ionisation, ion detection.
- Near-background-free → reach the most exotic isotopes.

CRIS: Collinear Resonance Ionisation Spectroscopy



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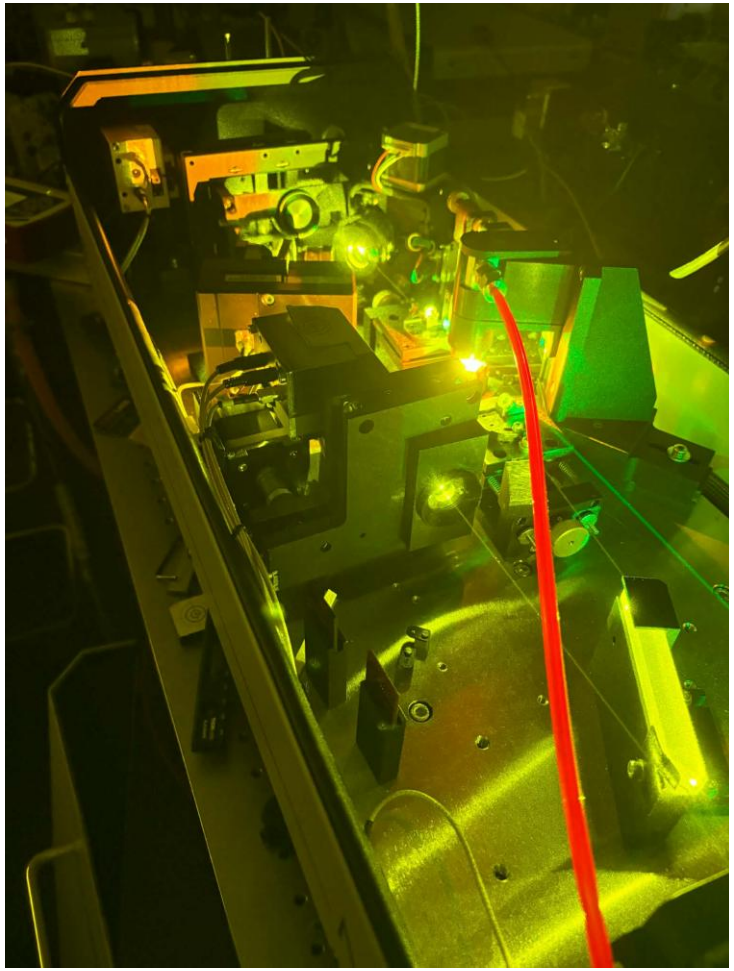
CRIS: Collinear Resonance Ionisation Spectroscopy

CLS @ IGISOL → V isotopes

- Production on thin target, recoil in gas cell→ ideal for refractory elements.
- Fluorescence detection.
- Photon background (depending on the ion beam isobaric purity).

CLS: Collinear Laser Spectroscopy



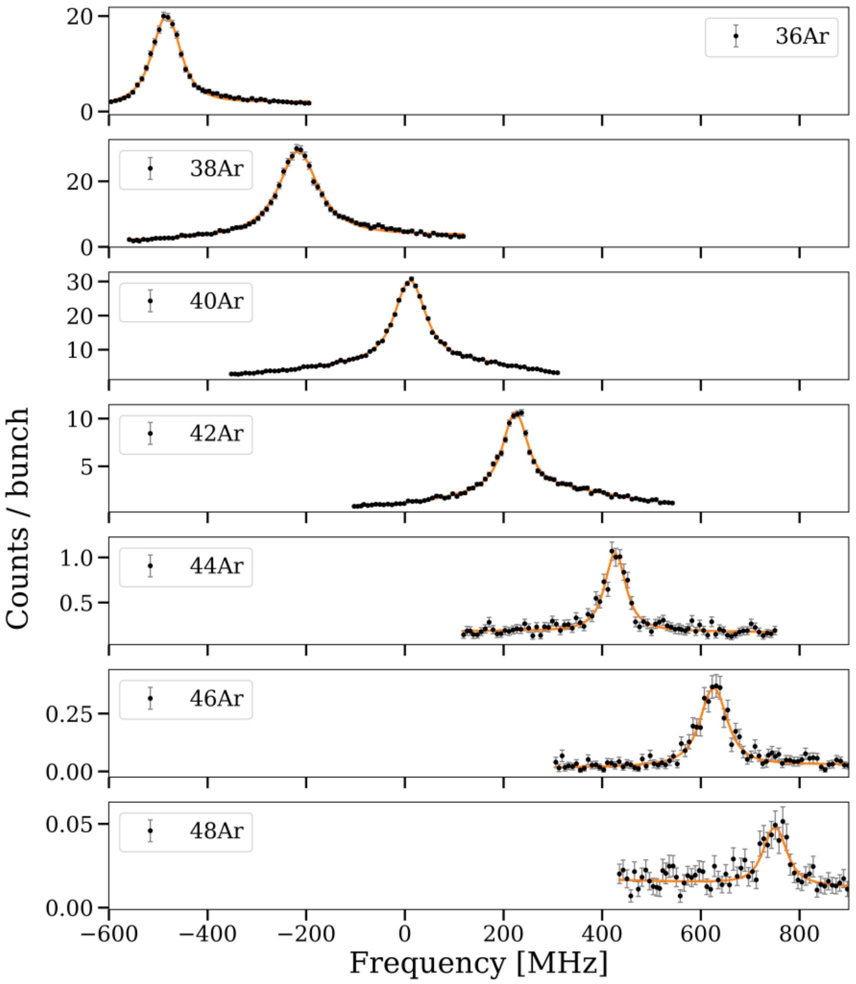
Part I

Argon

CRIS-ISOLDE campaign · $^{39-47}Ar$

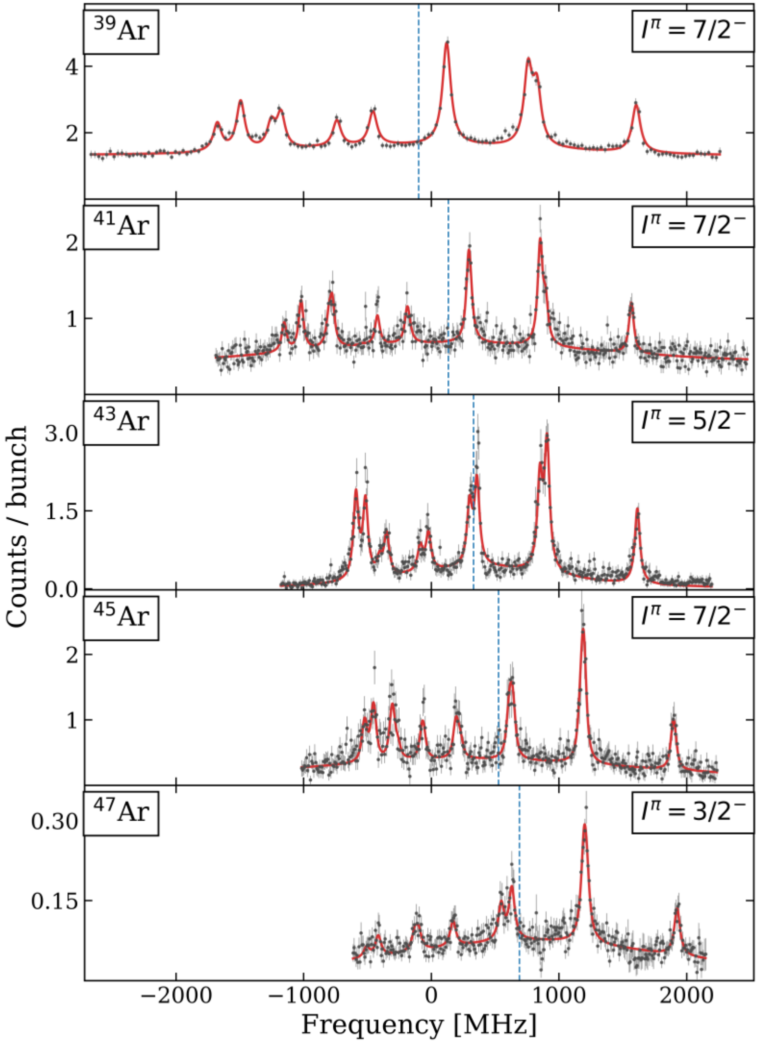
The Ar chain — CRIS campaign at ISOLDE

$^{39-47}$Ar hyperfine spectra recorded in the 2025 CRIS run



Even- even Ar isotopes, no hyperfine structure because of I=0

- Extended the Ar chain across $f_{7/2}$ and over the shell closure **N = 28**
- **Even isotopes:** radii only
- **Odd isotopes:** nuclear EM moments dominated by odd neutrons.
- Ground-state spins confirmed for **^{45}Ar (I = 7/2)** and **^{47}Ar (I = 3/2)**.



Fitted hyperfine spectra of $^{39-47}$Ar (data · black; total fit · red)

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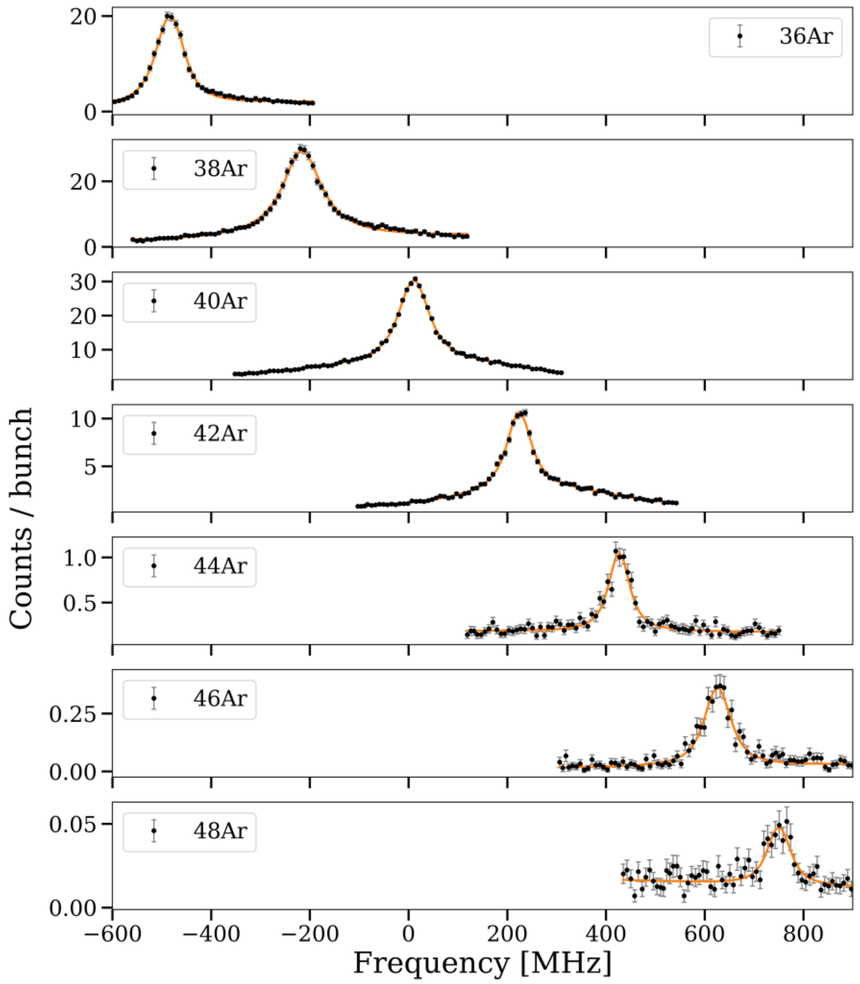

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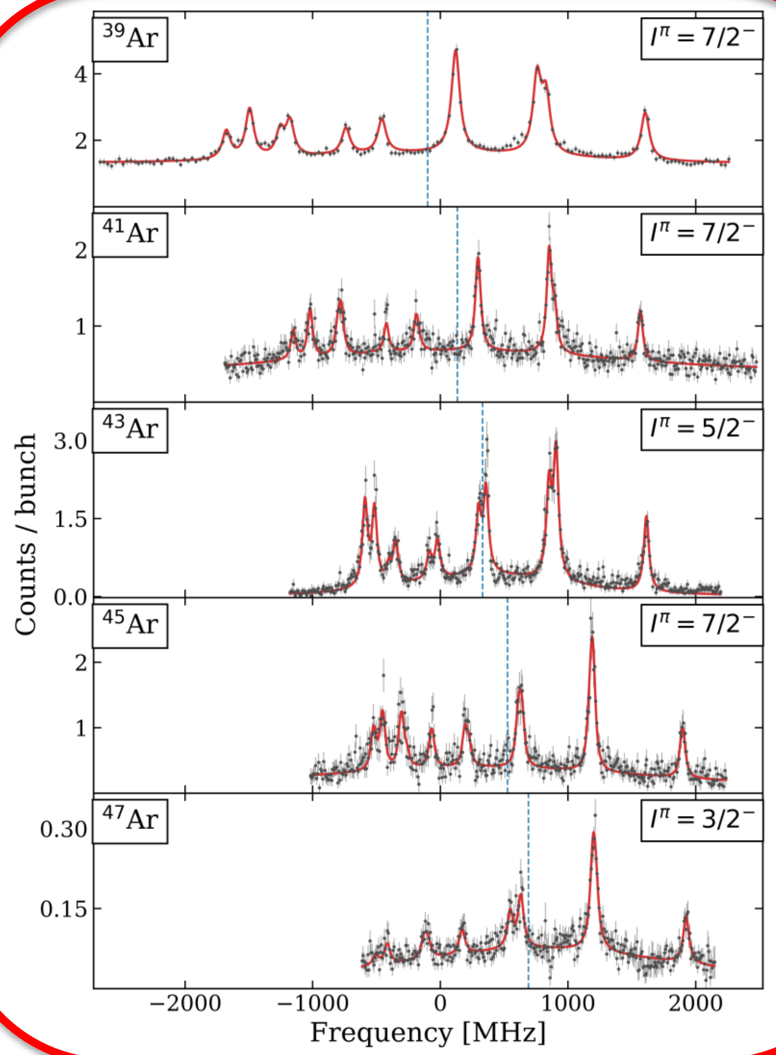
- In this talk we focus in **EM moments**.



