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Nuclear physics opportunities with electromagnetic moments beyond the quadrupole

Ruben de Groote

ECT* workshop

April 13, 2022

Laser spectroscopy and hyperfine structure

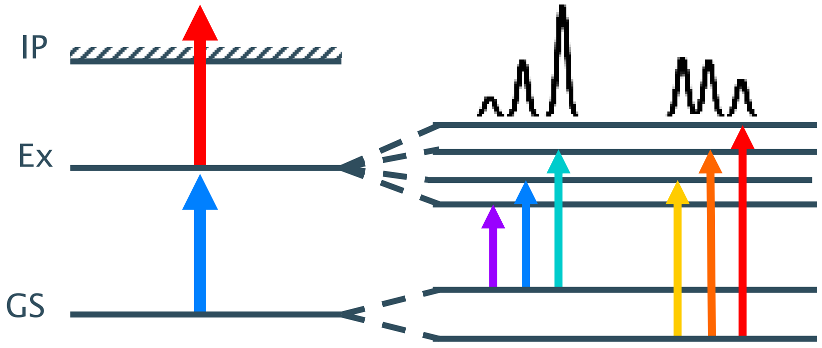
- Hyperfine structure links atomic and nuclear properties

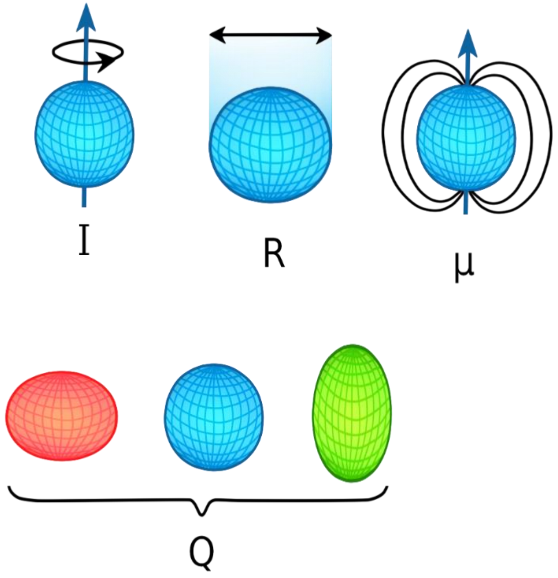
$$h\nu \sim \nu_0 + A\frac{C}{2} + B\frac{1}{4}\frac{(3/2)C(C+1)-2I(I+1)J(J+1)}{I(2I-1)J(2J-1)}$$

- Nuclear model-independent extraction of:

$\delta\langle r^2\rangle$ $A=\frac{\mu_I B_J}{IJ}$ $B=eQV_{zz}$

provided the atomic parameters are known (e.g. knowing mass and field shift is required)





Laser spectroscopy and hyperfine structure

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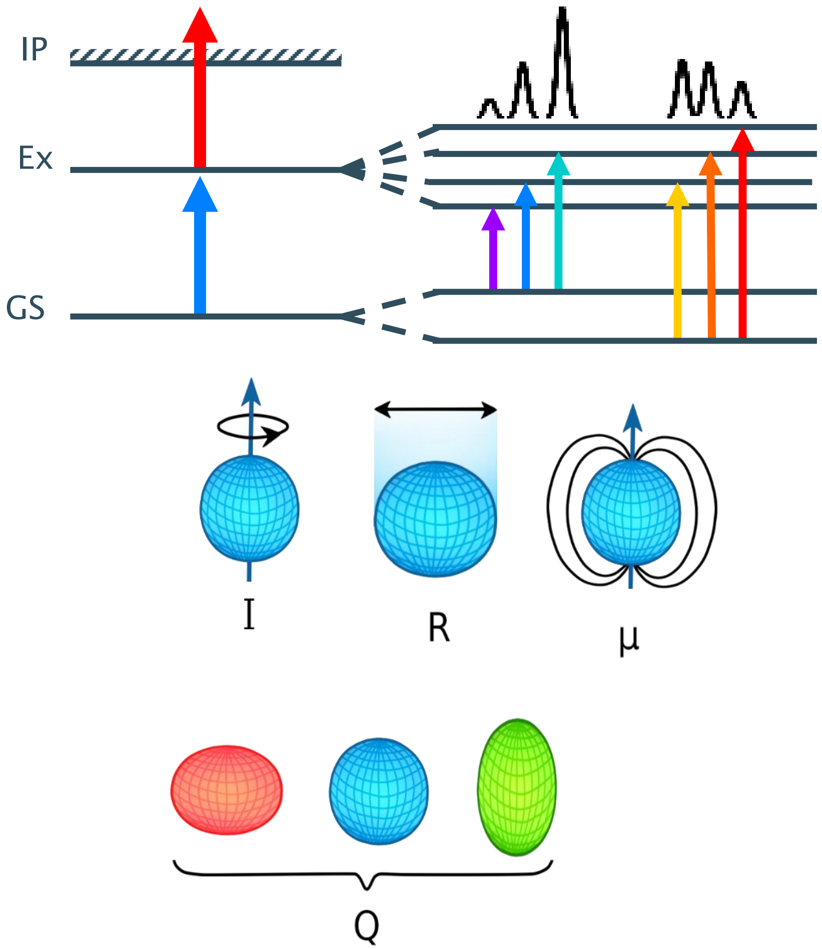
- Some nuance:
  - First-order expansion does not stop at 2nd multipole order!
  - Second-order perturbation theory: hyperfine mixing
  - Hyperfine anomaly



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Laser spectroscopy and hyperfine structure

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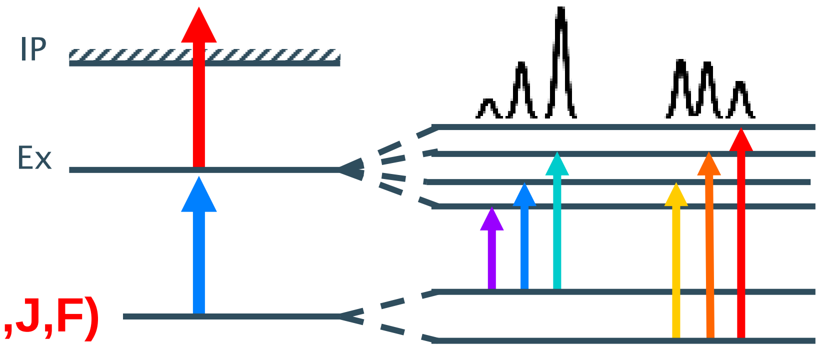
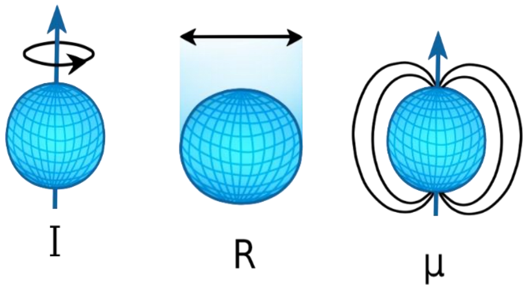
$$C = -\Omega \langle JJ|\, T_3^{(e)}\, |JJ\rangle$$





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  - / First-order expansion does not stop at 2nd multipole order!
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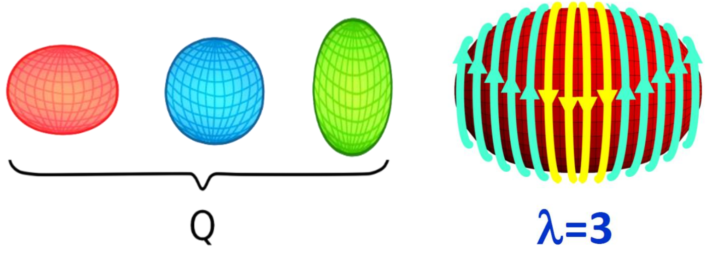
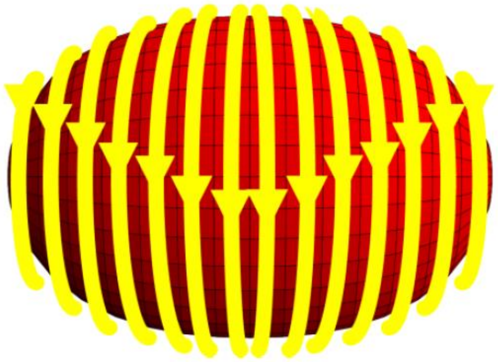


Figure by Jacek Dobaczewski

Magnetic properties of the nucleus

- Magnetic dipole moment:
  - Exceedingly useful probe of nuclear configuration
    - i.e. what orbit is a valence nucleon in?
    - Long chains of radioactive isotopes: study evolution of nuclear properties
  - Comparison with nuclear theory informs on wavefunction composition, purity, … and thus can test interactions, model spaces, …
  - **Over 800 measurements** of magnetic dipole moments to date!!



