

Charge radii and moments of $^{43-50}\text{Sc}$ ($Z = 21$), crossing $N = 28$, measured with bunched beam collinear laser spectroscopy at COLLAPS

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$\text{Sc: } Z = 21$	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55
$\text{Ca: } Z = 20$	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
$K: \text{ } Z = 19$	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53

General physics motivations: in Ca region ($Z = 20$)

➤ 3N forces:

- an important role to describe shell structure of n-rich Ca isotopes.
- needed to explain $N = 28$ shell closure using microscopic interaction.

----- J.D. Holt et al., J. Phys. G: Nucl. Part. Phys. 39, 085111 (2012).

★ The calcium and neighboring isotopic chains lie at the frontier of theoretical calculations with 3N forces.

----- K. Hebeler, J.D. Holt et al., Annu. Rev. Nucl. Part. Sci. 65, 457 (2015).

➤ Ab-initio calculation:

- binding energies/low-lying excitation spectra/charge radii/momenta in Ca region.

----- R.F. Garcia Ruiz et al., Nature Physics 12 (2016) 594; PRC 96, 044329 (2017)

★ The region around Ca provides an excellent experimental venue to confront predictions using ab-initio.

----- The 2015 LONG RANGE PLAN for NUCLEAR SCIENCE (United States)

➤ More theoretical methods:

- large scale shell models as used for ^{55}Sc low-lying excitation spectra

----- D. Steppenbeck et al., PRC accepted (2017) [arXiv:1710.07465](https://arxiv.org/abs/1710.07465)

- Density functions: describe the OES of Ca radii

----- P.-G. Reinhard and W. Nazarewicz PRC 95, 064328 (2017)

• Previous laser spectroscopy studies at ISOLDE

→ Provide nuclear ground state properties (**Nuclear spins, moments, and charge radii**)

	20										28					32		
Z = 21	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55		
Z = 20	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54		
Z = 19	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53		

IS-484 Ground-state properties of K-isotopes from laser spectroscopy

Results: PRL 110, 172503 (2013); Spins assignment/ proton shell re-inversion

PRC 90, 034321 (2014) : Shell evolution in K isotopes

PRL 113, 052502 (2014); p-n Pairing Correlations in the Self-Conjugate Nucleus ^{38}K

PLB 731, 97 (2014); Evolution of nuclear size above $N=28$

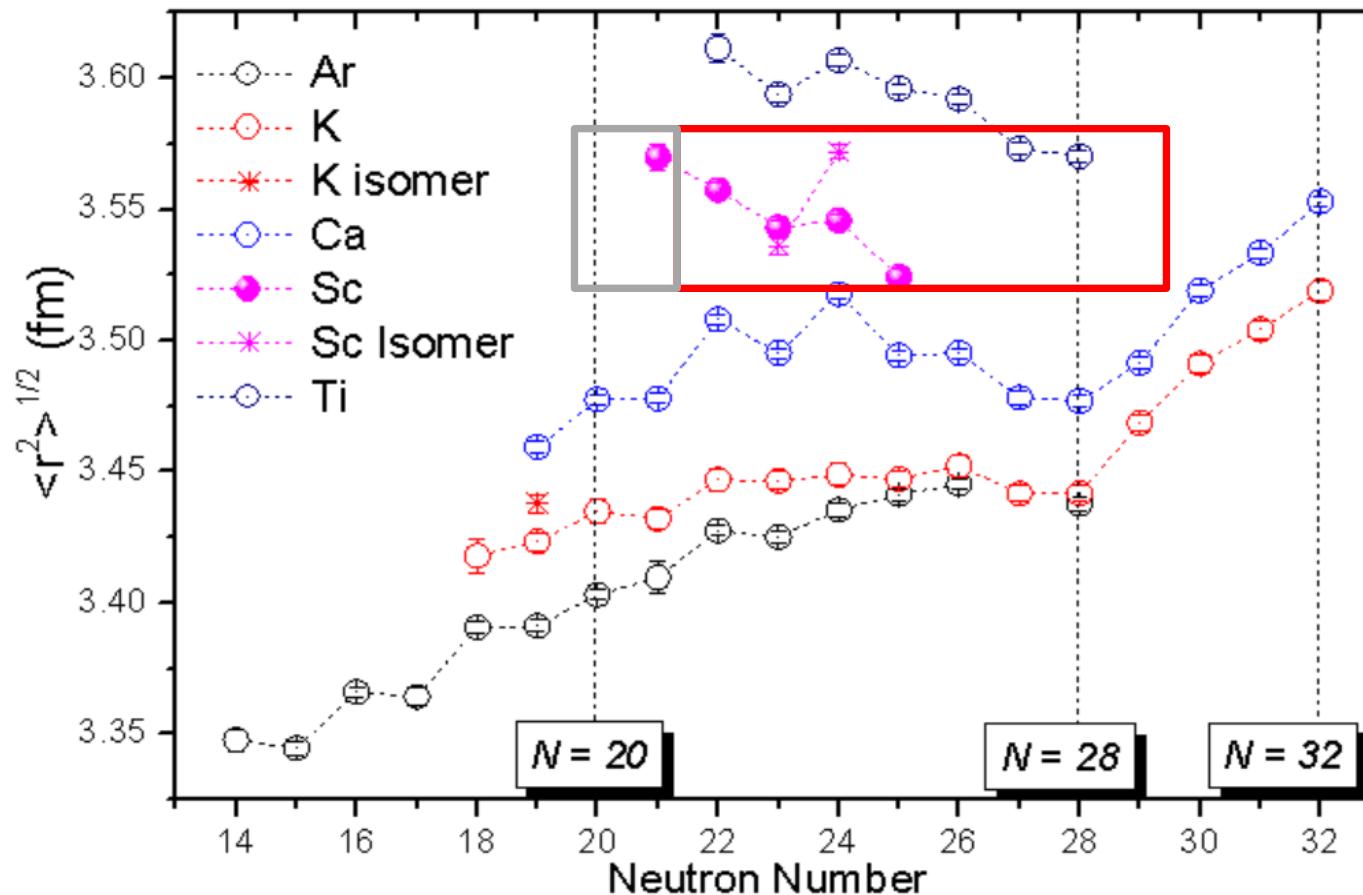
IS-529 Moments, Spins and Charge Radii Beyond ^{48}Ca

Results: PRC 91, 041304 (2015): Test of microscopic interaction NN+3N from chiral EFT

Nature Physics (2016): Test of ab-initio calculations

INTC-P-450: This proposal ($^{43-50}\text{Sc}$) @ at COLLAPS

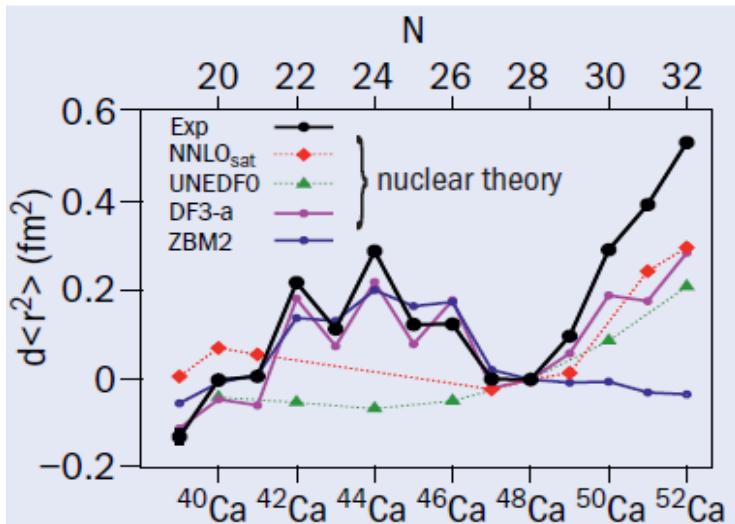
- Charge Radii Landscape: systematics in the region