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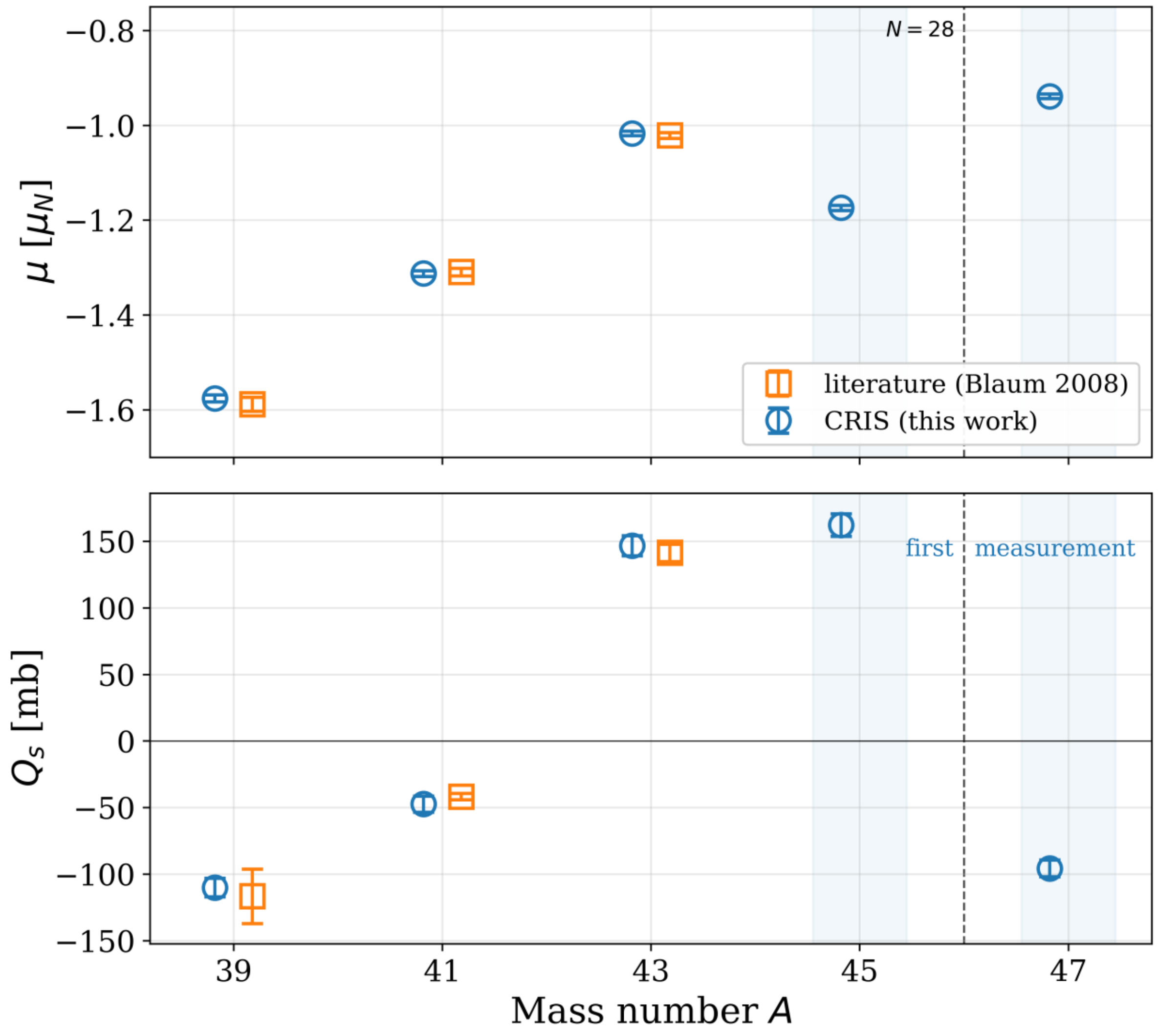
Moments — this work vs literature

CRIS matches the literature precision on ^{39,41,43}Ar and delivers the first moments of ^{45}Ar and ^{47}Ar



CRIS (blue open circles) vs literature (orange open squares: Blaum 2008)

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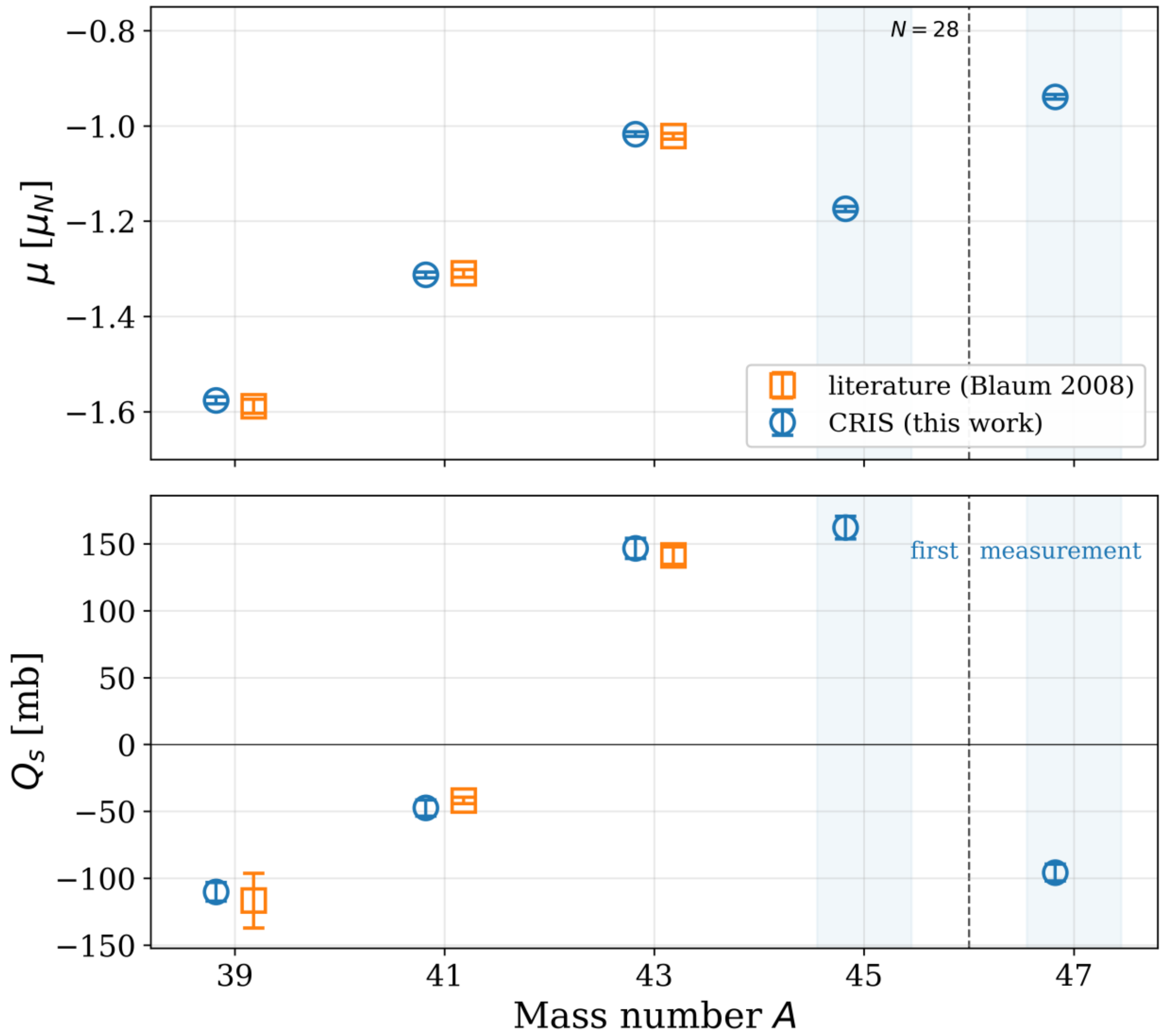
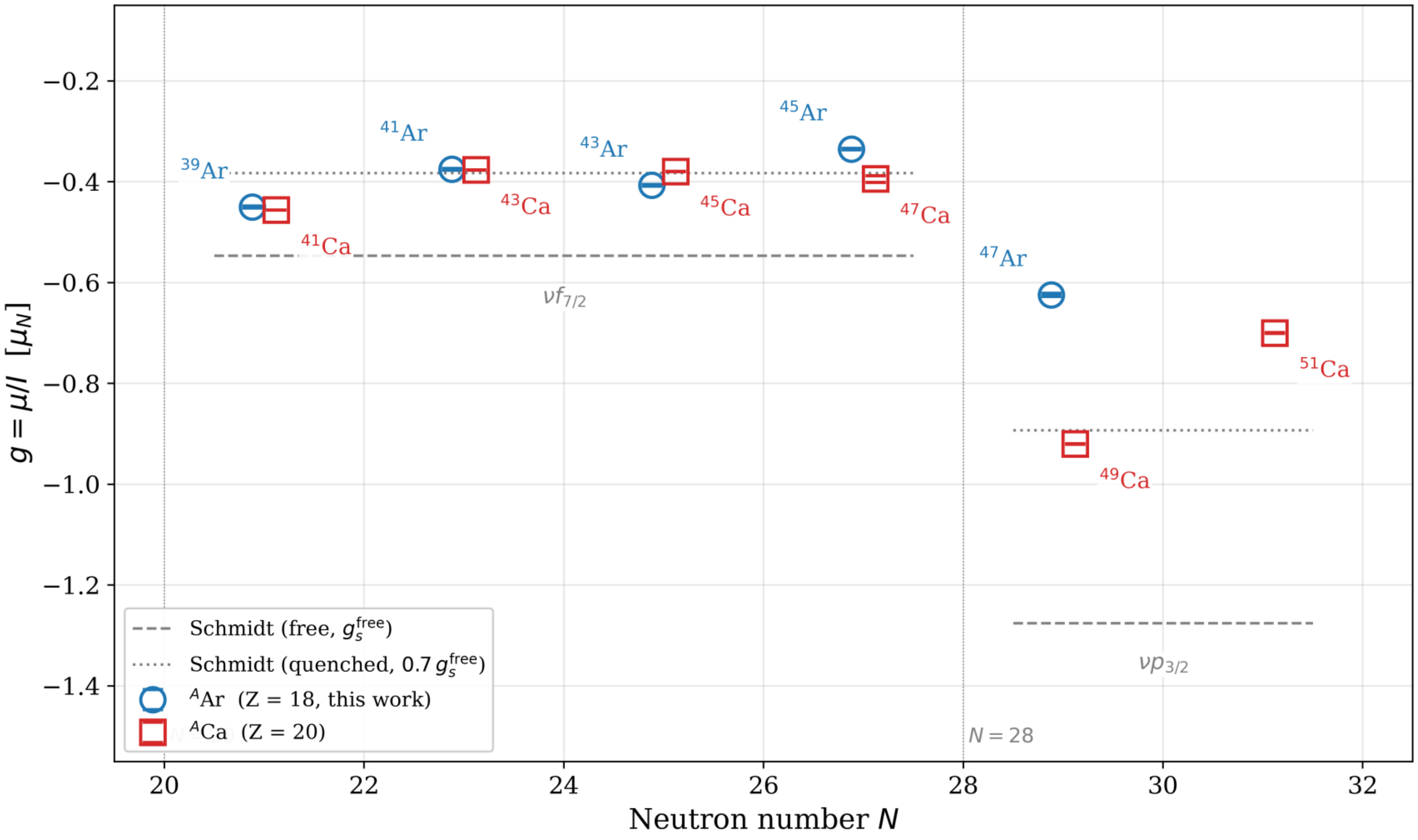


CRIS (blue open circles) vs literature (orange open squares: Blaum 2008)

- **^{39,41,43}Ar**: CRIS μ and Q_s **agree with the literature within 1σ.**
- The two new measurements in the neutron rich isotopes reveal the **increased sensitivity of the CRIS technique.** ^{47}Ar production rate was less than 1000 ions per sec.
- What do we actually learn from these 2 new measurements **one below and one over the shell closure**?