$\lambda=1$

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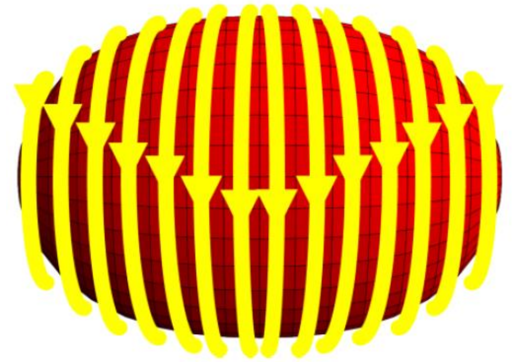
- Magnetic octupole moment:
  - A measure of ‘deviation from spherical symmetry’ of the distribution of magnetization
  - So far… **only 20 measurements**.



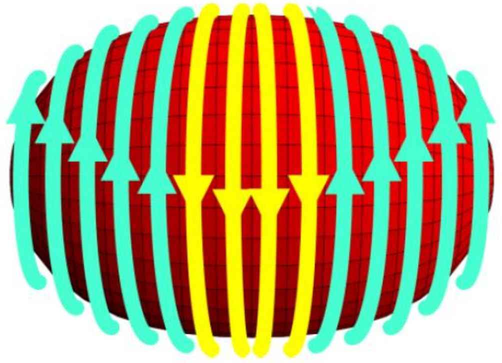


Figure by Jacek Dobaczewski

Magnetic properties of the nucleus

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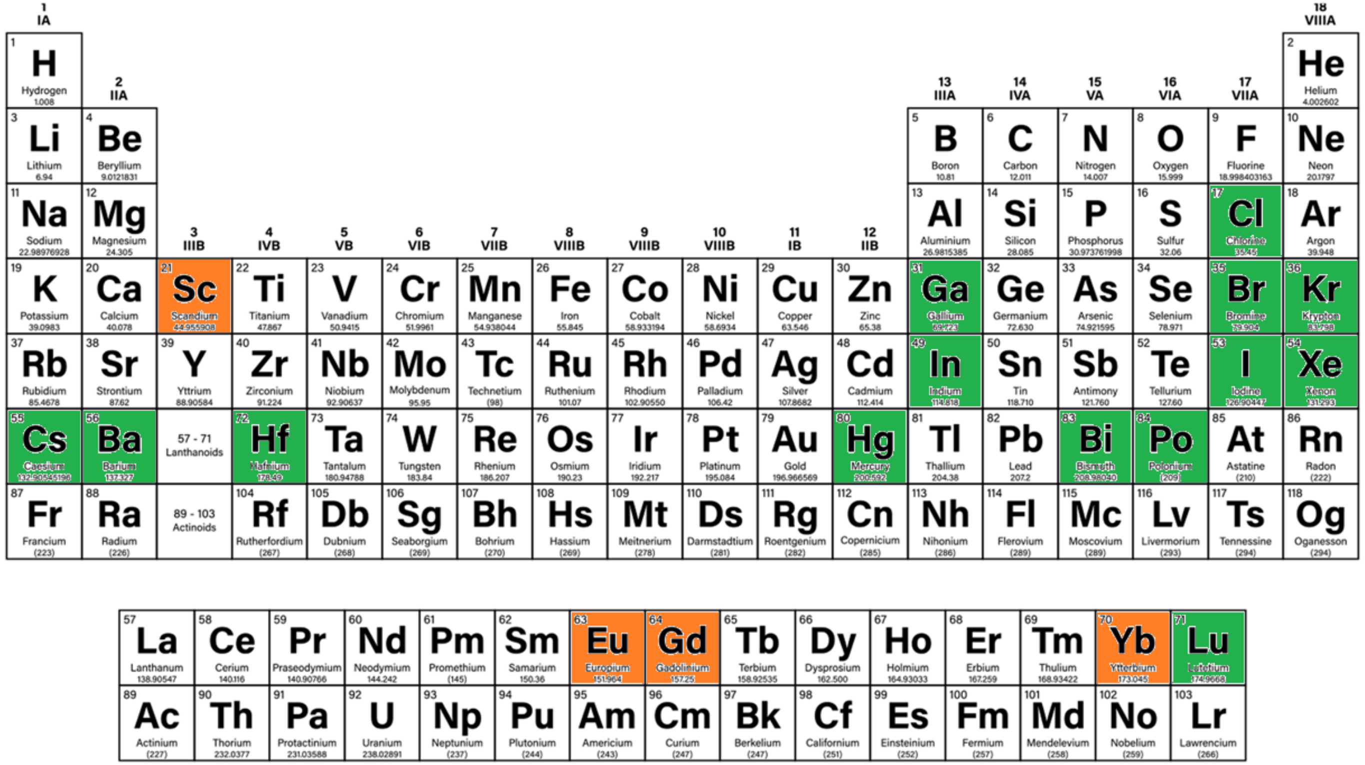
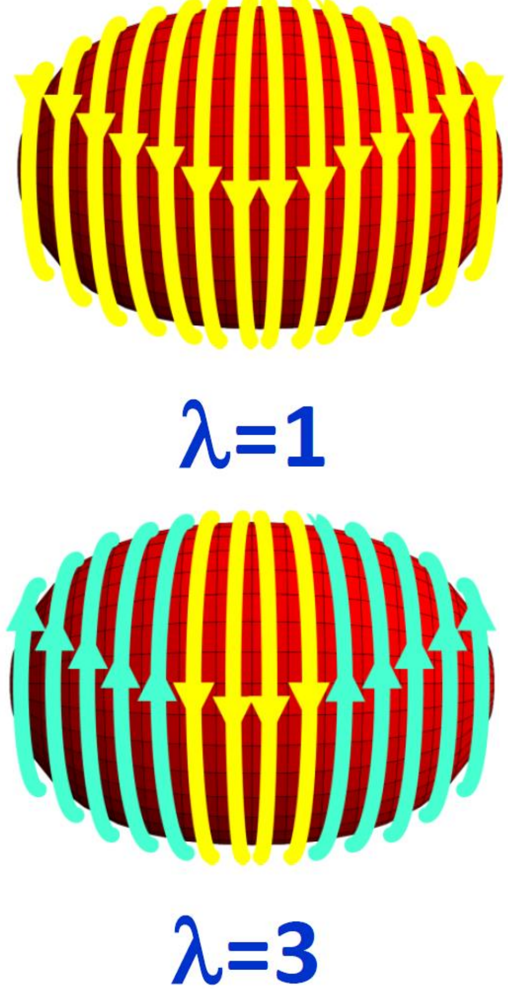




Dipole vs octupole

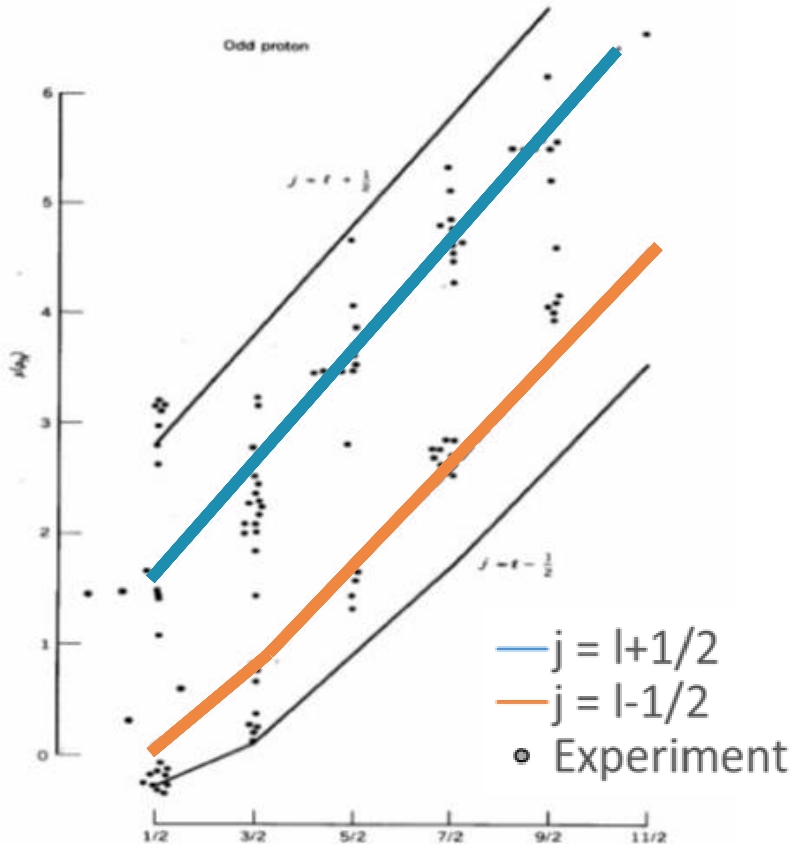
Interpretation from theory?