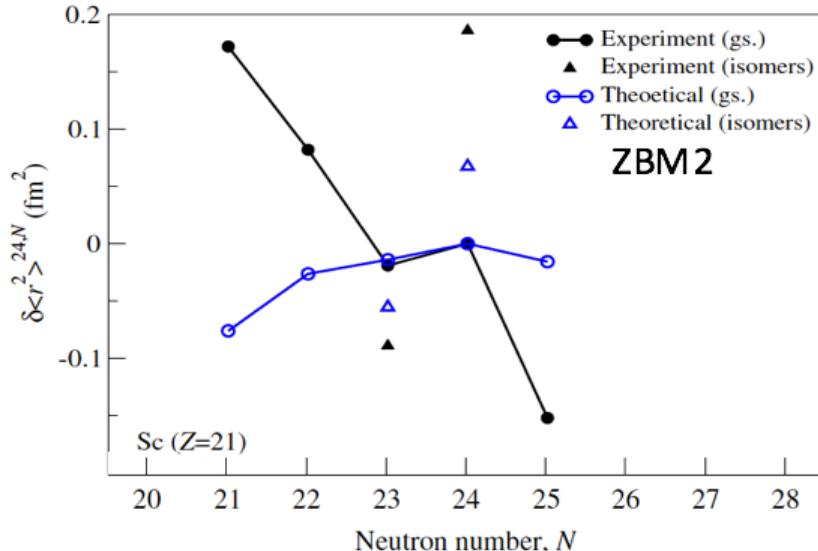
- The general behavior of Sc and Ti seems very different comparing with Ca, K
-- Experimental data is insufficient ! ! !
- Radii of Sc around $N = 28$ (investigated in this work)
- Radii of Sc approaching $N = 20$

• Charge Radii Landscape: benchmark for advanced nuclear theory

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



M Avgoulea et al., J. Phys. G: Nucl. Part. Phys. 38 (2011) 025104



- General trend of Ca radii can be predicted by most of the theory
-although the accurate description of charge radii is still a major challenge

- But for Sc, even the general trend of radii can't be predicted with ZBM2
- more experimental data is required to systematically investigate the general trend

- Ab-initio coupled-cluster calculations can be applied to $^{48-50}$ Sc Nature Physics 12 (2016) 594

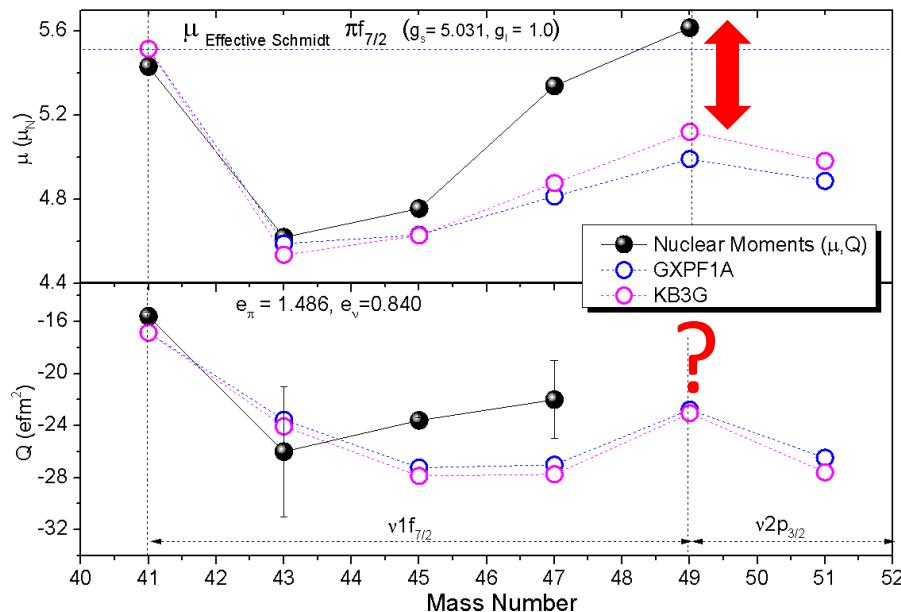
- New developed similarity renormalization group (IM-SRG) allows the extension of ab initio calculation to open-shell nuclei (e.g. $^{42-50}$ Sc) 50,55Sc; PRC 96, 044329 (2017) PRC (2017) accepted
Prediction for Sc radii is on going!!

- Additional theoretical effort has been put to study the OES of charge radii and firstly applied to Ca isotopes **Sc also ?**

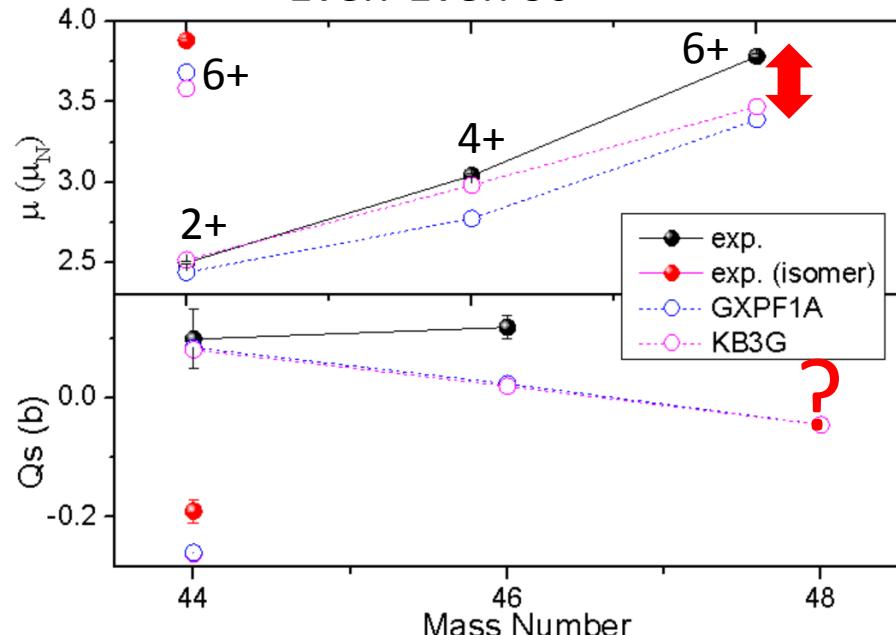
P.-G. Reinhard and W. Nazarewicz PRC 95, 064328 (2017)