Magnetic dipole moments — g-factor systematics

μ probes the single-particle content of the neutron valence orbits



g-factors for Ar (blue) compared with the Ca chain (red)

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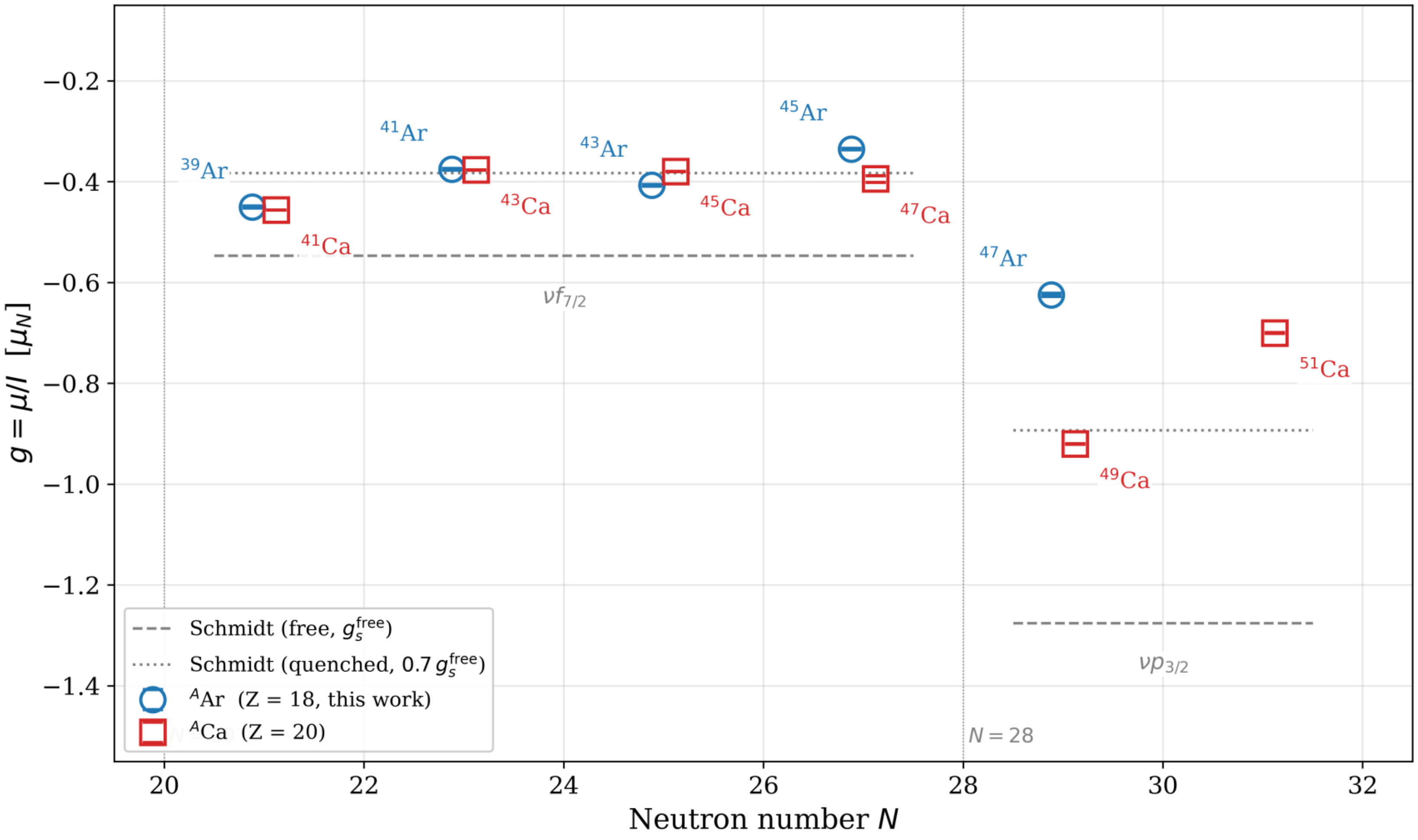

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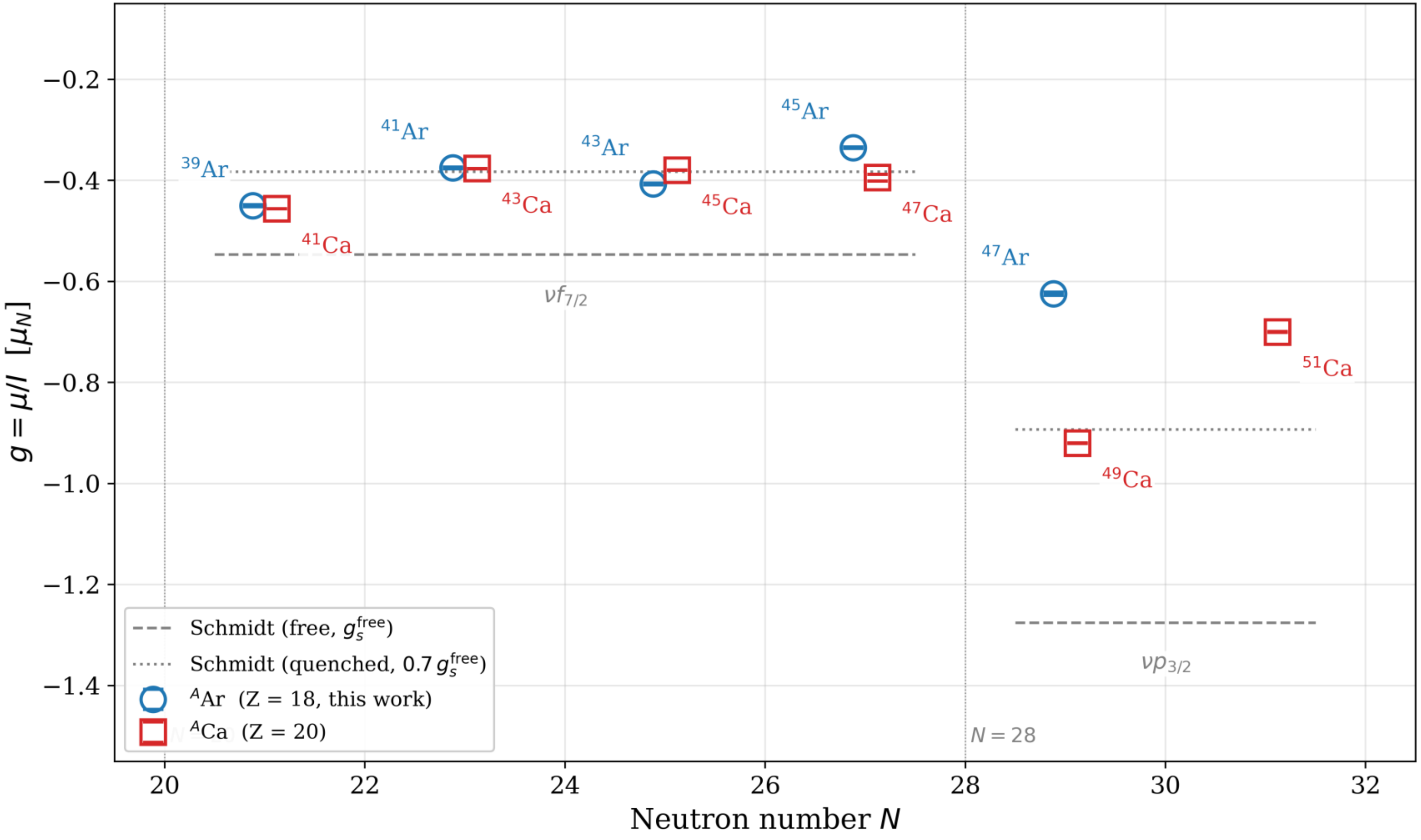

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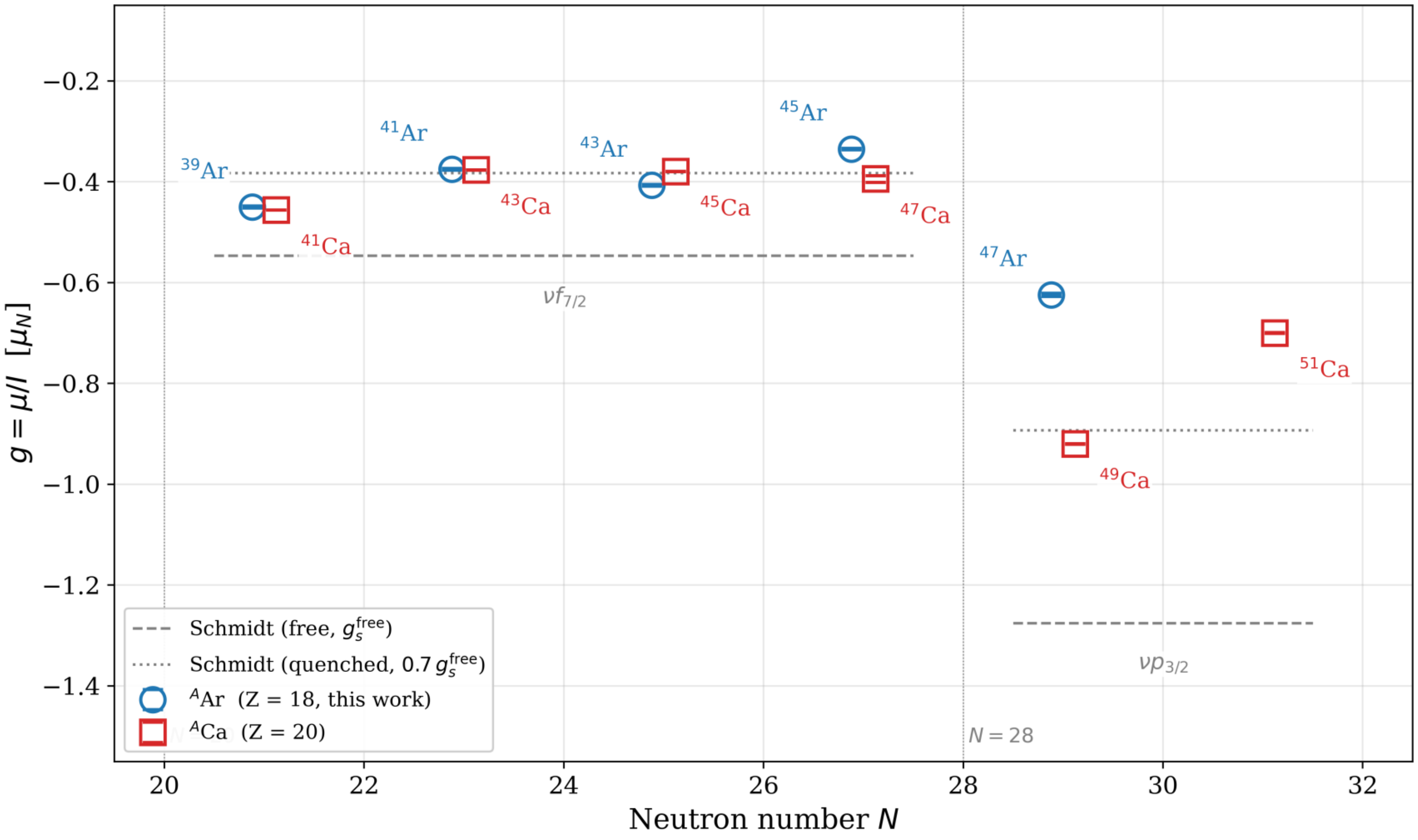

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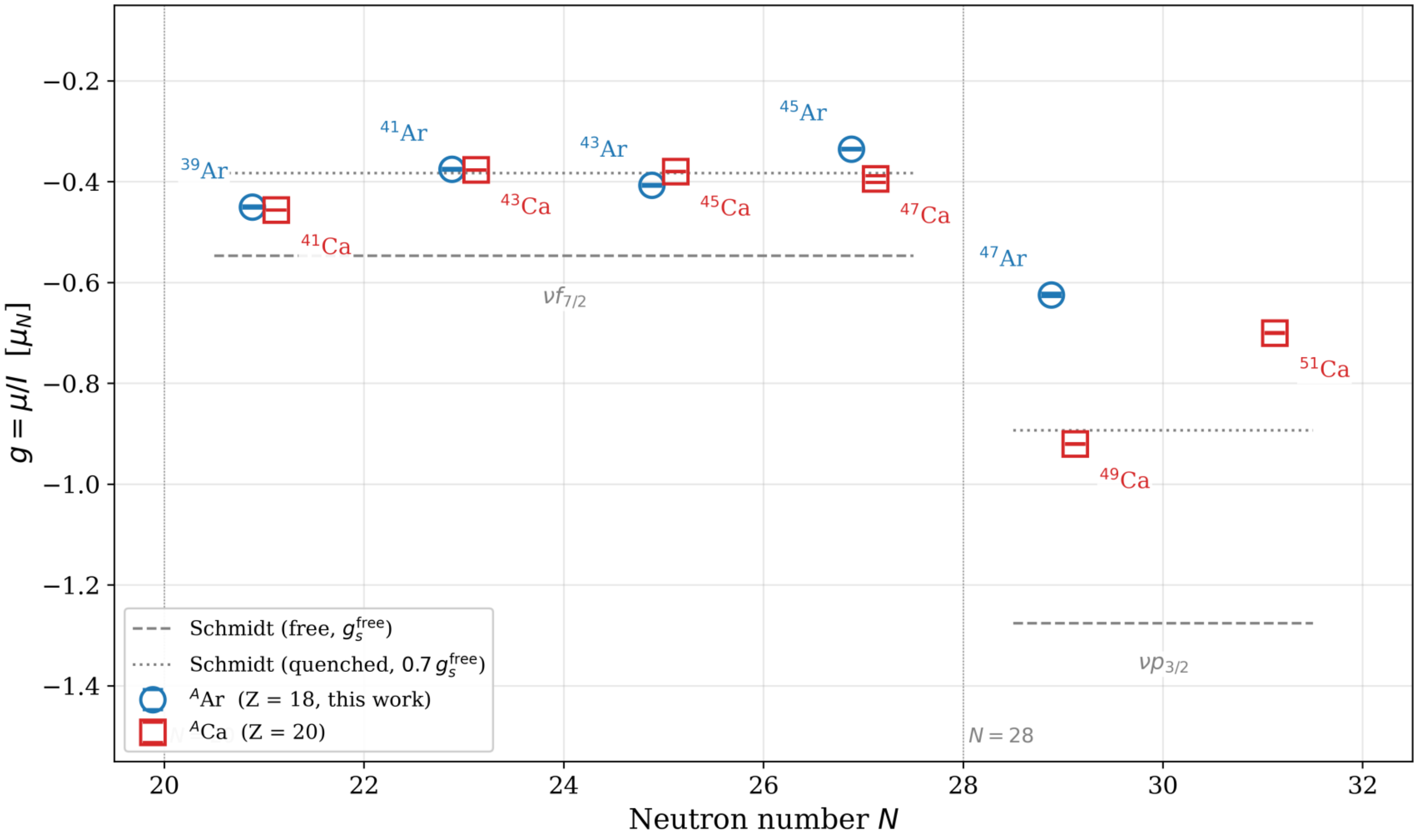