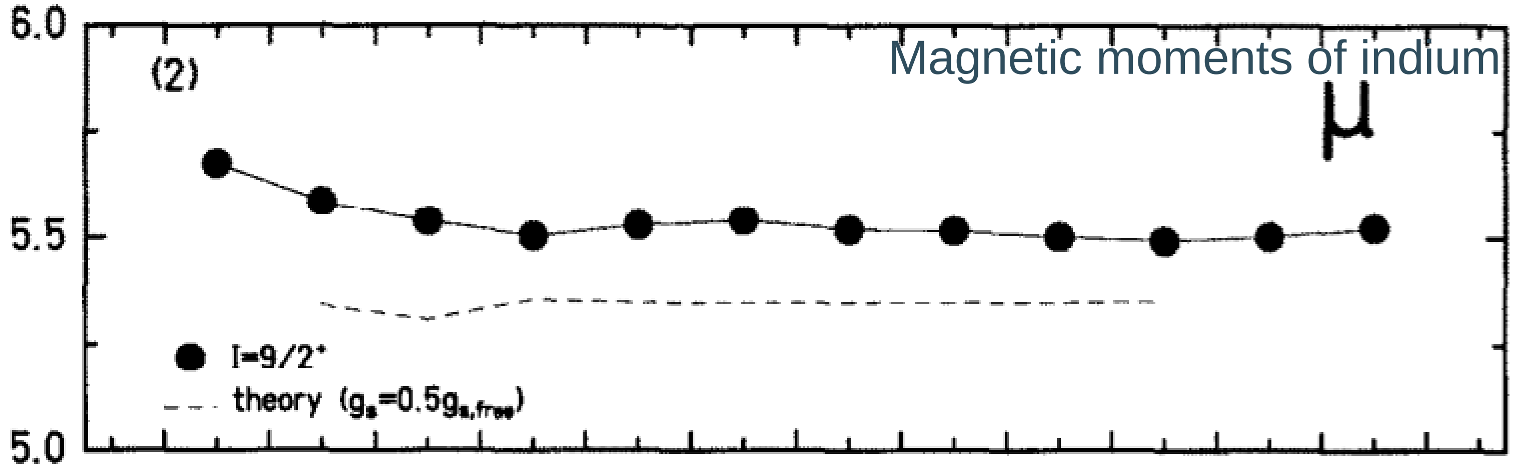
Single-particle estimates

= moment is determined by the valence nucleon

- Global agreement with effective single-particle model

- Example: longer indium chain with near-constant magnetic moments
  = textbook case?





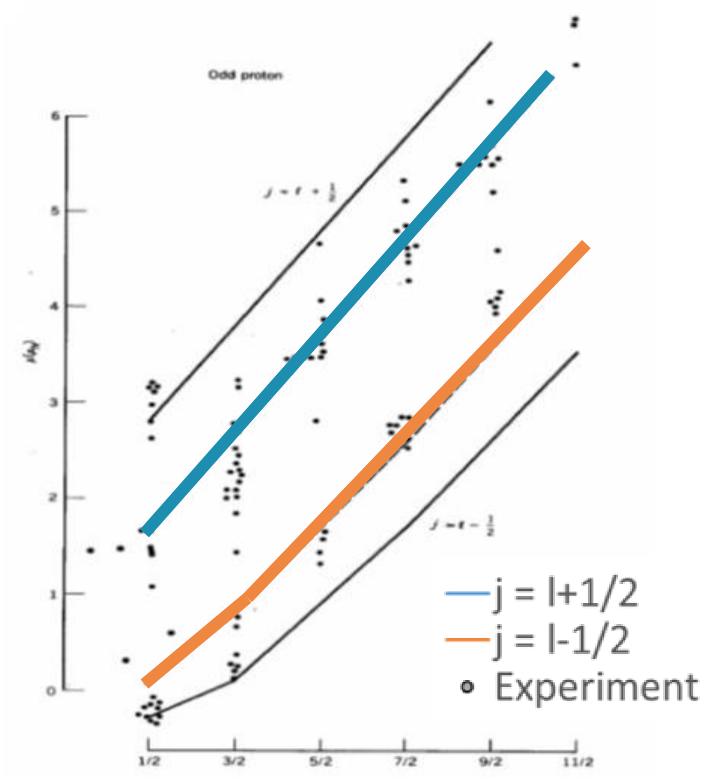
J. Eberz et al, Nuclear Physics A Volume 464, 1, 1987, 9-28

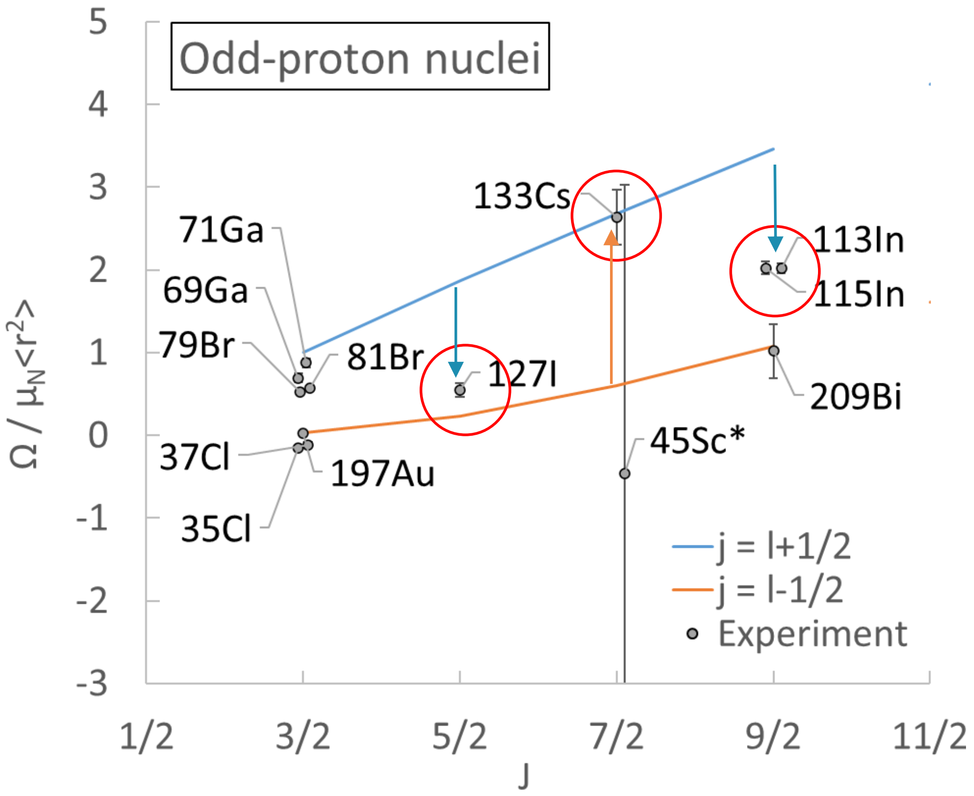
Dipole vs octupole

Interpretation from theory?

Single-particle estimates

- Single-particle picture works quite well for dipole moments
- Octupole moments: not so much
  - Higher sensitivity to configuration mixing?



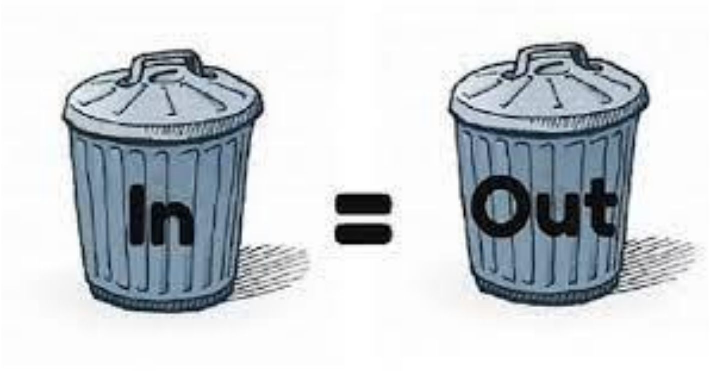


$$\Omega/\mu_N \langle r^2 \rangle = \frac{3}{2}\frac{2I-1}{(2I+4)(2I+2)} \times \begin{cases} (I+2)[(I-\frac{3}{2})g_l+g_s], & I=l+\frac{1}{2} \\ (I-1)[(I+\frac{5}{2})g_l-g_s], & I=l-\frac{1}{2} \end{cases}$$

Some caution…

- Systematic effects in the measurements
  - Measurements in lit. are all precise, but are they *accurate*?