• Magnetic and quadrupole moments

Even-Odd Sc



Even-Even Sc



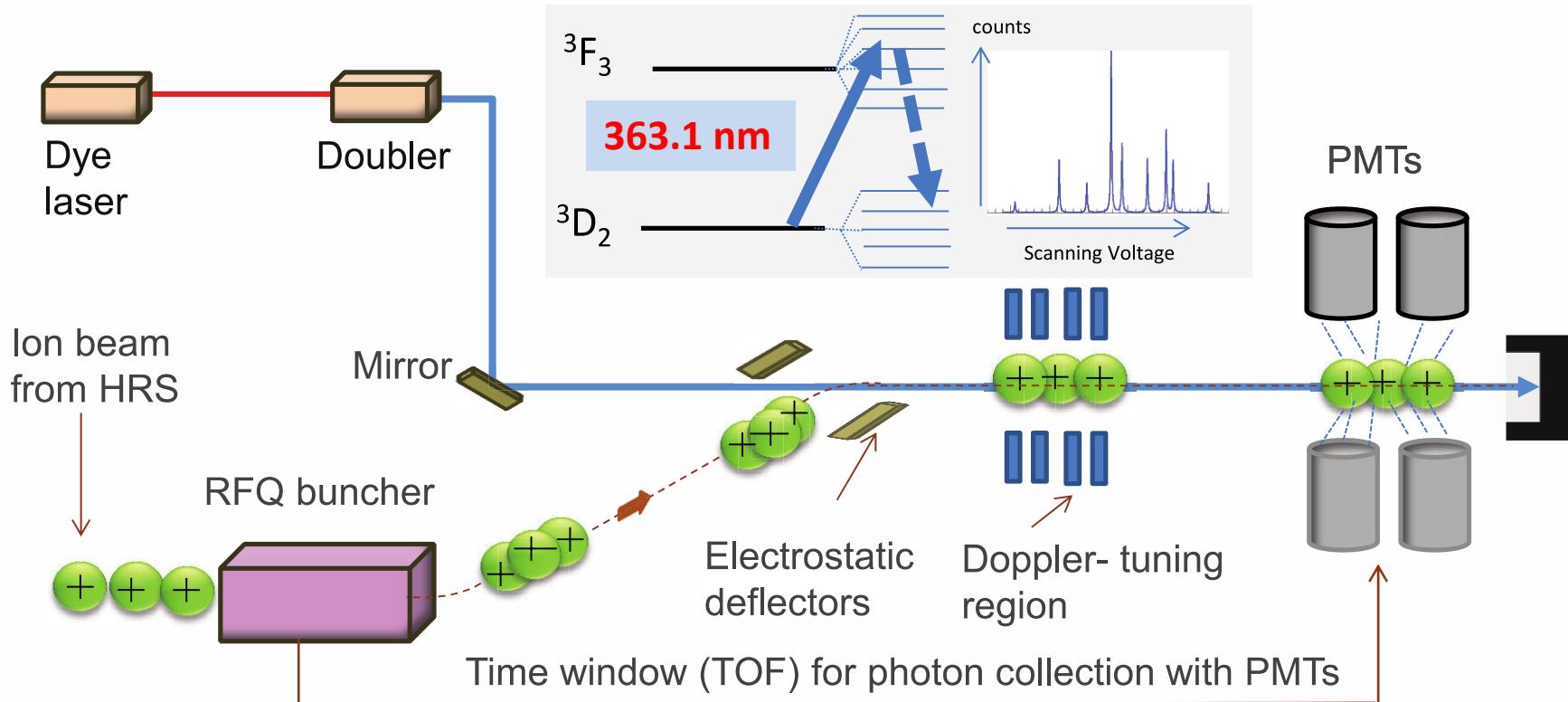
- The parabolic form of μ/Q for odd-A Sc shows the relative purity of the $7/2^-$ proton state
- Shell model calculation has large divergence around $N = 28$ for even- /odd-A isotopes
- 3N forces are missing ?* Ca: PRC 91, 041304(R)
- Requires shell model with larger model spaces ?* [55Sc: arXiv:1710.07465](https://arxiv.org/abs/1710.07465)

^{55}Sc energy level: SDPF-MUr interaction in sd-pf shell: produce the states from proton cross-shell excitations

- New developed similarity renormalization group (IM-SRG) allows the extension of ab initio calculation to open-shell nuclei (e.g. $^{42-50}\text{Sc}$).

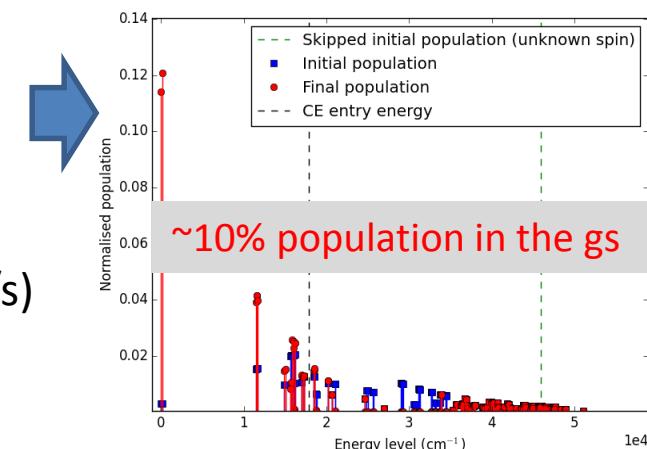
Prediction for Sc moments is on going!!

• Experimental method: Laser spectroscopy at a ionic transition of Sc



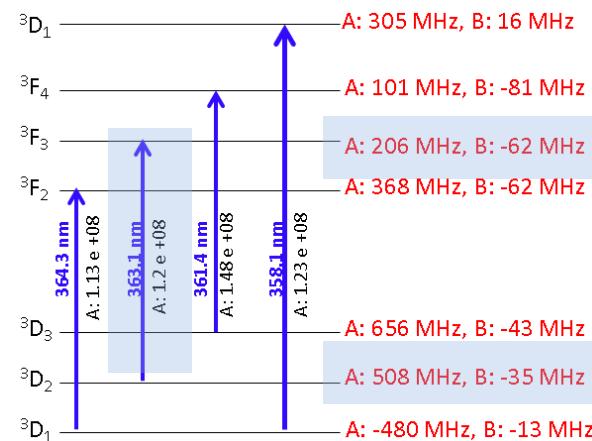
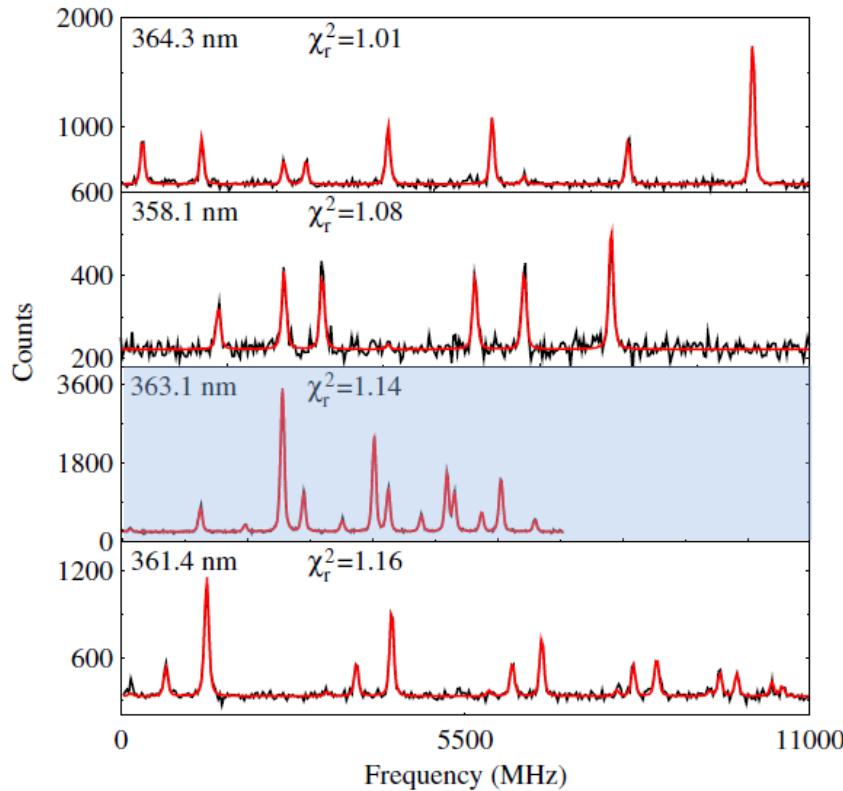
Benefits from ionic transition

- Gaining ~10 times overall efficiency
- Suppressing beam related background via the CEC process
- As has been demonstrated in Ca and Cd runs (few 100 ions/s)