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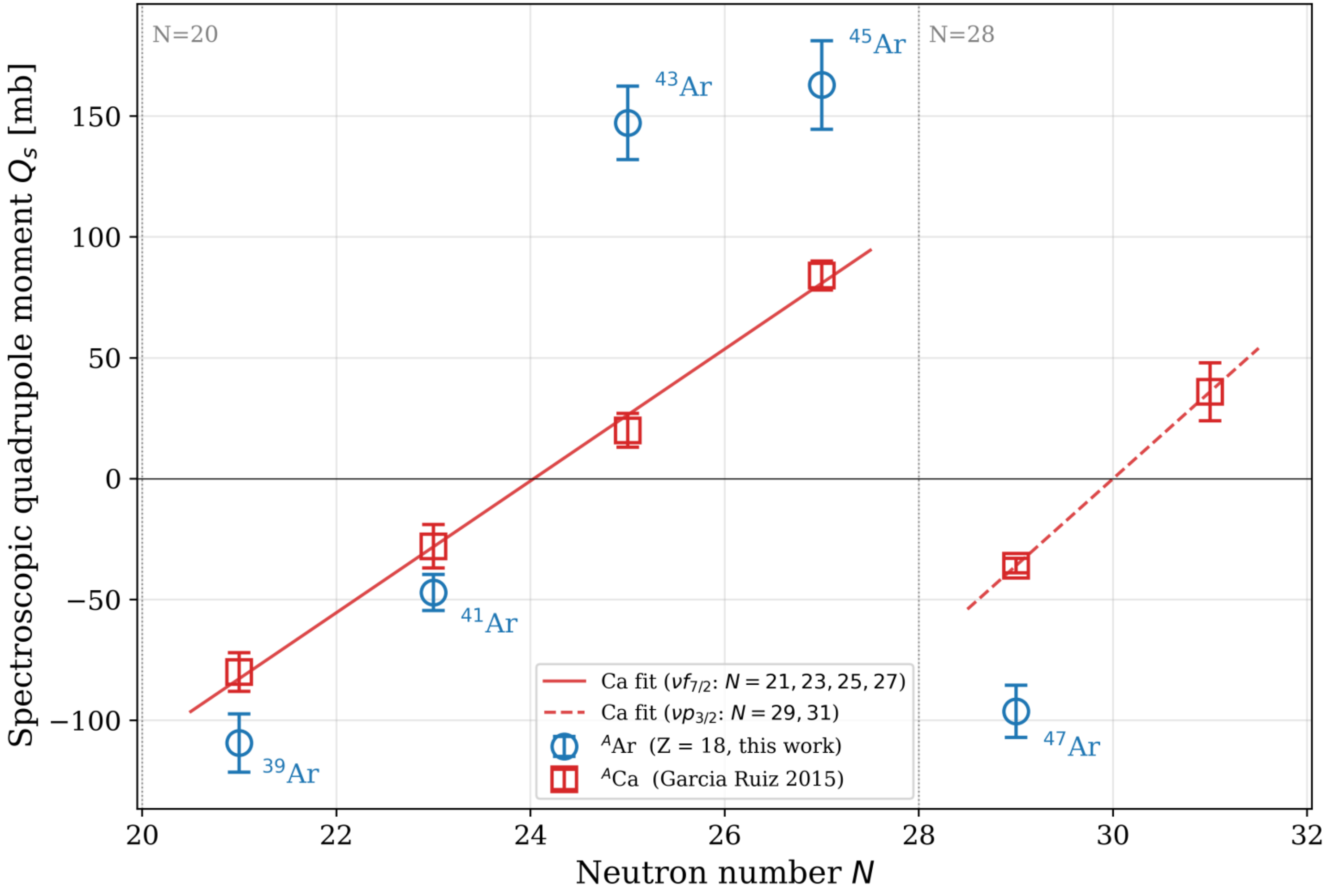
- N = 29 (^{47}Ar): **largest deviation in the chain** strong configuration mixing across N=28

Spectroscopic quadrupole moments

Enhanced mid-shell deformation and the N = 28 sign flip



Q_s(Ar) [blue] vs Q_s(Ca) [red, Garcia Ruiz 2015]; fits forced through (N=24, 0)

de Groote and Neyens, Handbook of nuclear physics

$$Q_S\left(j^{(n=2k+1)}, I = j\right) = -\frac{2j+1-2n}{2j-1} f(I,j)\, Q_{SP}$$

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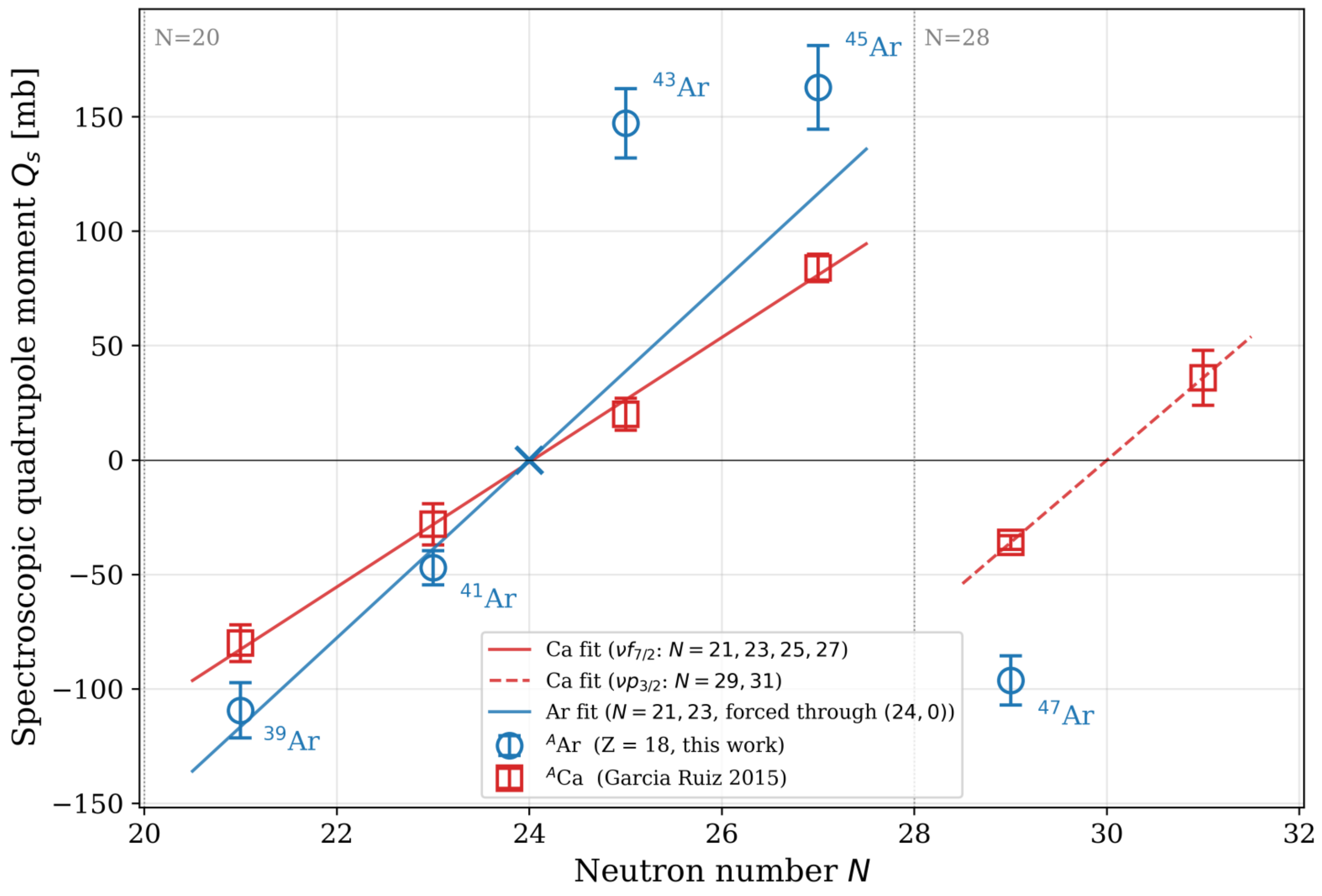

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- **Larger slope = softer proton core**: the 2πd3/2 in Ar sit at the proton Fermi surface, so every νf7/2 neutron induces a bigger core quadrupole than around the rigid Z = 20 core.

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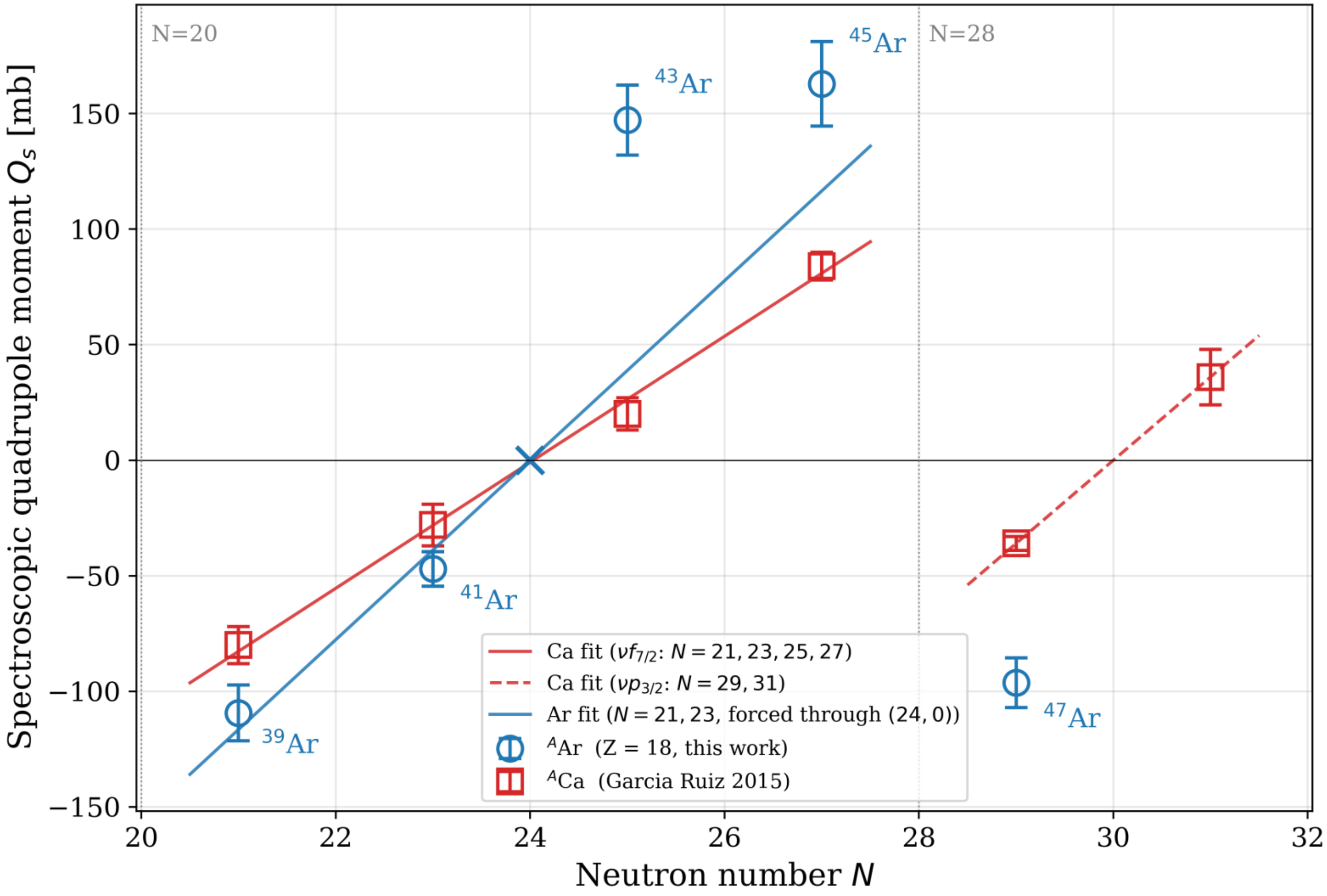

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> ▸ **Take-home: N = 28** is not rigid at Z = 18, the Ar Q_s and g factors show that the shell closure starts to **collapse**.

Part II

Vanadium

IGISOL campaign · $^{46-52}V$

Finding the best spectroscopy transition — offline survey

Stable $^{51}V^{+}$ studied offline to pick the most efficient line before the online run