- Atomic structure
  - C/Omega
  - Second-order hyperfine structure



Critical survey of literature through the lens of current theory would be of interest.

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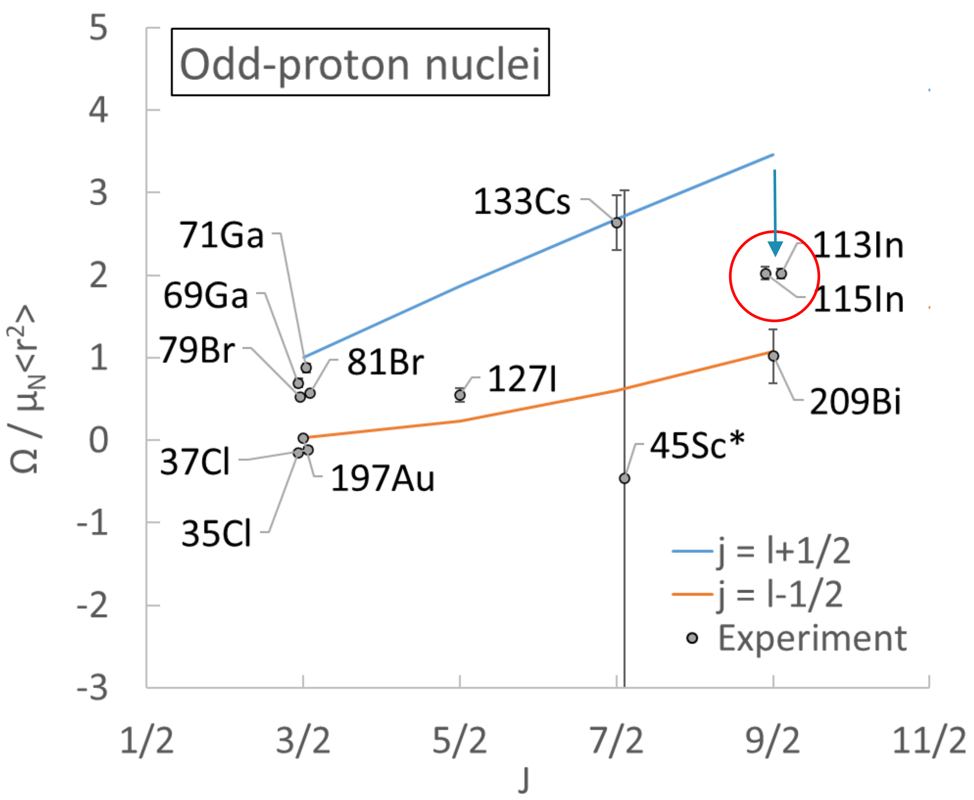
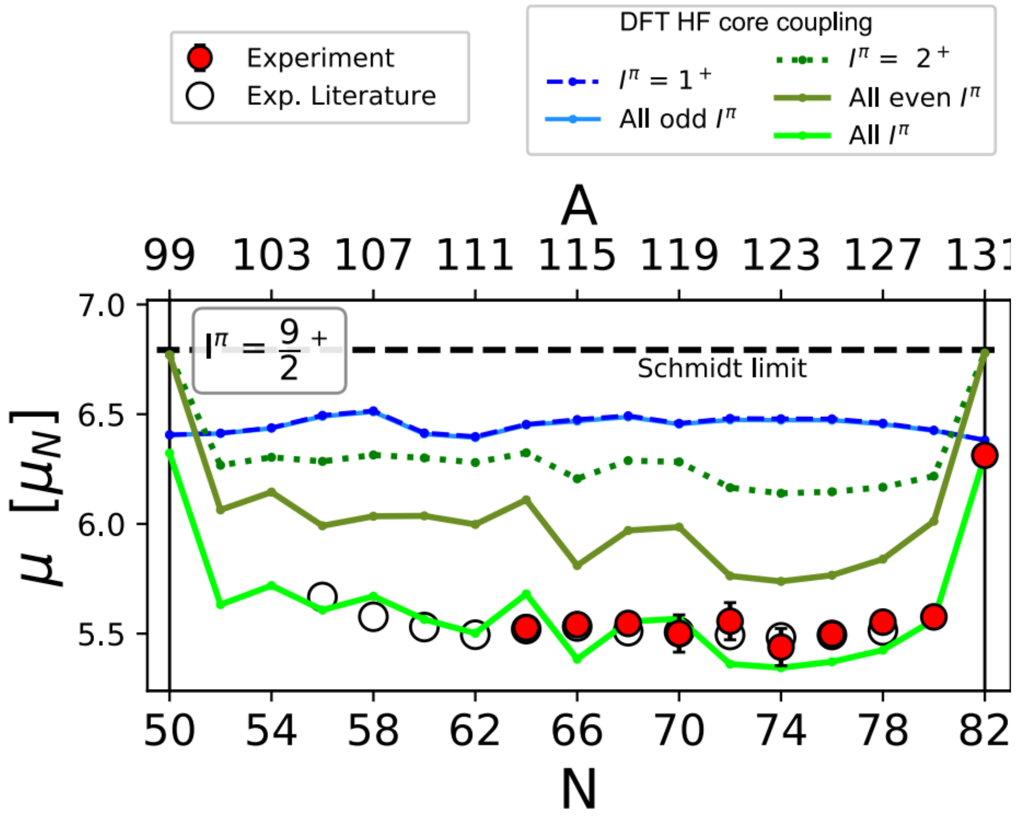
A textbook case of single-particle structure?





A. Vernon et al, accepted to Nature

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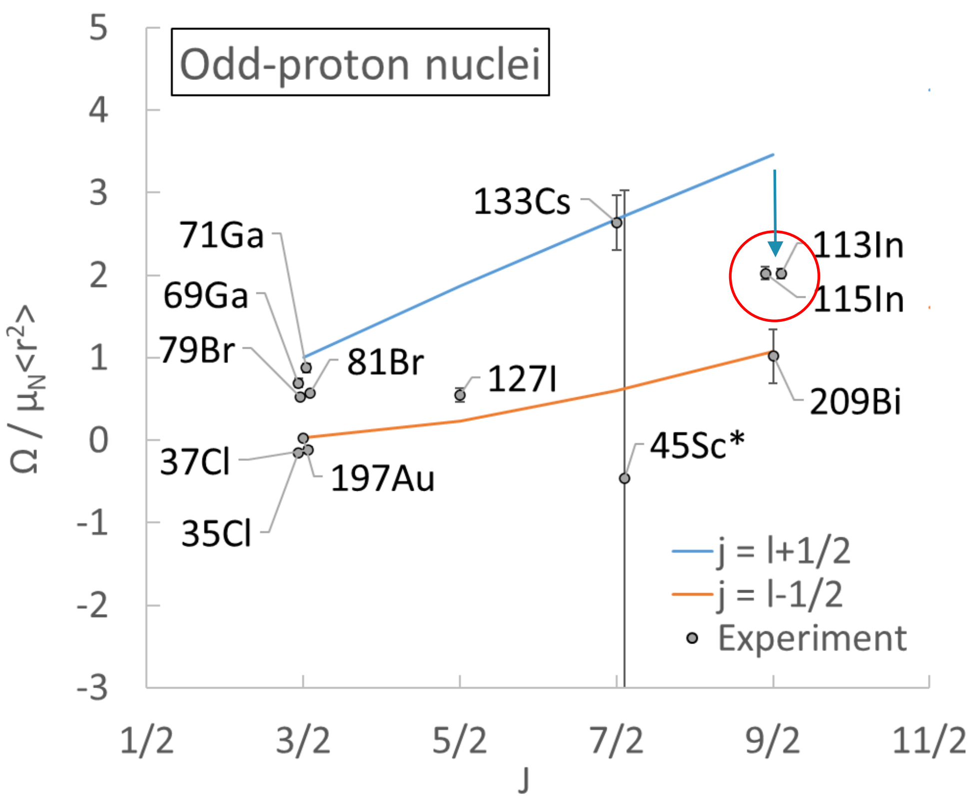