- **Experimental feasibility** : earlier laser spectroscopy study on Sc

Tested in **IGISOL** @Jyvaskyla

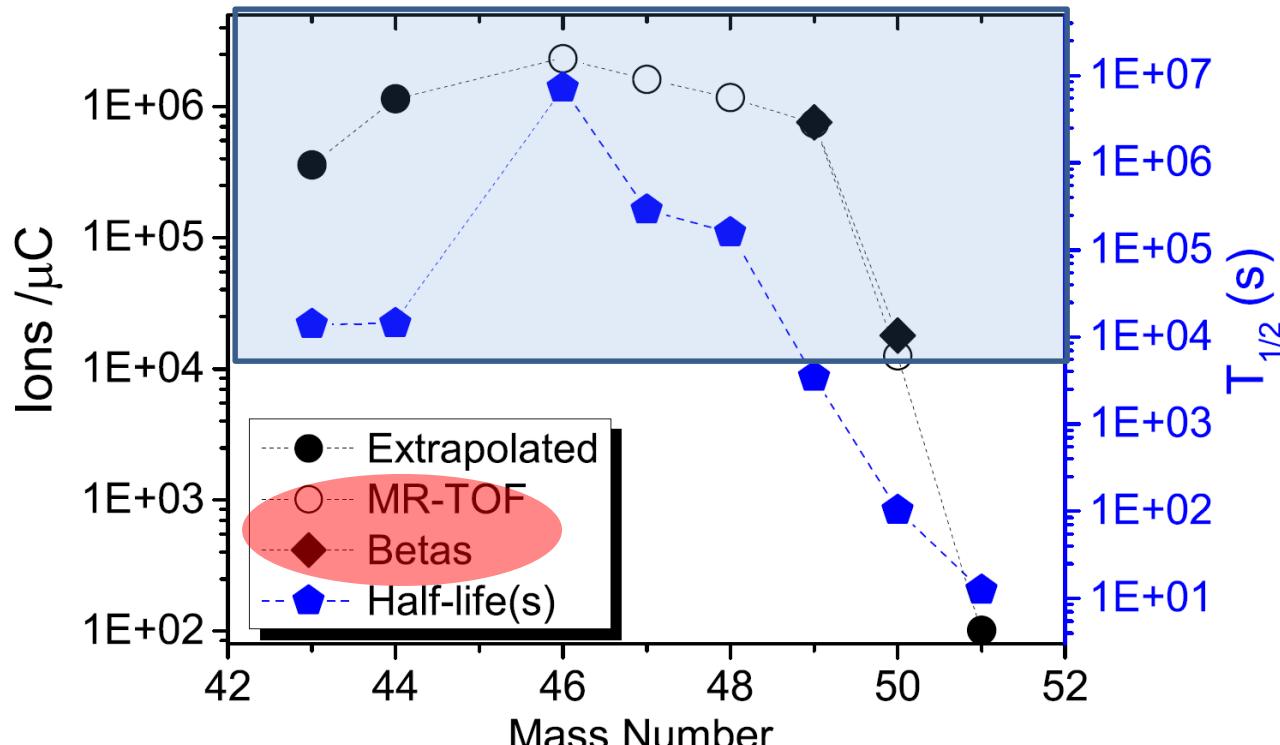


- Relative large transition strength
- Relative large A, B values
- Small scan range

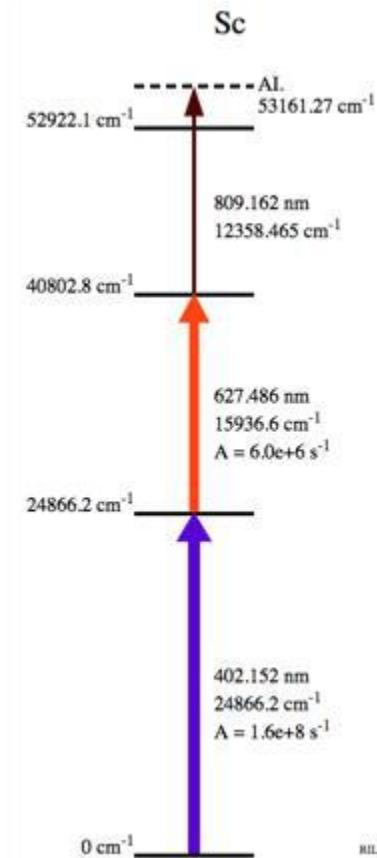
Well established and tested laser transition !!

- can easily access with frequency doubled Ti:Sa or Dye laser at COLLAPS

• Production yields and beam time request



Isotopes	Measured yield (/ μC)	Extrapolated yield (/ μC)	Number of shifts
$^{43-44m}\text{Sc}$		$> 10^5$	4.5
$^{46g,m}, -^{49}\text{Sc}$	$> 10^5$		7.5
^{50g}Sc	1.2×10^4		2
Stable beam			2



Total: 14 Online shifts + 2 stale beams for Setup

- To measure 10 states for $^{43-50}\text{Sc}$ including 3 isomers
- 5 states will be measured for the first time

Thanks for your attention!



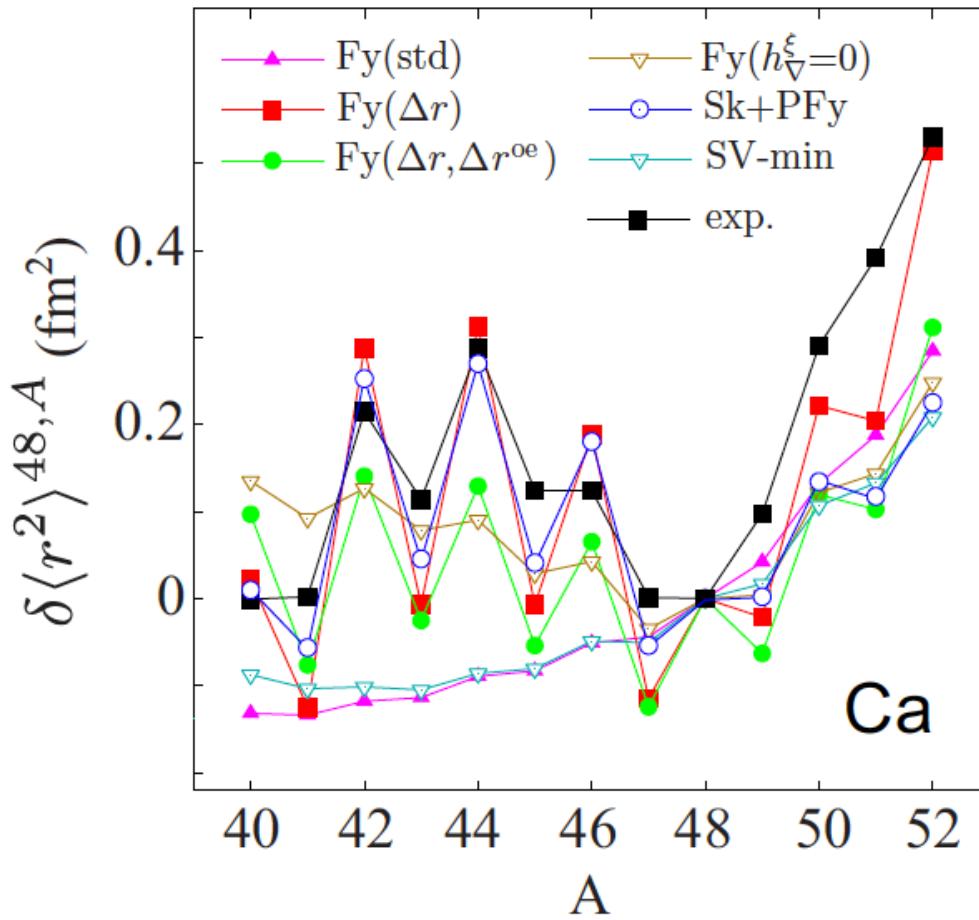


FIG. 4. Differential charge radii $\delta\langle r^2 \rangle^{48,A}$ (15) in Ca predicted by Fayans and Skyrme parametrizations as indicated, and compared to experiment.