FIRST COLLINEAR LASER SPECTROSCOPY STUDY OF VANADIUM ION

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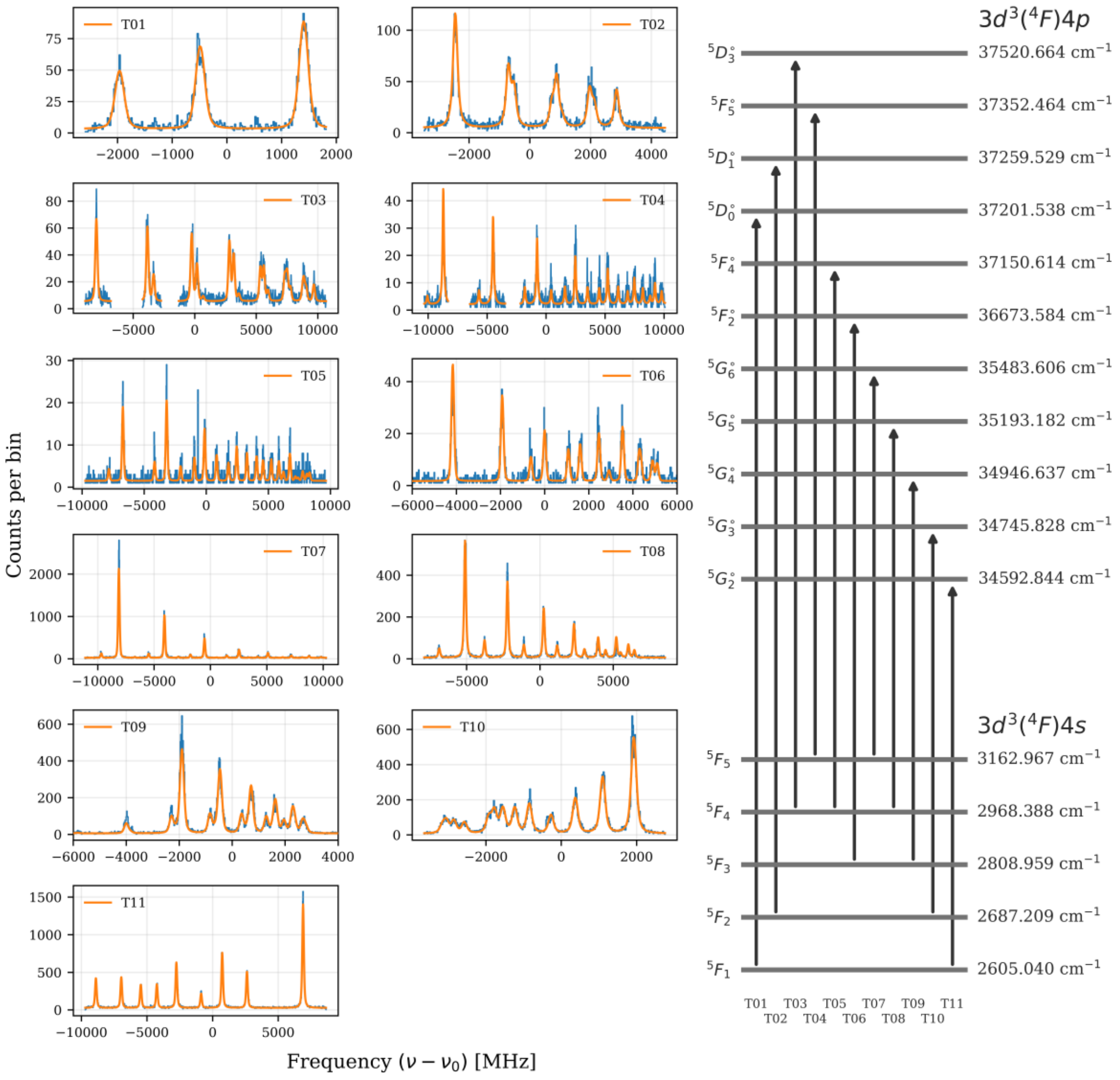
- **11 candidate transitions** from the $3d^34s \rightarrow 3d^34p$ manifold surveyed on stable $^{51}V^{+}$.
- Figure of merit: **spectroscopic efficiency** = photons detected per incident ion
- **Best line selected was T11** and carried into the online run on the exotic isotopes
- **Offline ^{51}V A, B constants** fix the calibration for the online extraction of μ.

Offline work published: **Karadimas et al., Sci. Rep. 16, 13670 (2026)**



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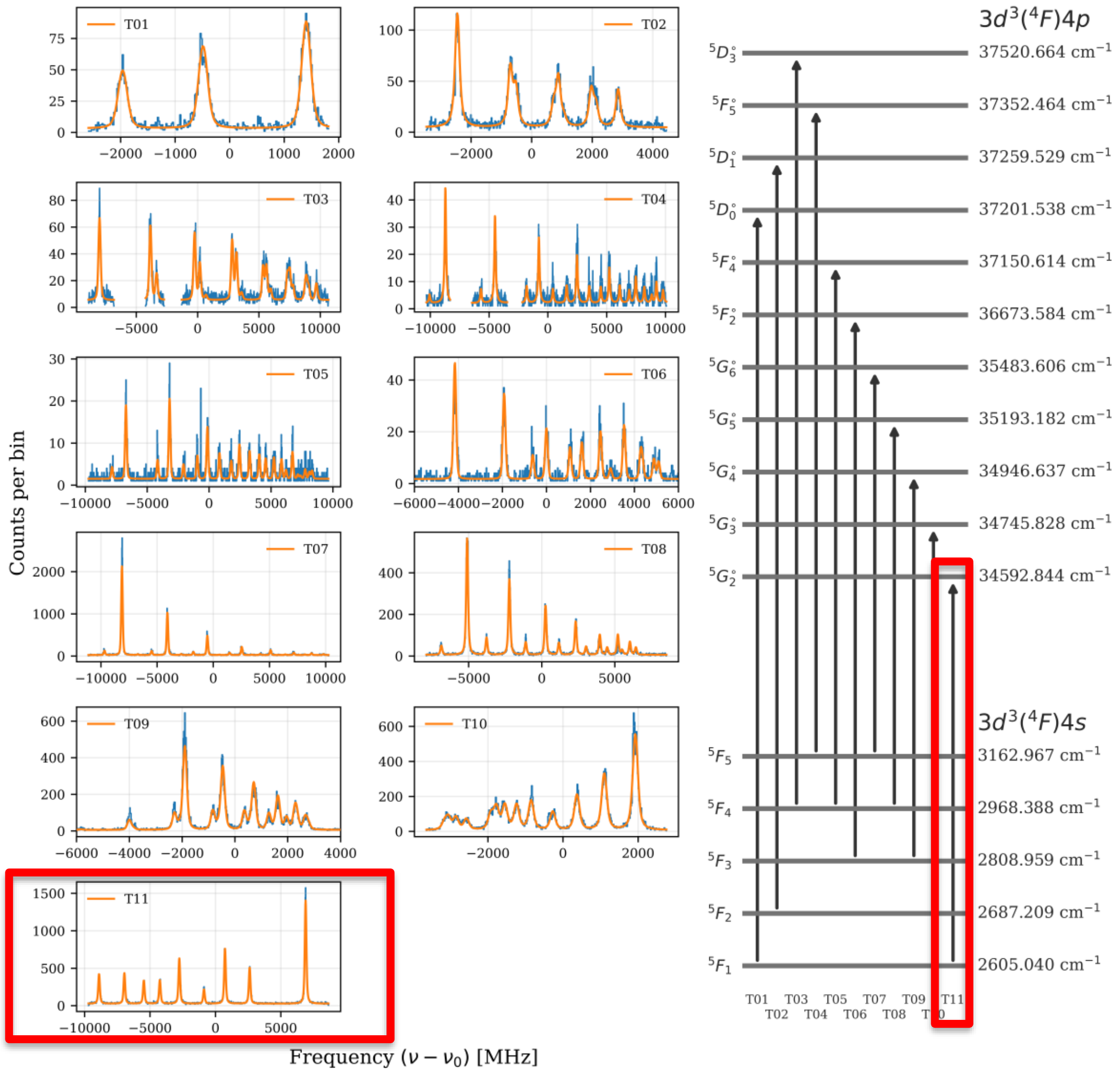
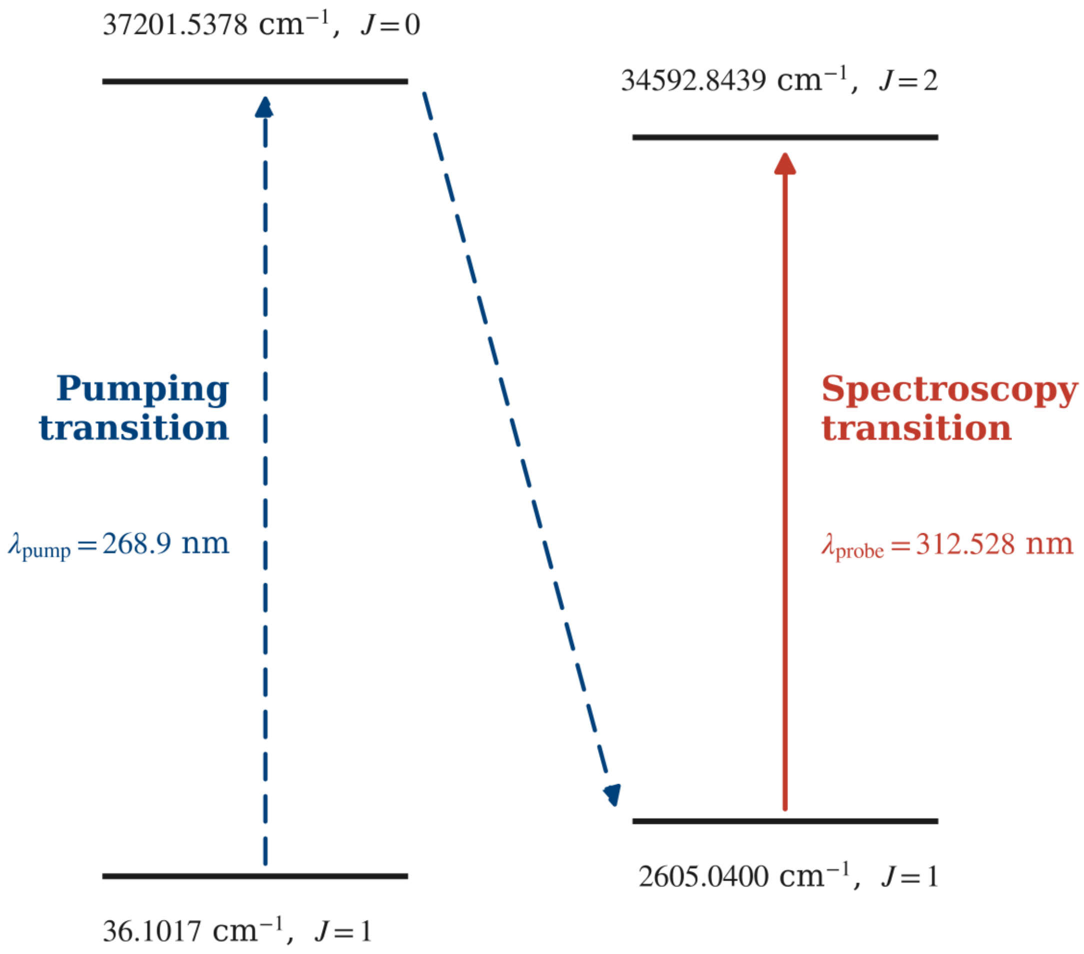


Boosting sensitivity with optical pumping

Populating a metastable level enhances the spectroscopy signal



V^{+} level scheme — pump → metastable, then probe on 312.5 nm

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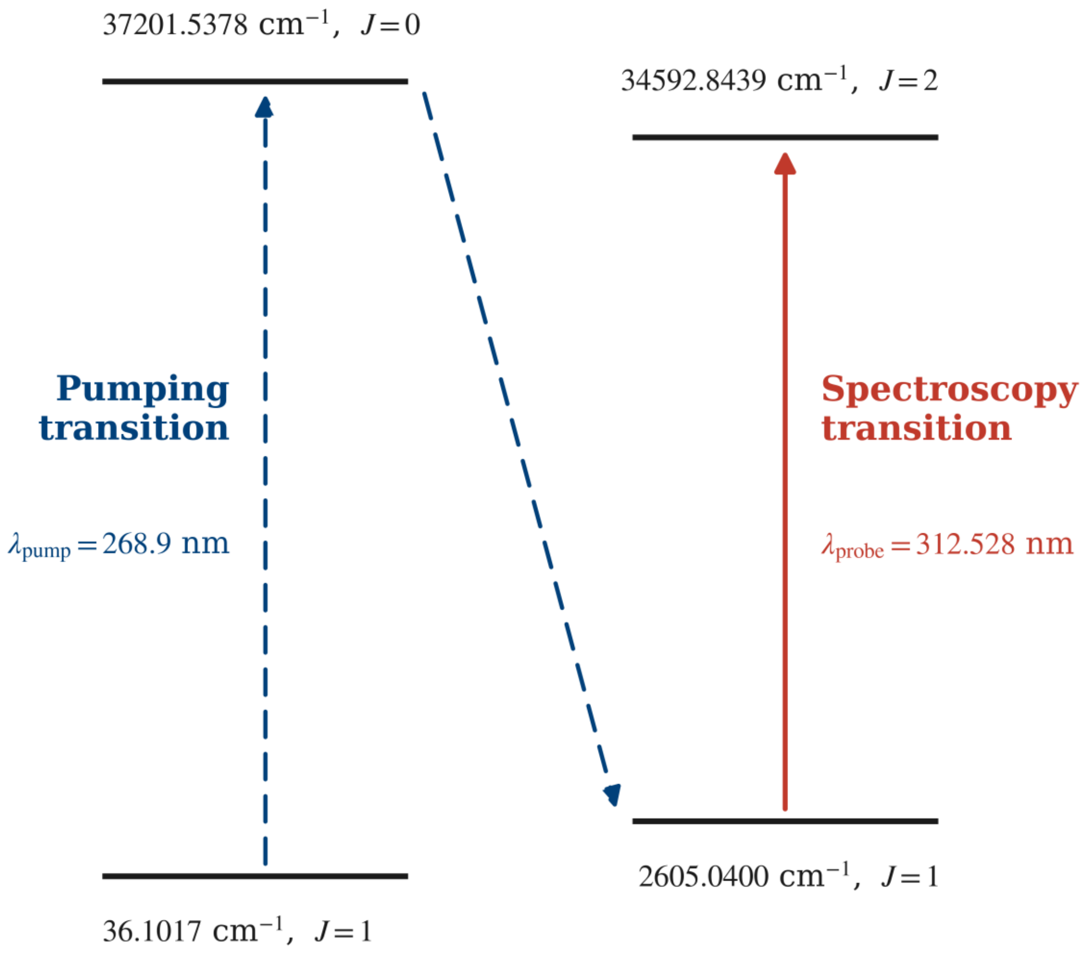
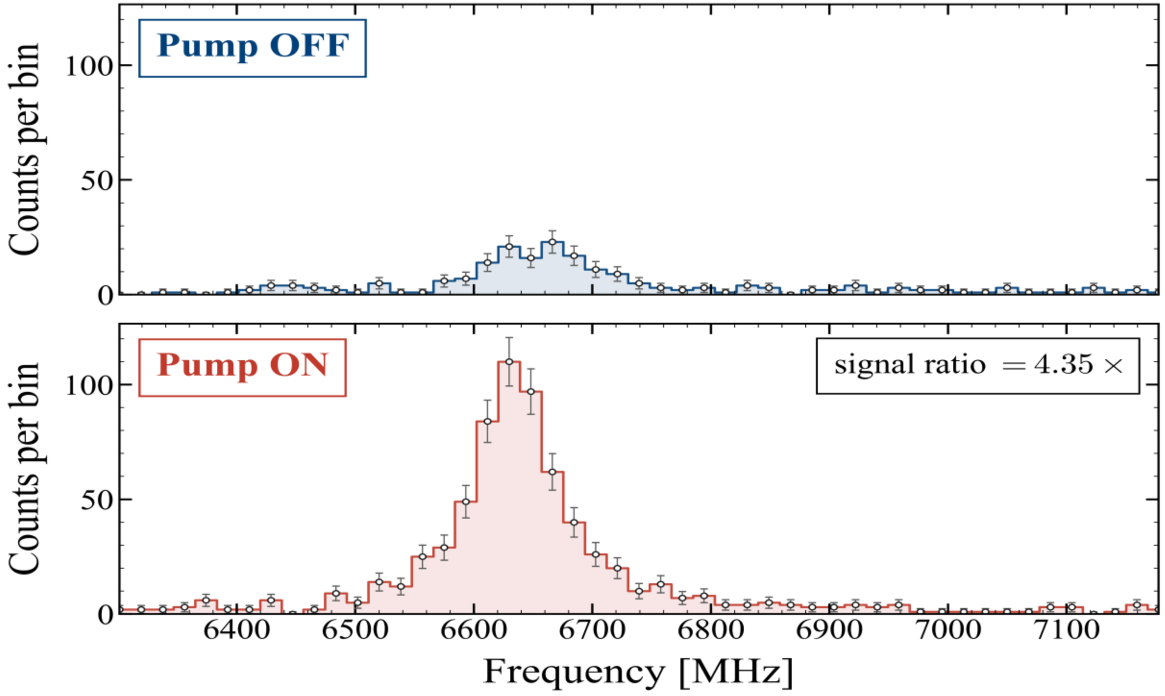