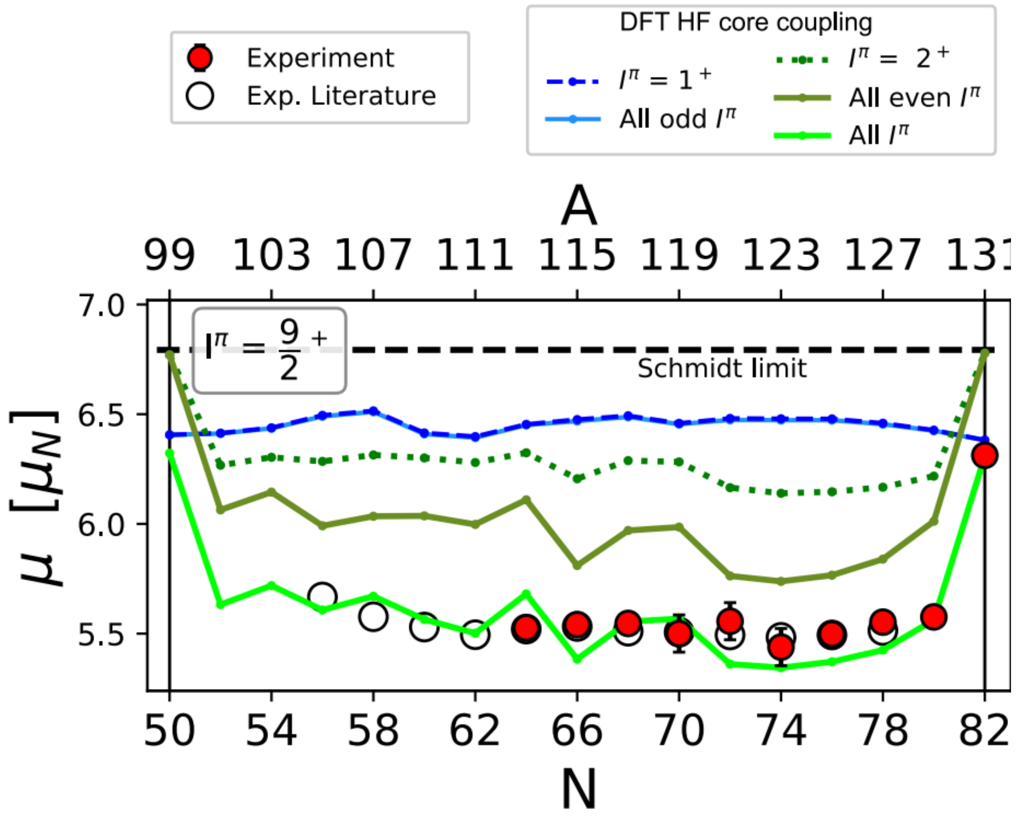

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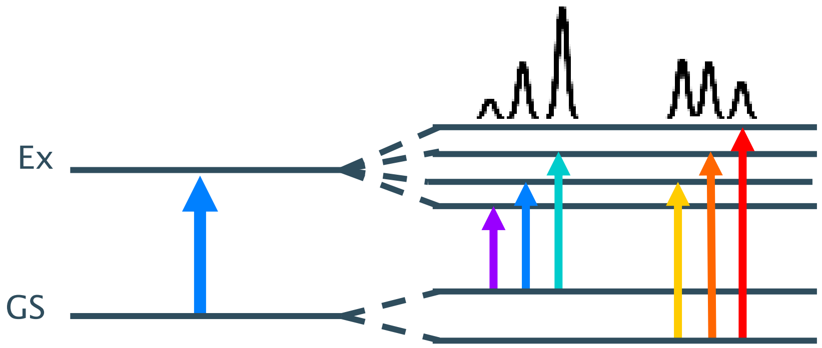
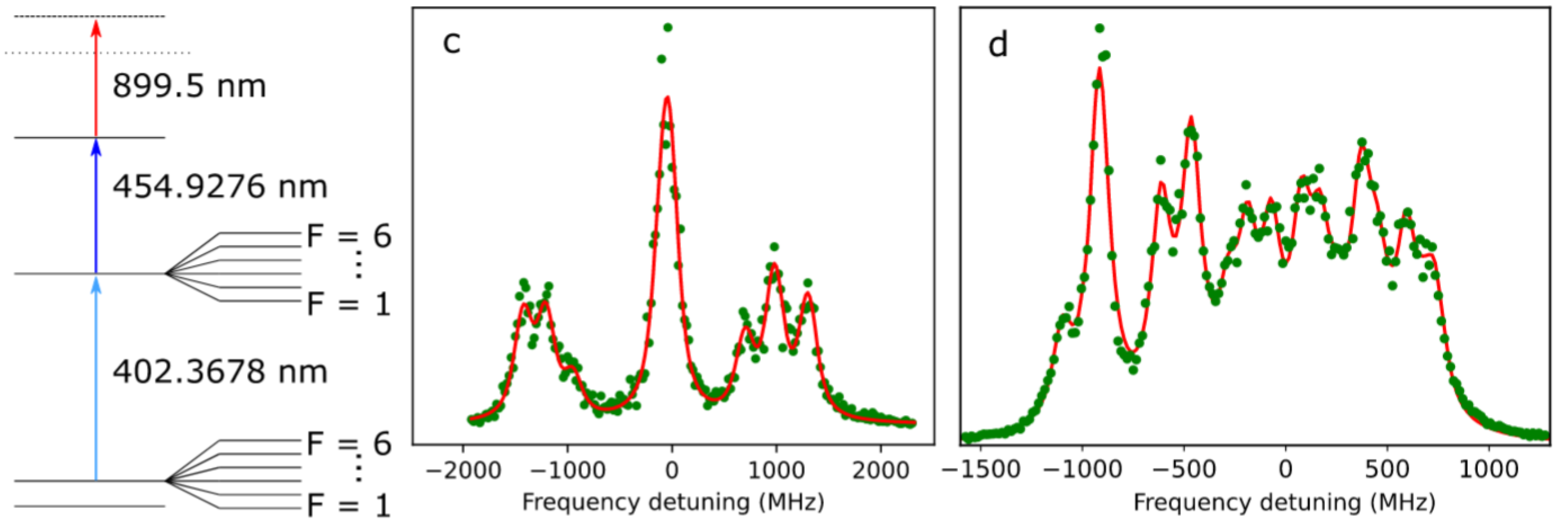
There is complimentary value in exploring this next-order magnetic observable

Moving forwards: highly precise and accurate hyperfine structure measurements

- ‘Standard’ laser spectroscopy is not sufficiently precise
- Example ^{45}Sc: Ca core + 1 proton
- Linewidth: MHz level (limited by lifetime of excited state)

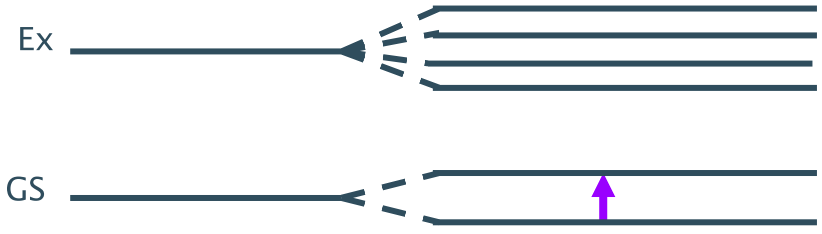


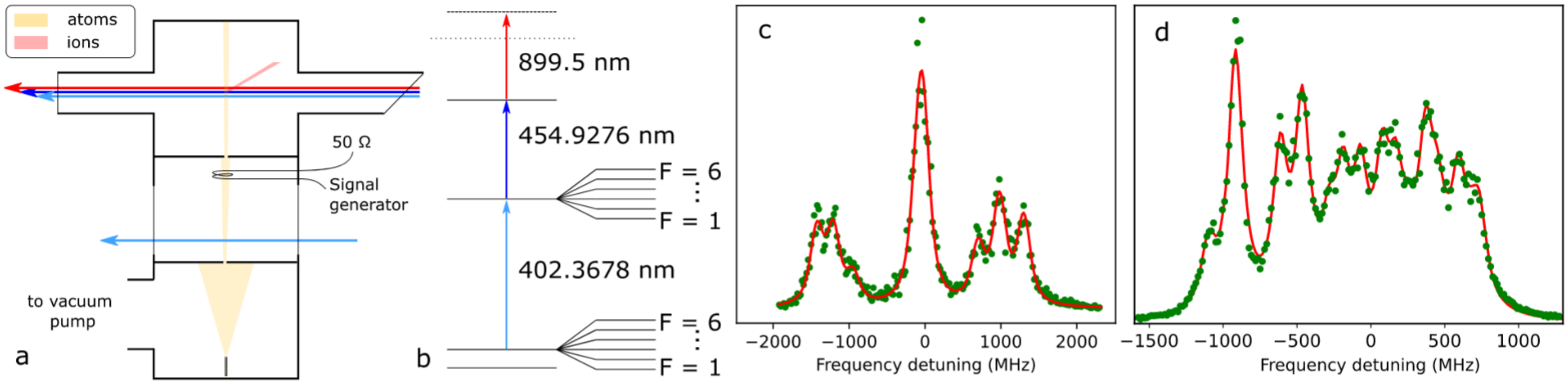


R.P. de Groote, J. Moreno, J. Dobaczewski et al., Physics Letters B 827 (2022) 136930