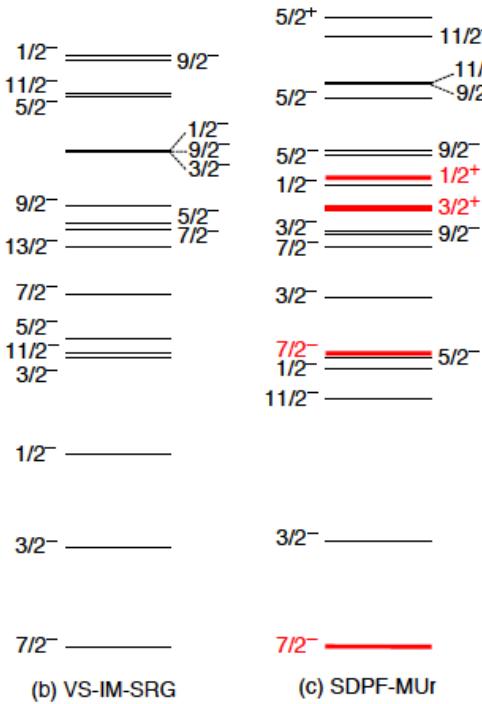
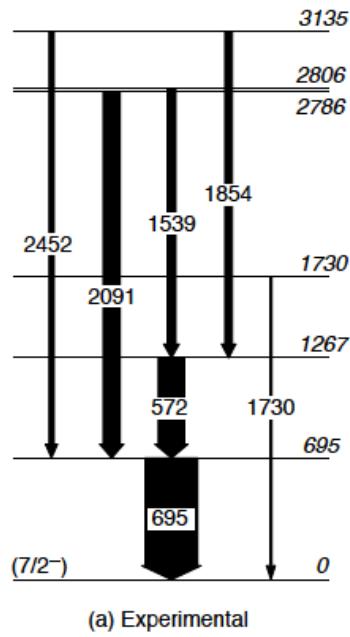
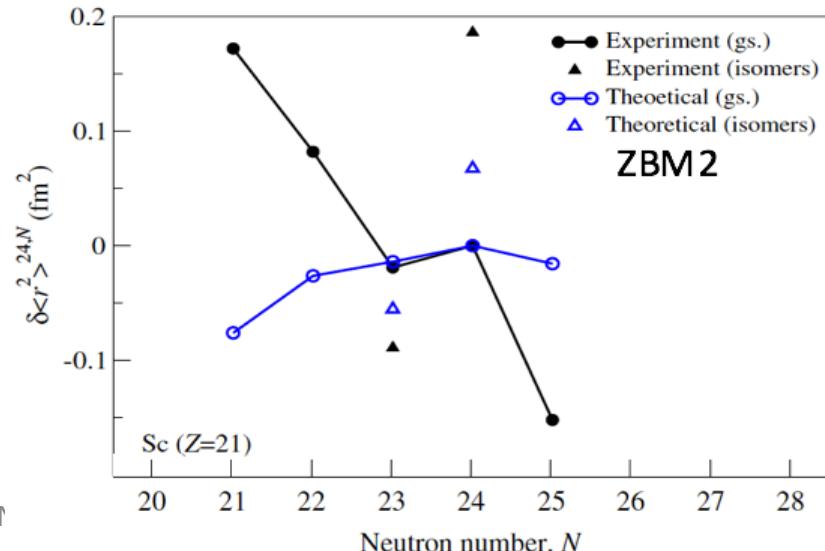
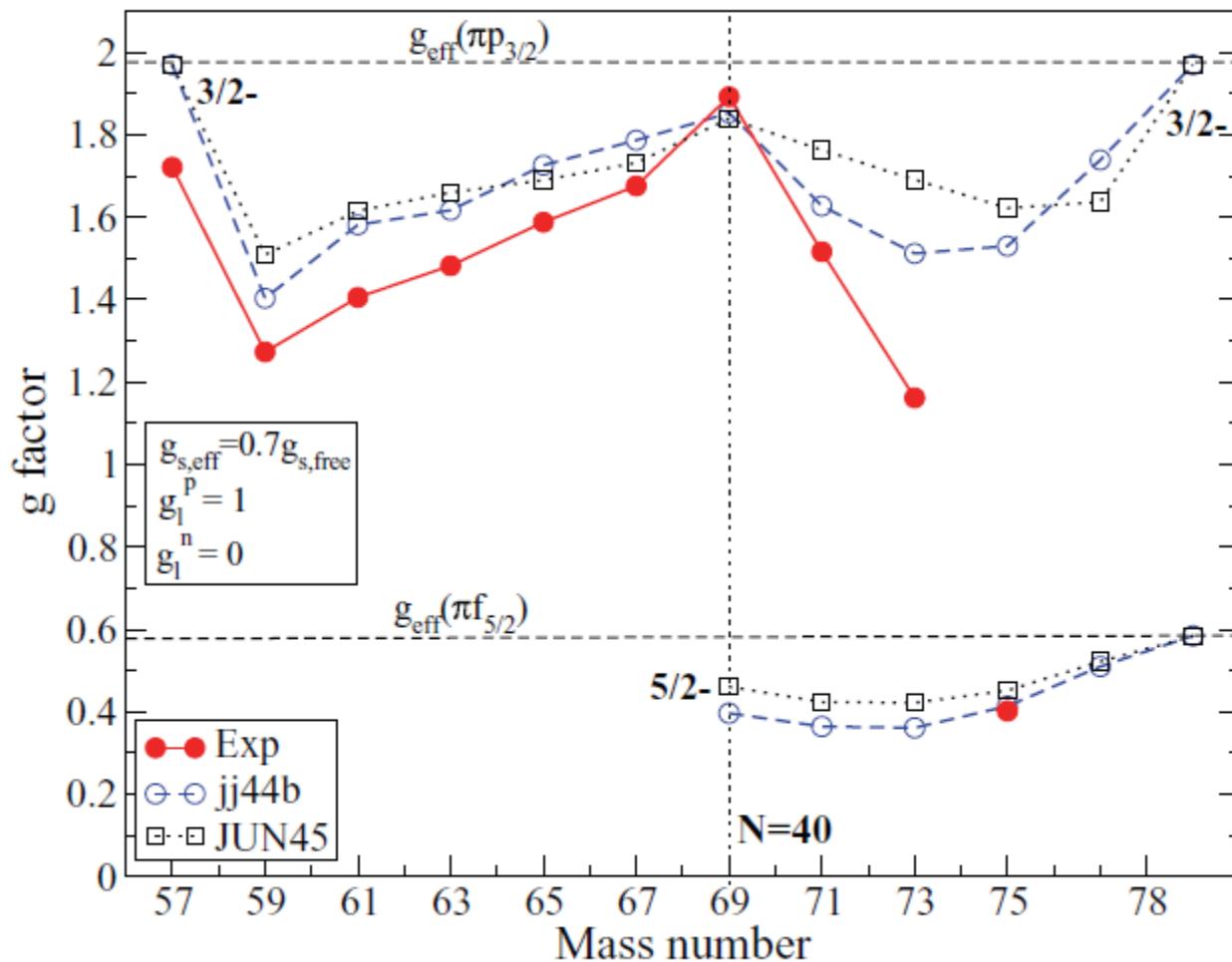


FIG. 3: (Color online) (a) Level scheme for ^{55}Sc deduced in the present work. The widths of the γ -ray lines are proportional to relative intensities measured in the $^9\text{Be}(^{56}\text{Ti}, ^{55}\text{Sc}+\gamma)X$ reaction. The columns labeled (b) VS-IM-SRG and (c) SDPF-MUR are predictions of ^{55}Sc spectra using the *ab initio* many-body method and large-scale shell-model calculations, respectively (see text for details). Note that a maximum of three states are displayed for each spin-parity in columns (b) and (c) in order to avoid clutter in the figure; in column (c), the four states with sizable cross sections as predicted by nuclear reaction theory for the one-proton removal reaction in Table II (the $7/2^-$ ground state and the $7/2^-$, $3/2^+$, and $1/2^+$ excited states predicted at 1.7, 2.5, and 2.7 MeV, respectively), which is discussed in the text below, are highlighted by thick red lines and red text. Spin-parity and energy labels on the levels are given by regular and italic fonts, respectively.