V⁺ level scheme — pump → metastable, then probe on 312.5 nm

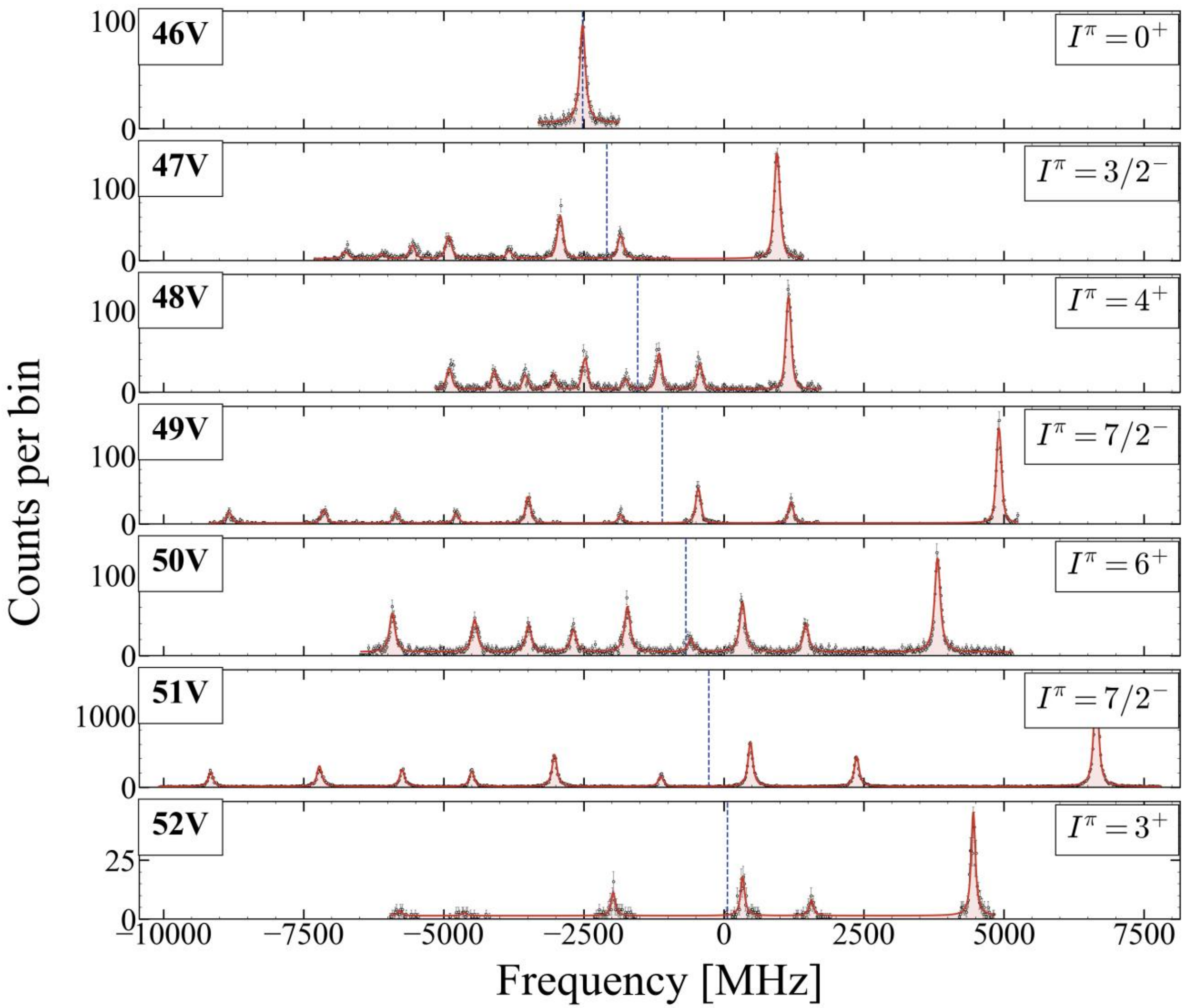


Signal on the ^{51}V line without / with the pump laser → ≈ 4× gain

- Pump laser at **268.9 nm** transfers ions to a long-lived metastable state.
- Spectroscopy performed on the **312.5 nm** probe transition.
- **≈ 4× signal enhancement** — essential for the short-lived exotic isotopes.

V isotope chain — all proposed isotopes measured

From N = Z to beyond N = 28



Merged online scans of $^{46-52}V^{+}$; dashed line = fitted centroid

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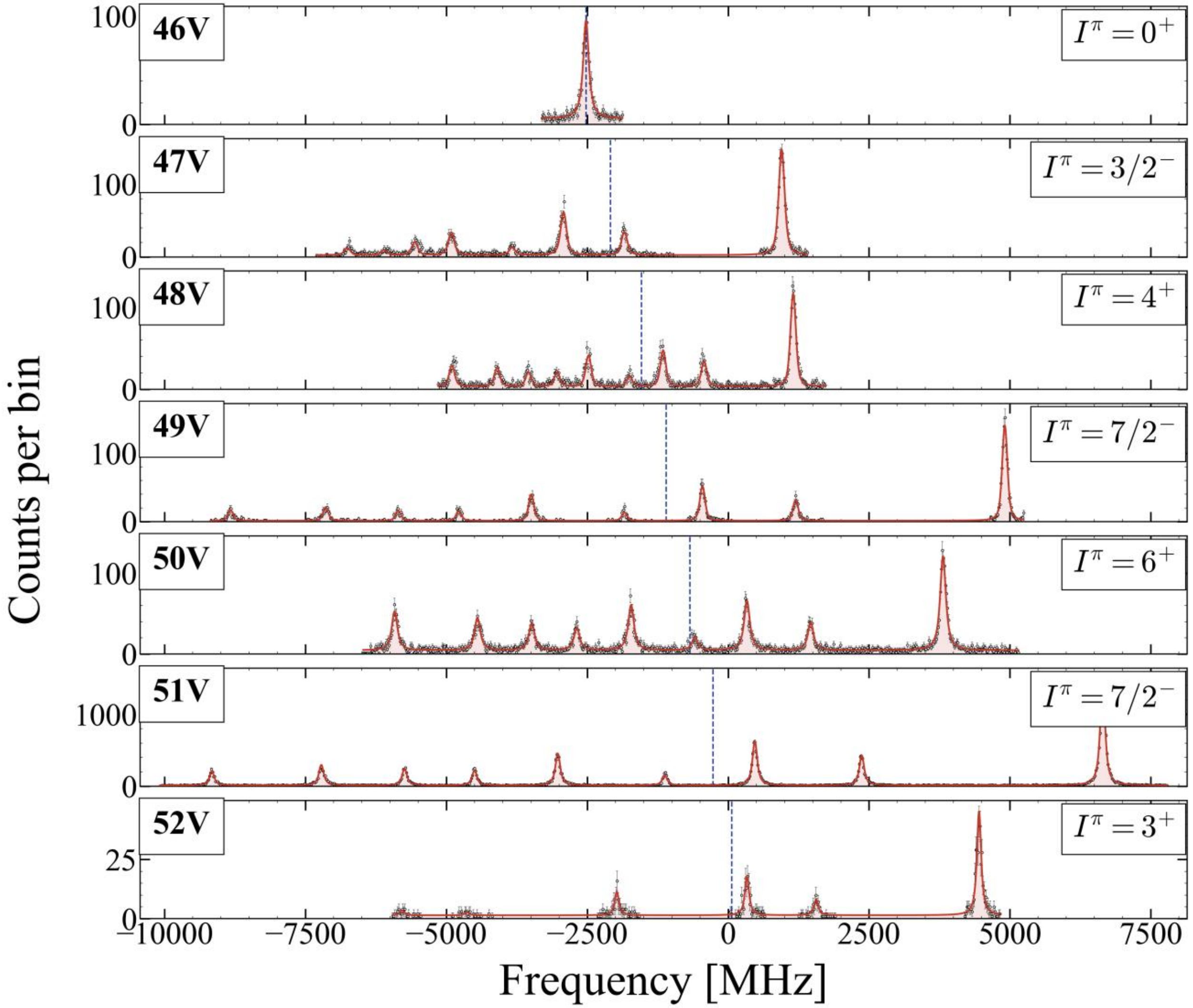
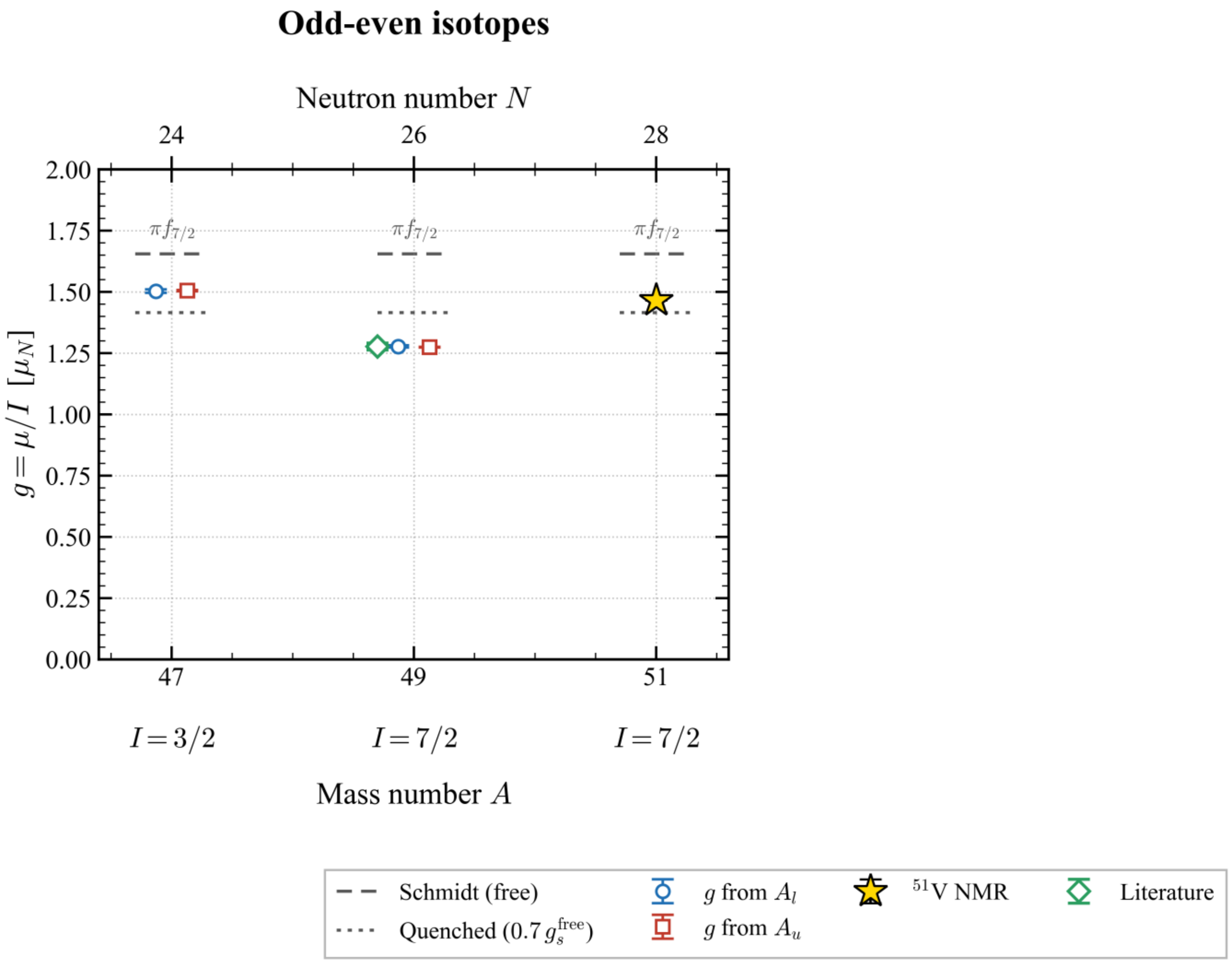


Merged online scans of $^{46-52}V^+$; dashed line = fitted centroid

- **All proposed isotopes successfully measured** — ^{46}V to ^{52}V
- Coverage from **N = Z** (^{46}V, N = 23) across the f7/2 shell to **beyond N = 28** (^{52}V, N = 29)
- Laser background only **~400 photons/s** on the PMT ⇒ sensitivity to very weak yield
- **First direct spin assignment for ^{52}V**: first measurement with collinear laser spectroscopy