Moving forwards: highly precise and accurate hyperfine structure measurements

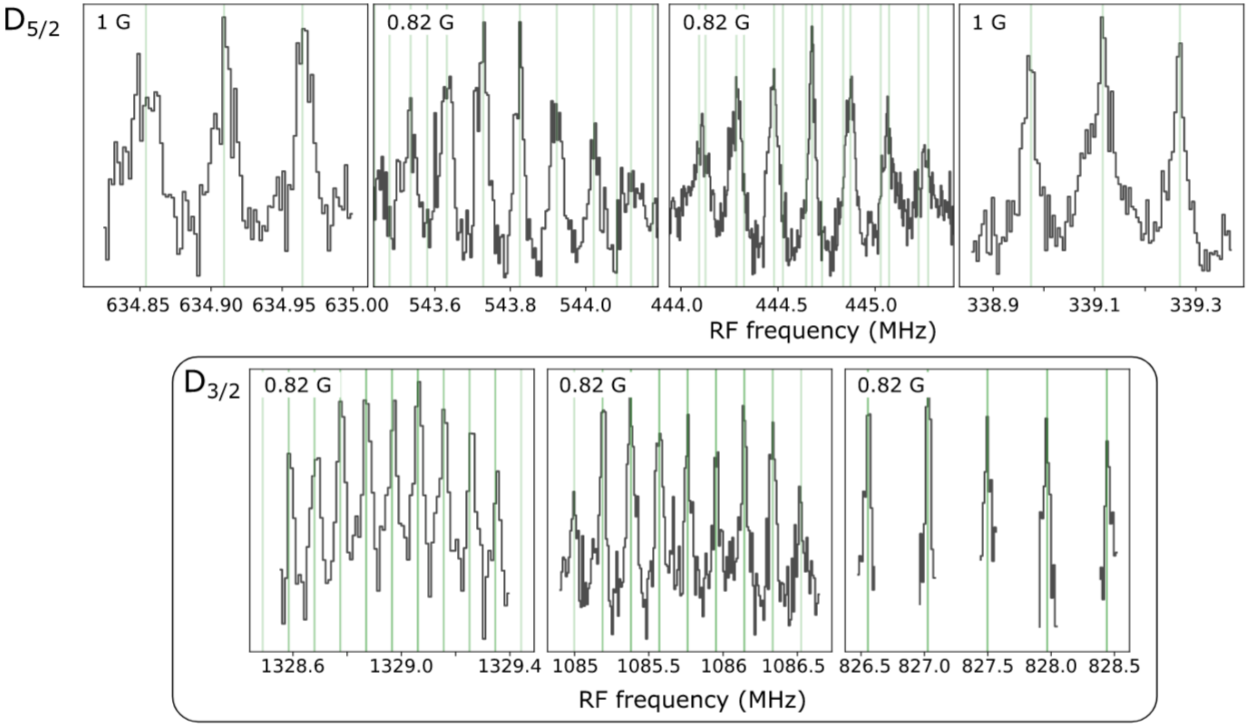
- ‘Standard’ laser spectroscopy is not sufficiently precise
- Example ^{45}Sc: Ca core + 1 proton
- Linewidth: MHz level (limited by lifetime of excited state)
- Direct excitations within hyperfine manifold with rf/microwave required
  - Linewidth ~ 1 / interaction time





R.P. de Groote, J. Moreno, J. Dobaczewski et al., Physics Letters B 827 (2022) 136930

RF scans: (F, m) -> (F', m) resonances



20 kHz width

Many resonances due to Zeeman splitting

Hyperfine constants ~ 100x more precise

		Expt. this work	
		Uncorrected	Corrected
$D_{3/2}$	A [MHz]	269.55817(5)	269.55844(7)[3]
	B [MHz]	-26.3531(9)	-26.3596(5)[5]
	C [kHz]	-0.010(22)	0.039(28)[2]
	$\Omega\,[\mu_N \mathrm{b}]$	0.17(38)	-0.68(49)[6]
$D_{5/2}$	A [MHz]	109.03275(7)	109.03297(5)[3]
	B [MHz]	-37.3954(12)	-37.3745(8)[15]
	C [kHz]	0.31(8)	-0.062(59)[17]
	$\Omega\,[\mu_N \mathrm{b}]$	-1.92(51)	0.39(37)[11]

R.P. de Groote, J. Moreno, J. Dobaczewski et al., Physics Letters B 827 (2022) 136930

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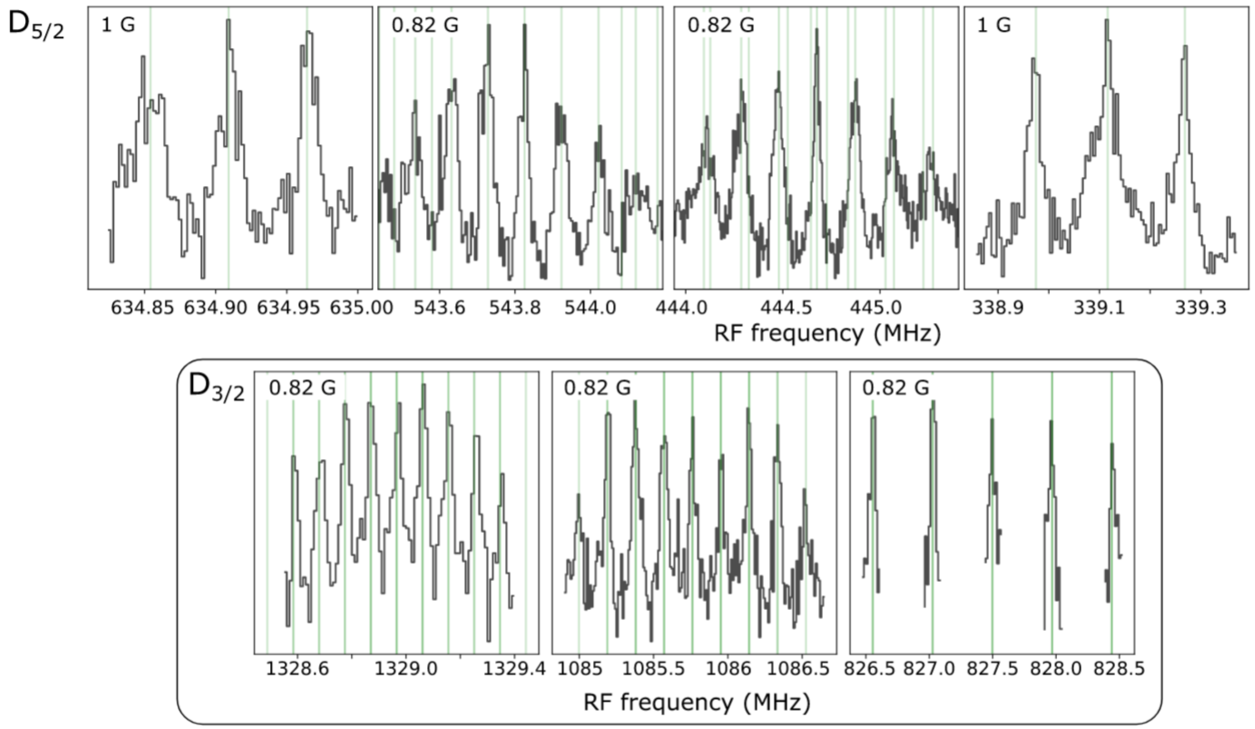