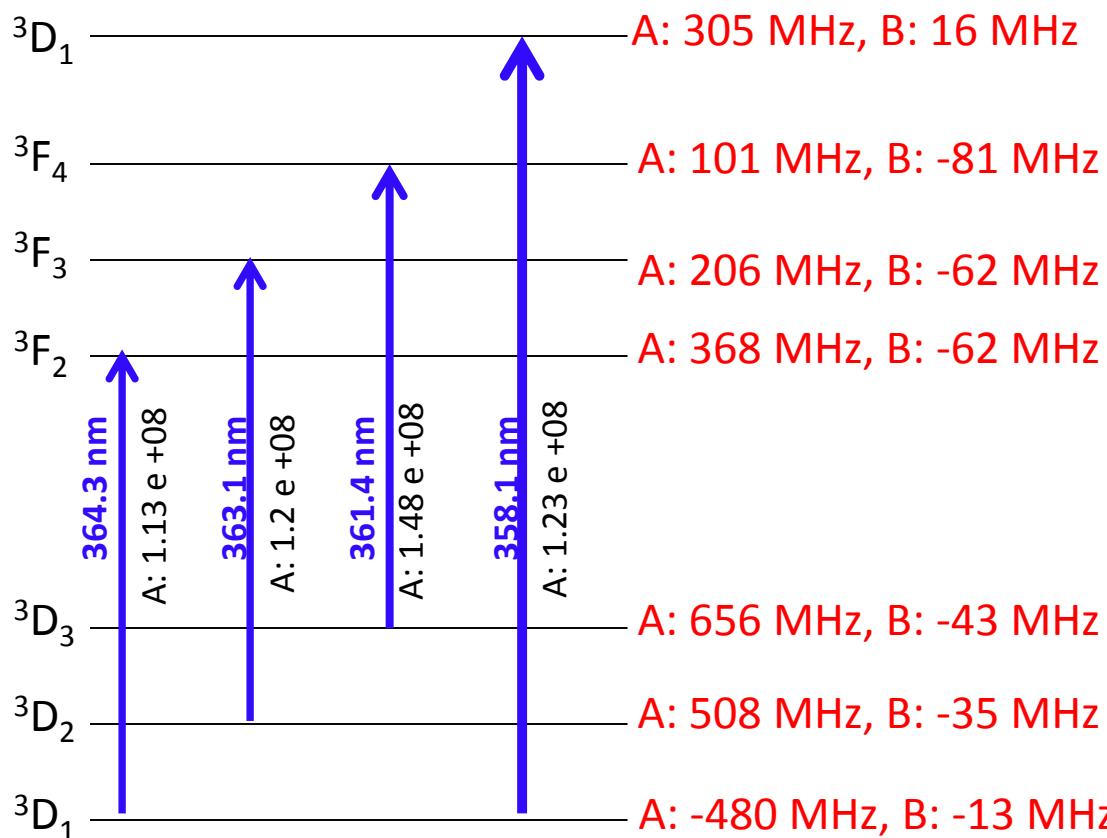
Table 4. Scandium isotope and isomer shifts, $\delta\nu^{A,A'} = \nu^{A'} - \nu^A$, measured on the 363.1 nm ionic transition, separate mass-shift and field-shift components, and the extracted ms charge radii, $\delta\langle r^2 \rangle_{\text{exp}}^{A,A'} = \langle r^2 \rangle^{A'} - \langle r^2 \rangle^A$. All ground state values are with respect to $A = 45$, and isomeric state values are quoted with respect to the corresponding ground state. The errors quoted in parenthesis are statistical and those in square brackets represent the systematic errors arising from uncertainties in the scaling factors F and M_{SMS} . For comparison, $\delta\langle r^2 \rangle_{\text{SM}}^{A,A'}$ from the shell-model calculations of this work are included.

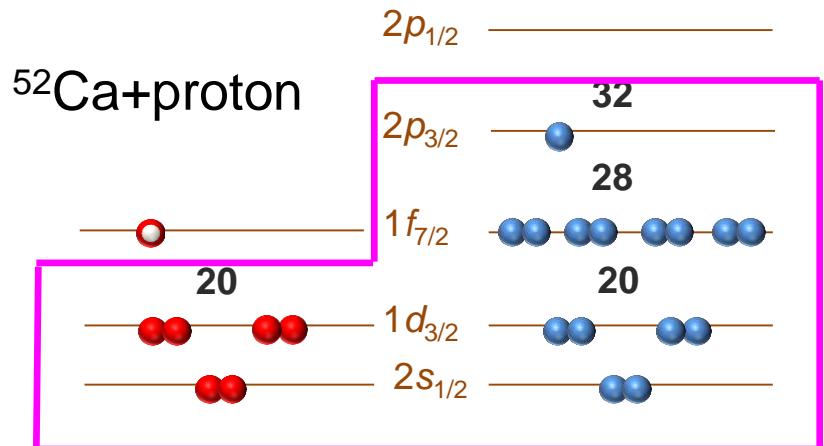
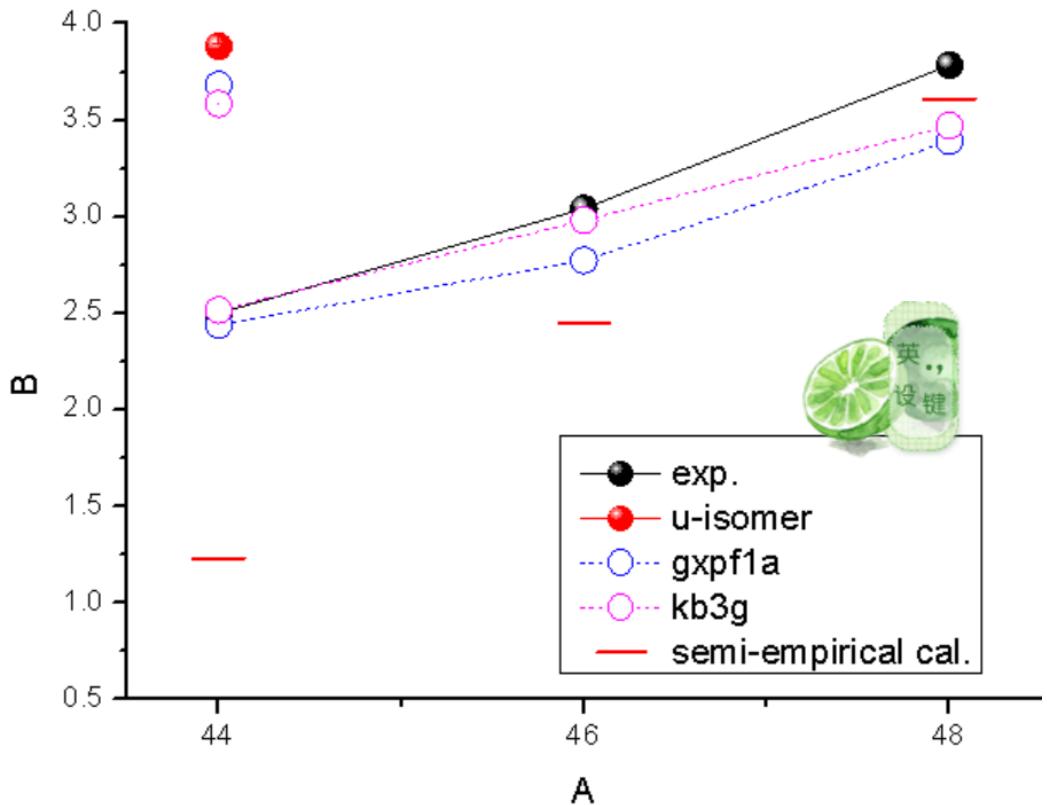
A	A'	$\delta\nu^{A,A'} (\text{MHz})$	$\delta\nu_{\text{MS}}^{A,A'}$	$\delta\nu_{\text{FS}}^{A,A'}$	$\delta\langle r^2 \rangle_{\text{exp}}^{A,A'} (\text{fm}^2)$	$\delta\langle r^2 \rangle_{\text{SM}}^{A,A'} (\text{fm}^2)$
45	42	-985(11)	-924	-61	+0.172(31)[136]	-0.076
45	43	-631(5)	-602	-29	+0.082(14)[88]	-0.026
45	44	-287(4)	-294	+7	-0.019(11)[43]	-0.014
44	44m	+25(4)	0	+25	-0.070(11)[10]	-0.041
45	45	0	0	0	0	0
45	45m	-66(2)	0	-66	+0.186(6)[26]	+0.068
45	46	+336(3)	+282	+54	-0.152(8)[46]	-0.016