Preliminary magnetic dipole moments

First look at g = μ / I along the V chain



g-factors from A_l (blue) and A_u (red); ^{51}V NMR reference (gold star)

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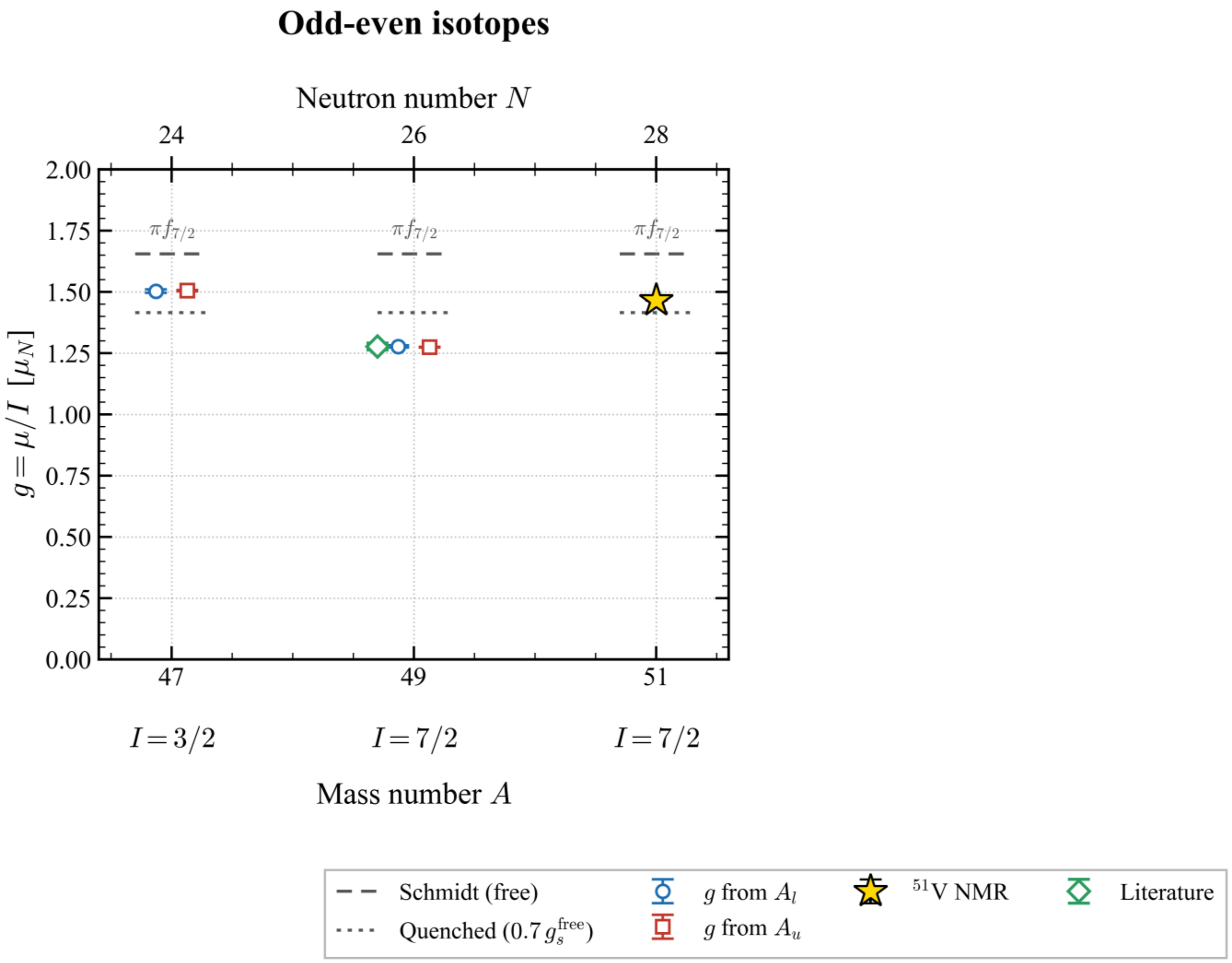

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- **^{47}V (I=3/2, not 7/2)** : higher-seniority ground state, same v=3-type mixing seen in ^{43}Ar **proton-side analogue**
- **^{49}V**: proton g dips **below quenched Schmidt** hint of mild proton-side mixing approaching N=28.

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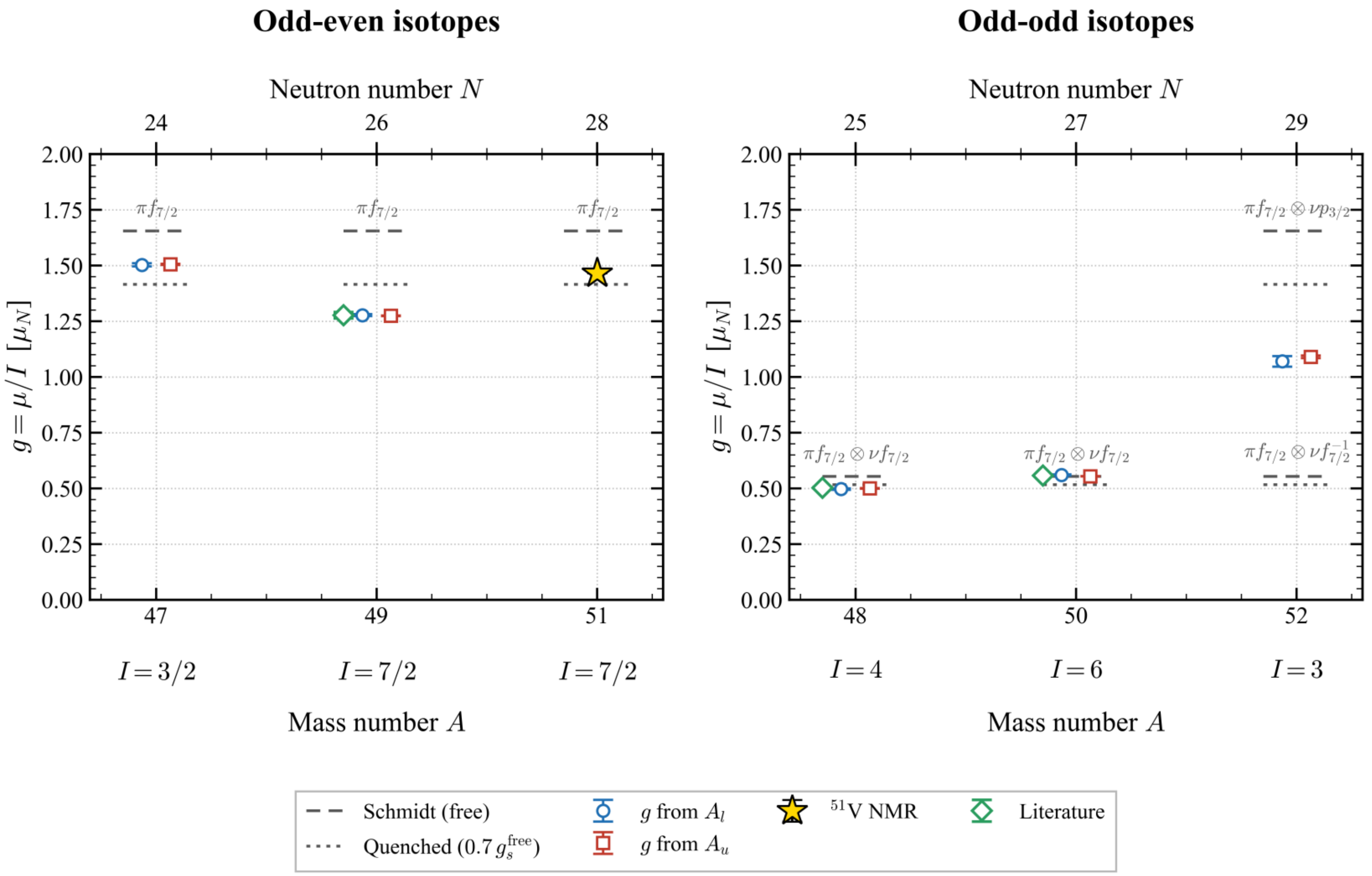

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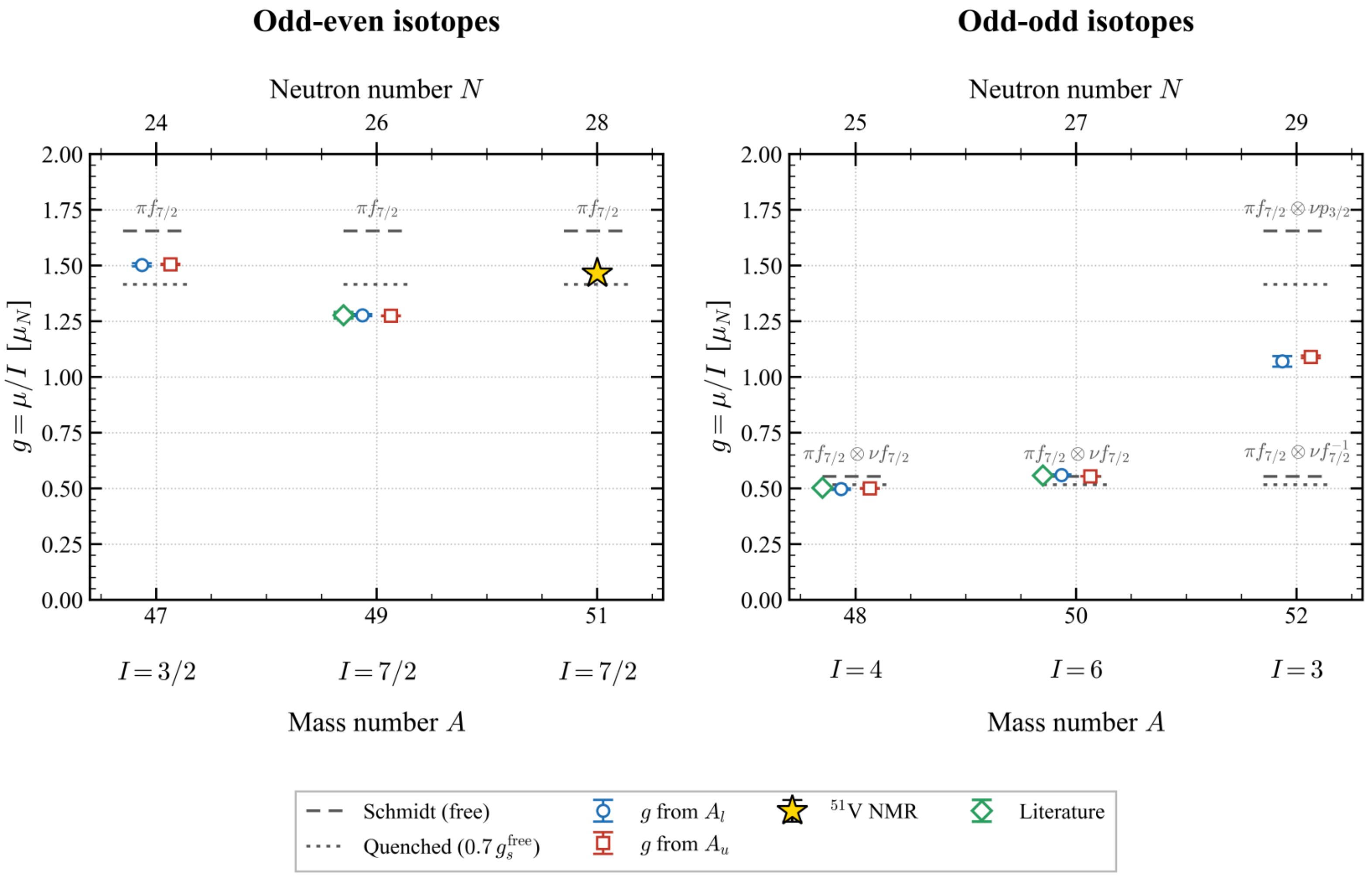

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Odd - odd

- **^{48}V, ^{50}V (πf7/2⊗νf7/2)**: g factors in agreement with **additivity** of πf7/2 and νf7/2.
- **^{52}V (I=3, πf7/2⊗νp3/2)**: neutron crosses into p3/2 at N=29 **configuration mixing across N=28**, same shell-crossing signature as ^{47}Ar, now seen from the proton-coupled side.

Conclusions and Outlook

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- **Ar and V probe different aspects of nucleon nucleon interaction:** Ar (even Z) is **neutron-driven** with the $\pi d_{3/2}$ core only polarised; V (odd Z) is **proton-driven,** with the odd $\pi f_{7/2}$ proton directly coupled to $\nu f_{7/2}$ ($N \leq 28$) or $\nu p_{3/2}$ ($N \geq 29$).