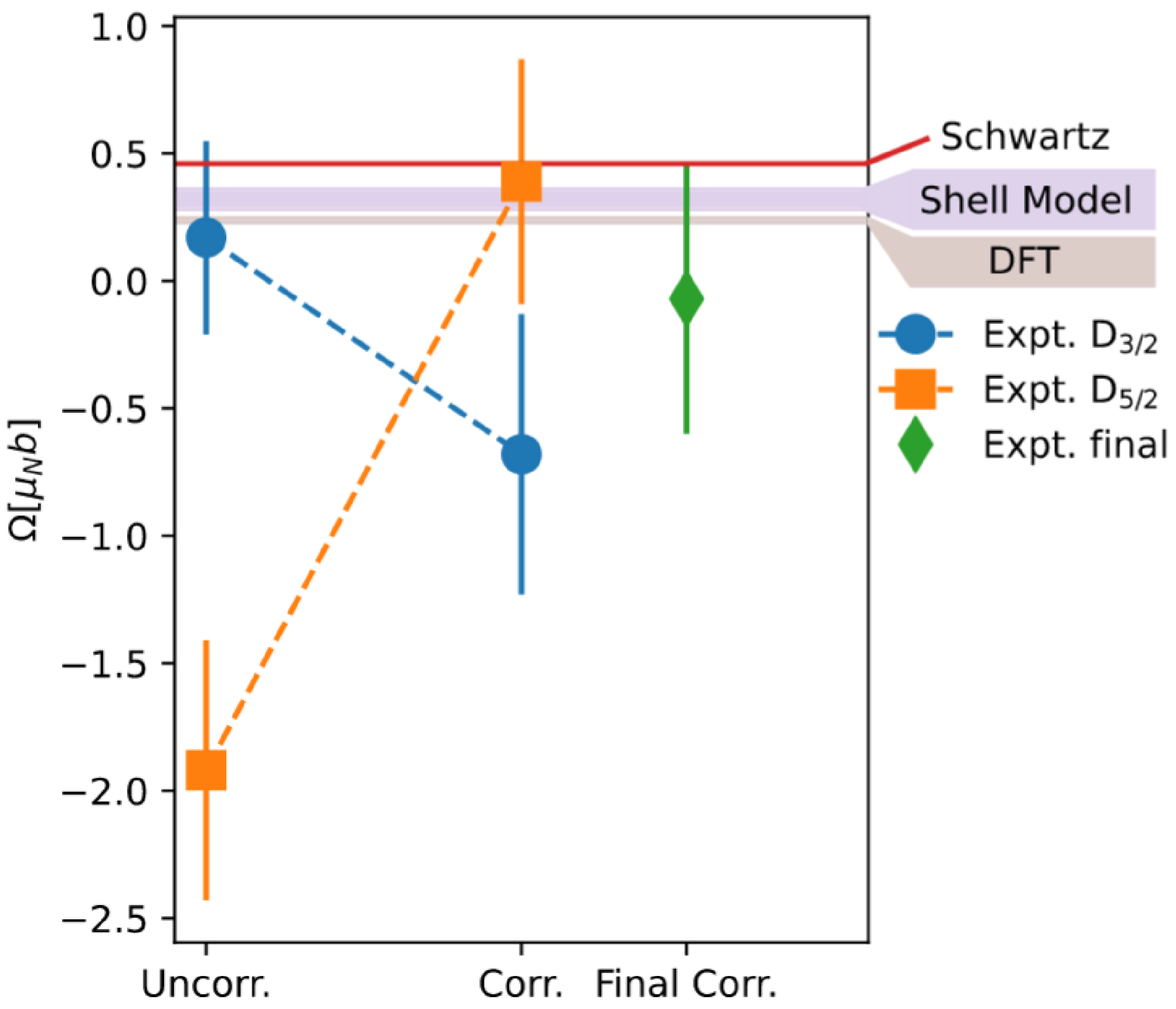

20 kHz width
Many resonances due to Zeeman splitting

DFT calculations by Jacek (talk Friday)

R.P. de Groote, J. Moreno, J. Dobaczewski et al., Physics Letters B 827 (2022) 136930

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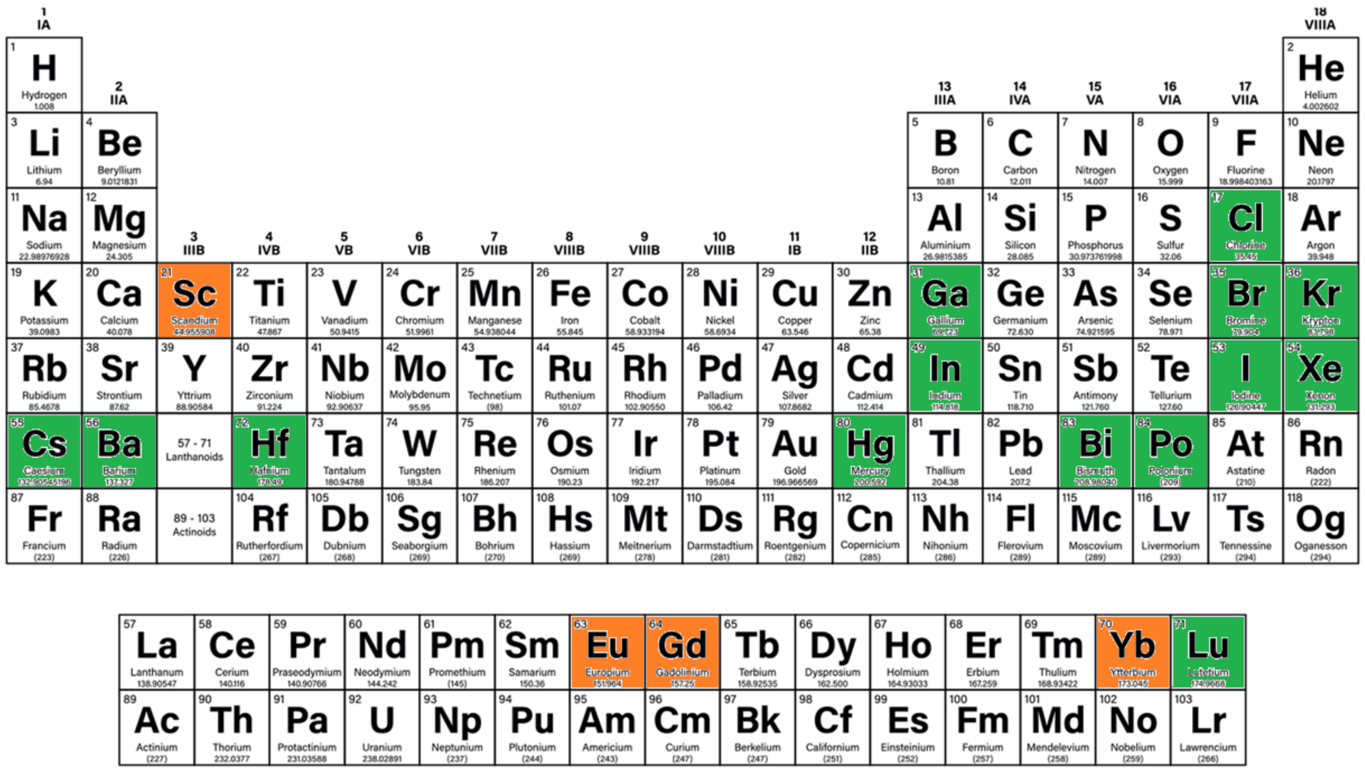
Future perspectives

- ‘Conventional’ laser double-resonance experiments
    - Room to explore stable elements!

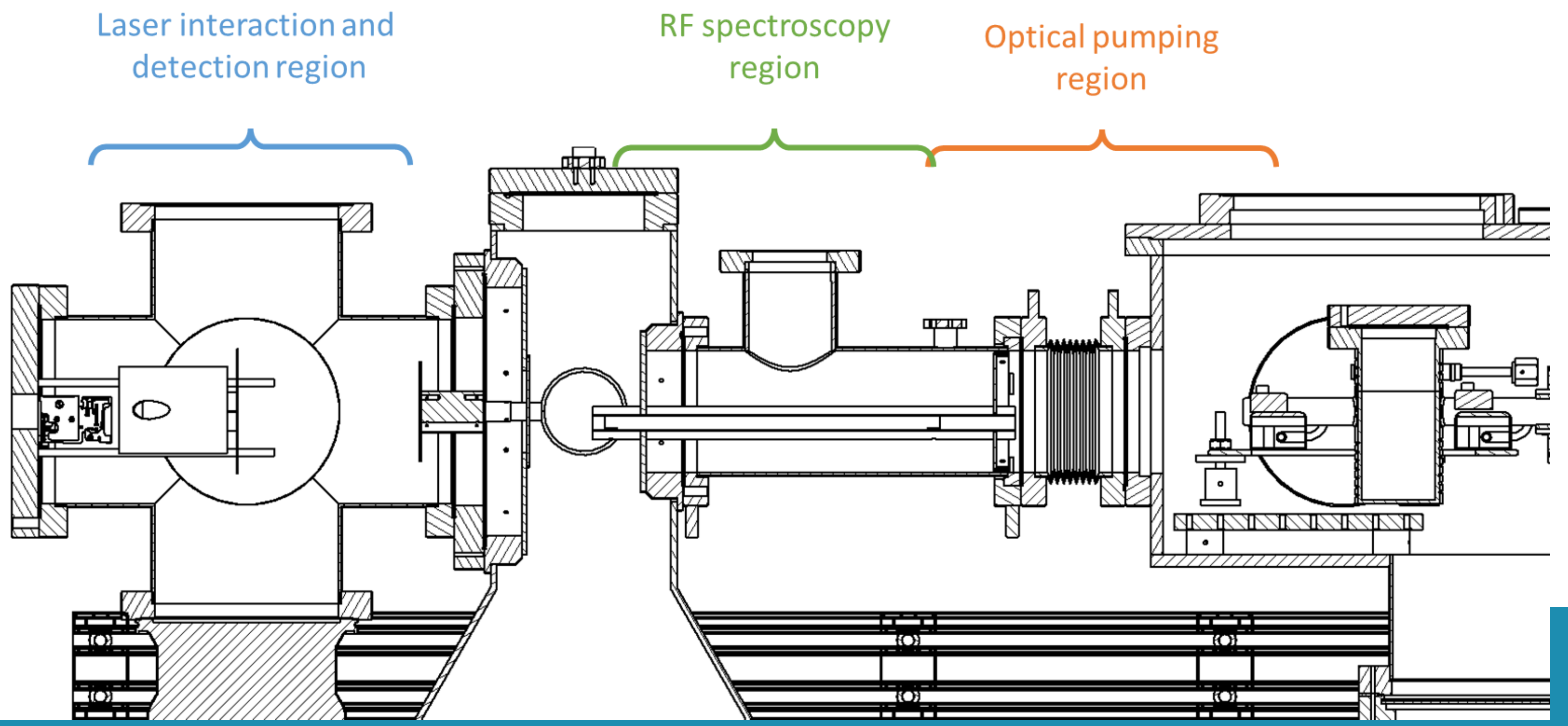


Future perspectives

- ‘Conventional’ laser double-resonance experiments
  - Room to explore stable elements!
  - Implementations optimized for radioactive species (e.g. in collinear geometry)