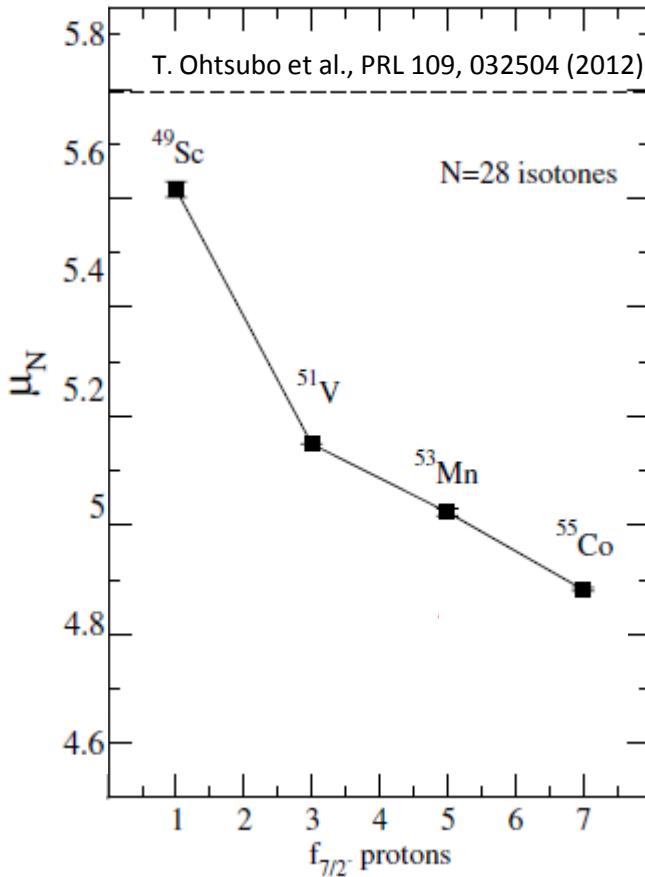
λ (nm)	Lower level	Upper level	A_l (MHz)	B_l (MHz)	A_u (MHz)	B_u (MHz)	Efficiency (photon/ion)
364.3	3D_1	$^3F_2^o$	-479.9(5)	-12.6(19)	+368.3(3)	-61.7(32)	1/29 000
358.1	3D_1	$^3D_1^o$	-479.9(5)	-17.6(37)	+305.3(6)	+16.3(36)	1/150 000
363.1	3D_2	$^3F_3^o$	+507.9(1)	-34.4(15)	+205.7(1)	-62.3(19)	1/27 000
361.4	3D_3	$^3F_4^o$	+656.2(6)	-43(14)	+101.5(5)	-81(14)	1/25 000



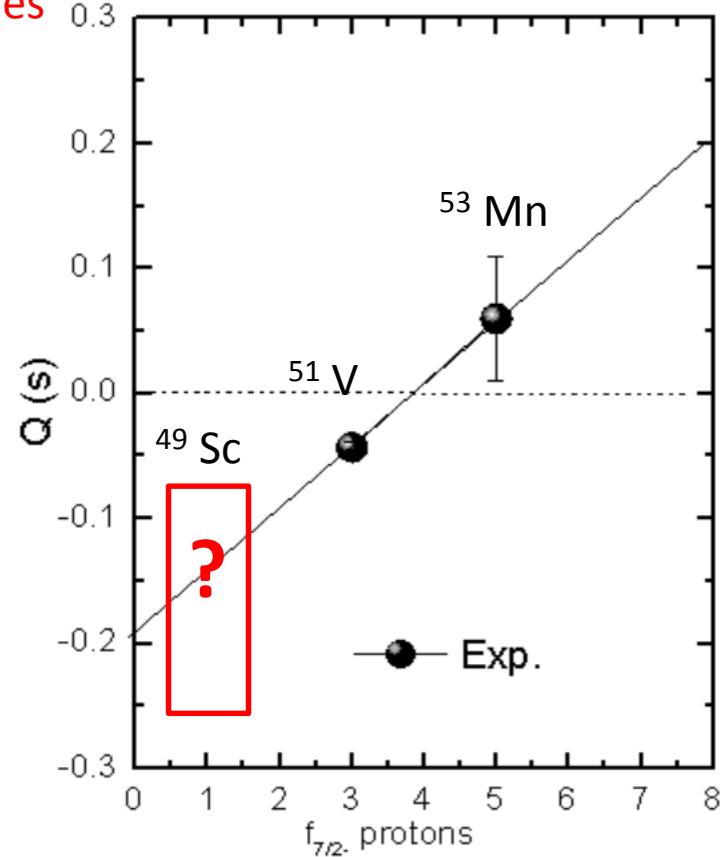


$$\mu(J) = \frac{J}{2} \left[\frac{\mu(J_\pi)}{J_\pi} + \frac{\mu(J_\nu)}{J_\nu} + \left(\frac{\mu(J_\pi)}{J_\pi} - \frac{\mu(J_\nu)}{J_\nu} \right) \frac{J_\pi(J_\pi + 1) - J_\nu(J_\nu + 1)}{J(J + 1)} \right]$$

• Magnetic and quadrupole moments



$N = 28$ isotones



- μ : shows the relative purity of the states from $(\pi f_{7/2})^n$: details in PRL 109, 032504 (2012)
- Due to the $(\pi f_{7/2})^n$ configurations Q should follow a simple linear trend with proton number and cross 0 at the mid-shell ($n=4$)
 - in the case of seniority 1 scheme. D.T. Yordanov et al., Phys. Rev. Lett. **110**, 192501 (2013).

Q measurement of ^{49}Sc at $Z = 21$ will complete the picture

NOTE: Target #565 on shelf for 1.5 year: still needs to be tested with “fresh” rather than “matured” target.

Safety Clearance granted (1806800) but final laser safety clearance still to be issued.