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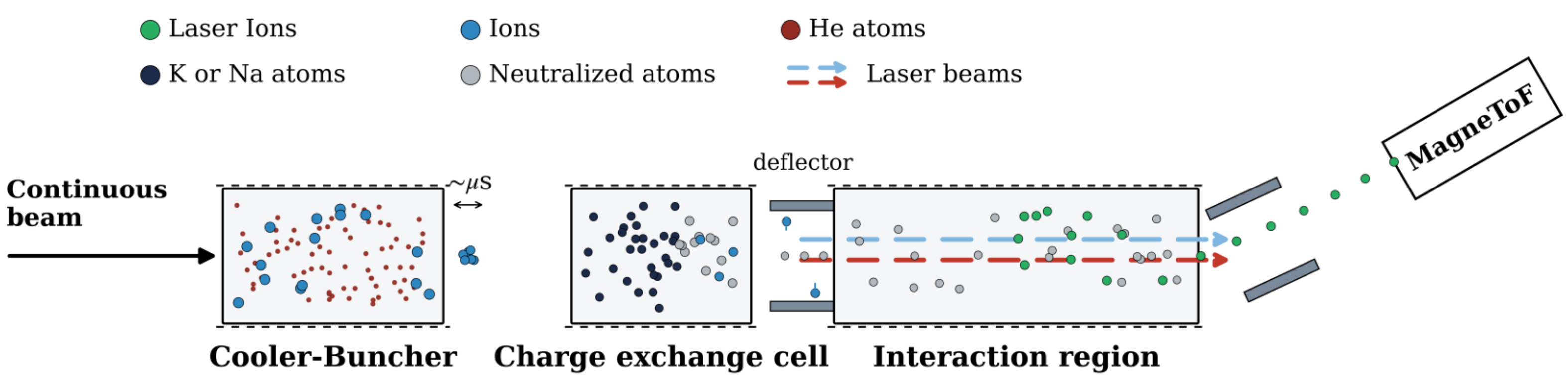
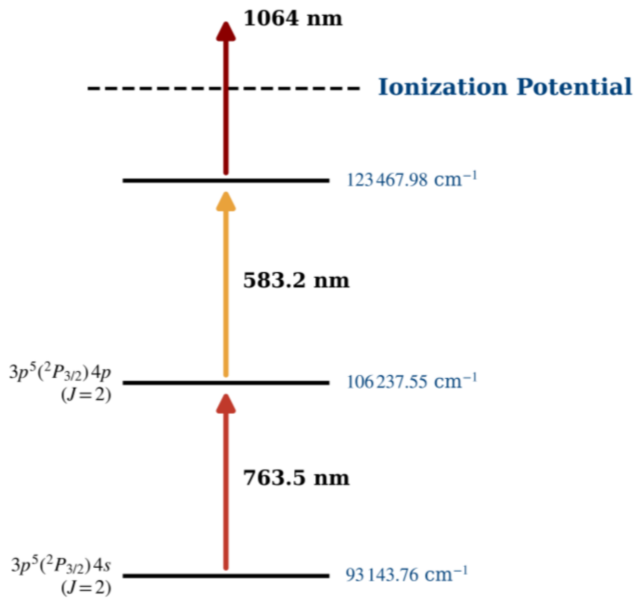
- **Going lighter, CLS below Ar** → Cl, S, P, Si chains are largely **unexplored by laser spectroscopy.**

Thank you for your attention!

Special thanks to Nuclear Moments Group, CRIS and IGISOL collaborations.

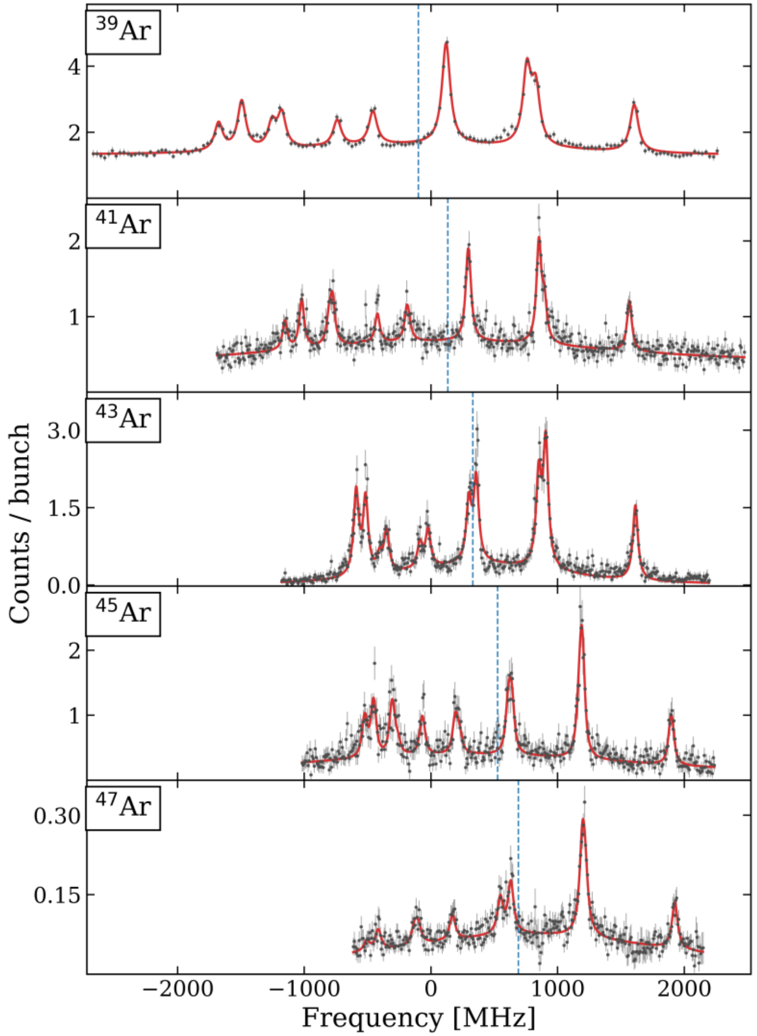




Ionisation scheme used for Ar I

Scanning the first step resolves the **hyperfine pattern**. In the end, only atoms that were **on resonance** with that first step are re-ionized and measured.

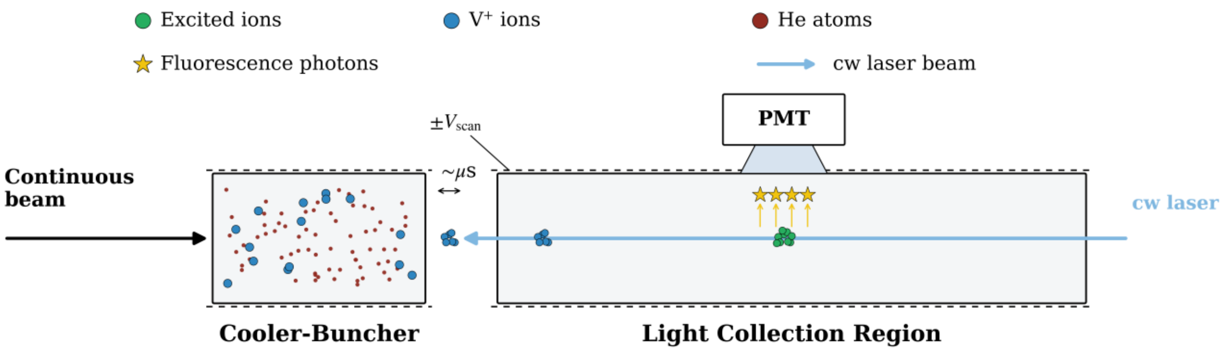
- Extended the Ar chain across $f_{7/2}$ and over the shell closure **N = 28**
- Ground-state spins confirmed for **^{45}Ar (I = 7/2)** and **^{47}Ar (I = 3/2)**.



Fitted hyperfine spectra of $^{39-47}$Ar (data · black; total fit · red)

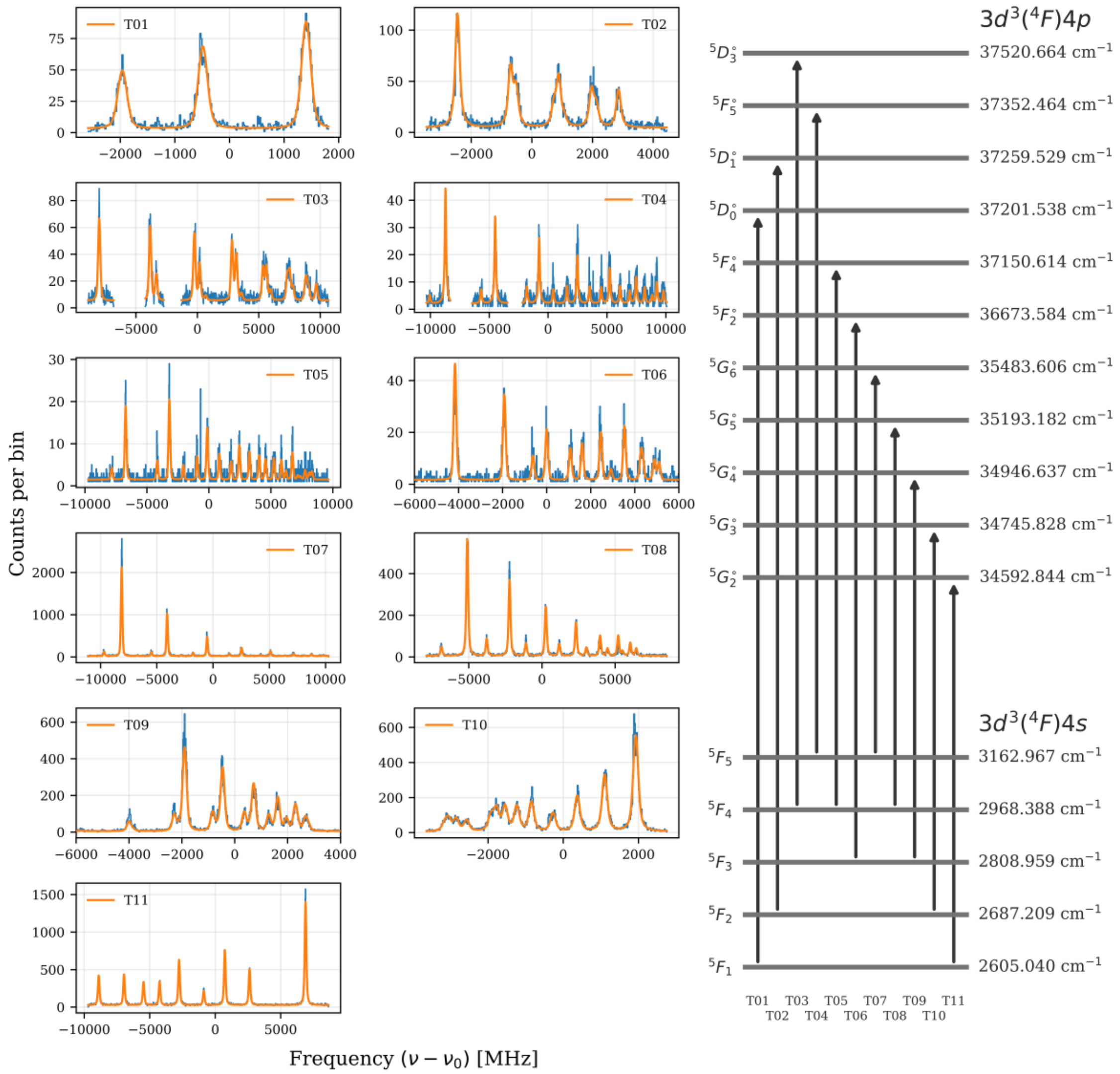
Finding the best spectroscopy transition — offline survey

Stable $^{51}V^{+}$ studied offline to pick the most efficient line before the online run



- **11 candidate transitions** from the $3d^34s \rightarrow 3d^34p$ manifold surveyed on stable $^{51}V^{+}$.
- Figure of merit: **spectroscopic efficiency** = photons detected per incident ion
- **Best line selected was T11** and carried into the online run on the exotic isotopes
- **Offline ^{51}V A, B constants** fix the calibration for the online extraction of μ

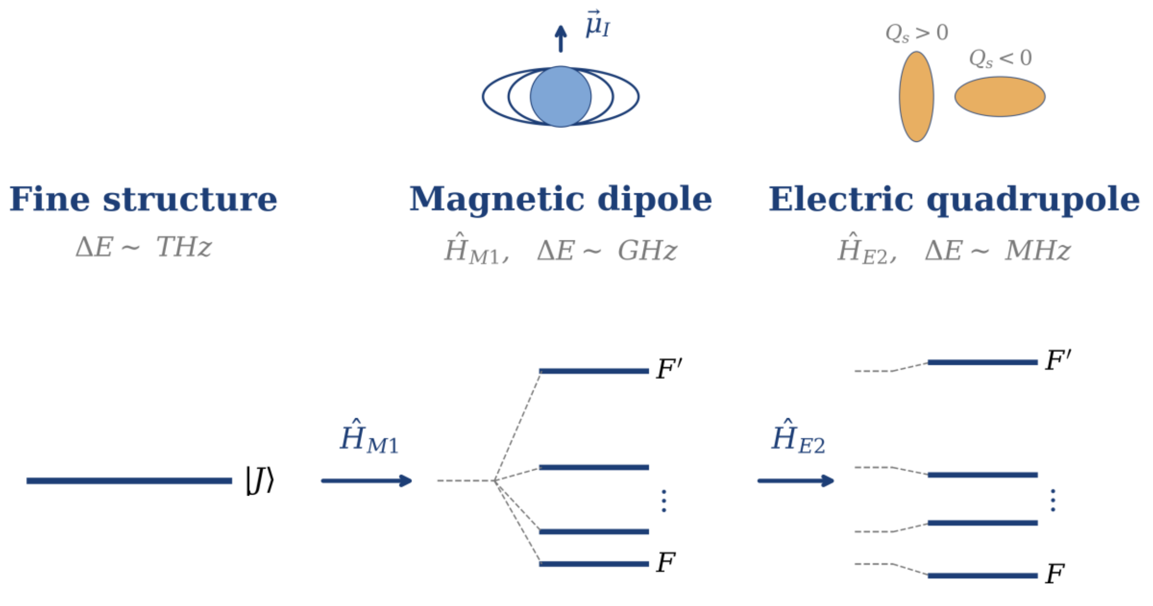
11 candidate transitions T01–T11 measured offline on $^{51}V^{+}$



Karadimas et al., **Sci. Rep. 16, 13670 (2026)**

Collinear laser spectroscopy

The hyperfine fingerprint delivers μ, Q_s and $\delta\langle r^2\rangle$ model-independently



$F = I + J \quad \cdot \quad A \leftrightarrow \mu \quad \cdot \quad B \leftrightarrow Q_s$

Two techniques, one goal:

CRIS @ ISOLDE → Ar isotopes

- Step-wise resonance ionisation, ion detection
- Near-background-free → reach the most exotic isotopes

CRIS: Collinear Resonance Ionisation Spectroscopy

CLS @ IGISOL → V isotopes

- Gas-cell stopping ideal for refractory V
- Fluorescence detection on a fast ionic beam

CLS: Collinear Laser Spectroscopy

Conservation of hyperfine parameter ratio in Ar