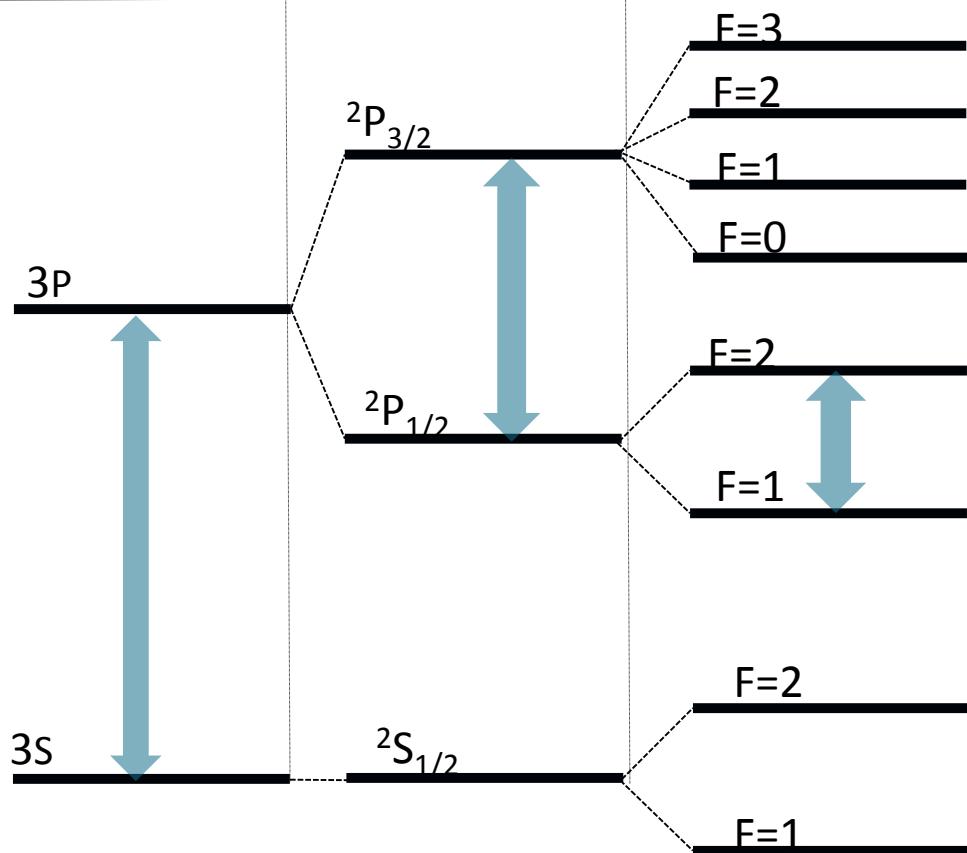
-- please refer to COLLAPS safety file

What is Laser spectroscopy

--Spectroscopy of electronic transitions of atoms/ions

Electronic energy level structure

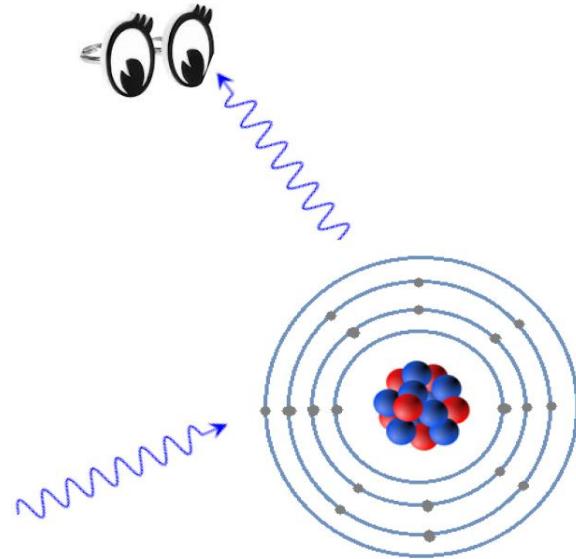
THz	eV	GHz	eV	MHz	eV
~508	2.1	~500	$\sim 10^{-3}$	~200	$\sim 10^{-6}$



l

$$J = l + s$$

$$F = J + I(\text{nuclear spins})$$



Only in **HFS** precision level,
nuclear information are involved

How??

Probe the hyperfine structure

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

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

Atomic parameters

- Magnetic dipole HF parameter

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

I, μ

- Electric quadrupole HF parameter

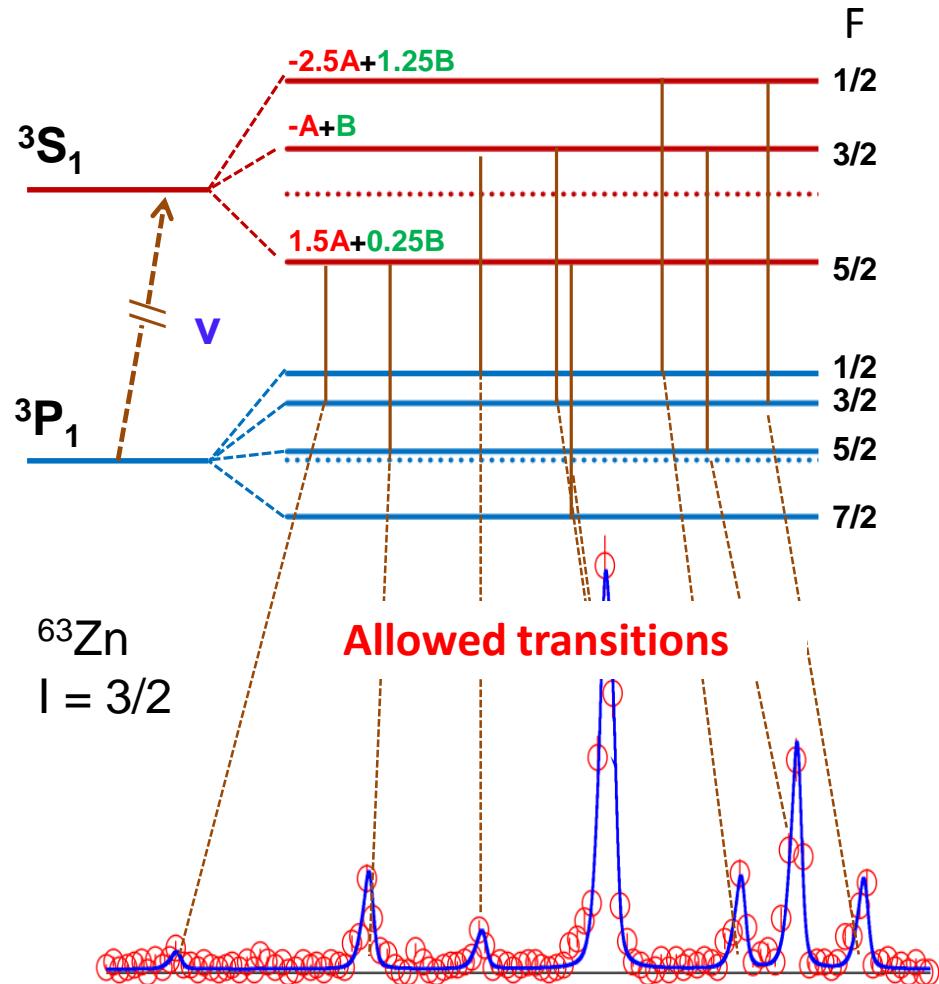
$$B = eQV_{zz}$$

Q

- Centroid v_0
Isotopes shift

$$\langle r^2 \rangle^{1/2}$$

$$\delta\nu_{FS} = \frac{2\pi Z}{3} \Delta |\psi(0)|^2 \delta \langle r^2 \rangle^{A,A'}$$



Observables from laser spectroscopy ---and its link to nuclear information