MARIE CURIE ACTIONS

Proof-of-concept experiments coming soon (?) @ JYU ACCLAB



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- ‘Conventional’ laser double-resonance experiments
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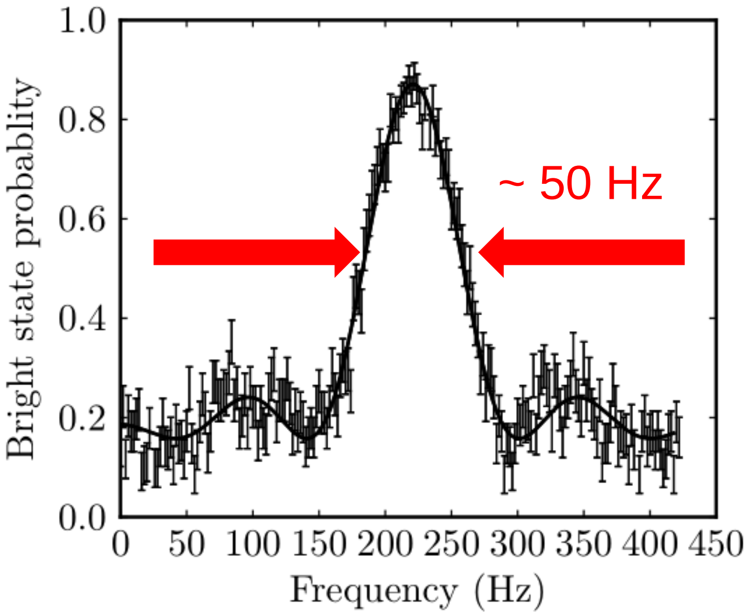
- Experiments in atom and ion traps
  - Precision ~ 1/interaction time…
  - Demonstration with stable barium



$$\Omega\left({}^{137}\mathrm{Ba}^{+}_{\mathrm{D}_{3/2}}\right) = 0.05057(54)\ (\mu_{\mathrm{N}} \times \mathrm{b}),$$
$$\Omega\left({}^{137}\mathrm{Ba}^{+}_{\mathrm{D}_{5/2}}\right) = 0.0496(37)\ (\mu_{\mathrm{N}} \times \mathrm{b}),$$

Optics Express Vol. 20, Issue 19, pp. 21379-21384 (2012)

Future perspectives

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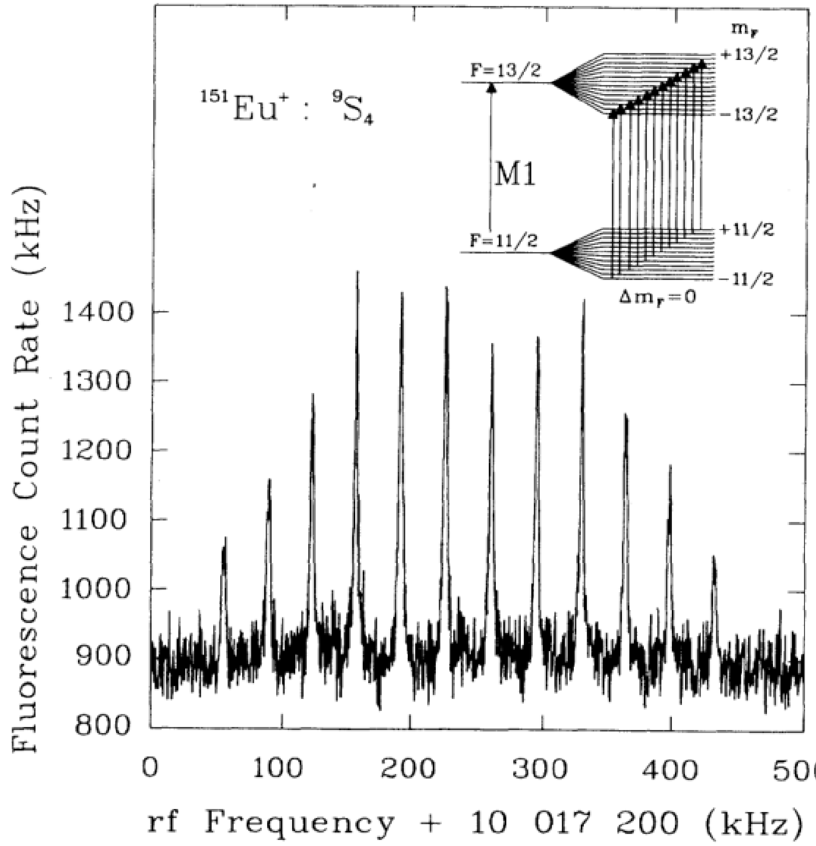
  - Precision ~ 1/interaction time…
  - Demonstration with stable barium, europium

Fit No.	hfs constant	$^{151}Eu^+$ (Hz)	$^{153}Eu^+$ (Hz)	$^{151}Eu^+$:^{153} Eu^+
VI	*A*	1 540 297 394(13)	684 565 993(9)	2.250 034 927(35)
	B	−660 862(231)	−1 752 868(84)	0.377 02(13)
	C	26(23)	3(7)	9(22)
	D	−6(5)	−5(2)	1.2(1.1)



O. Becker et al, PRA vol 45, 5, 1993

Future perspectives

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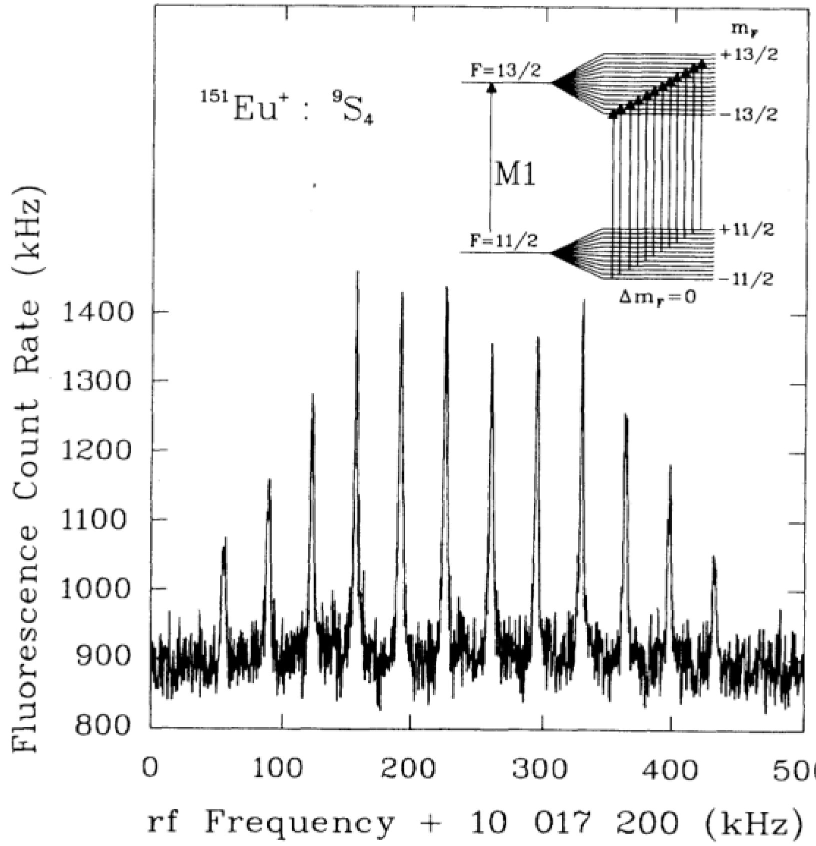
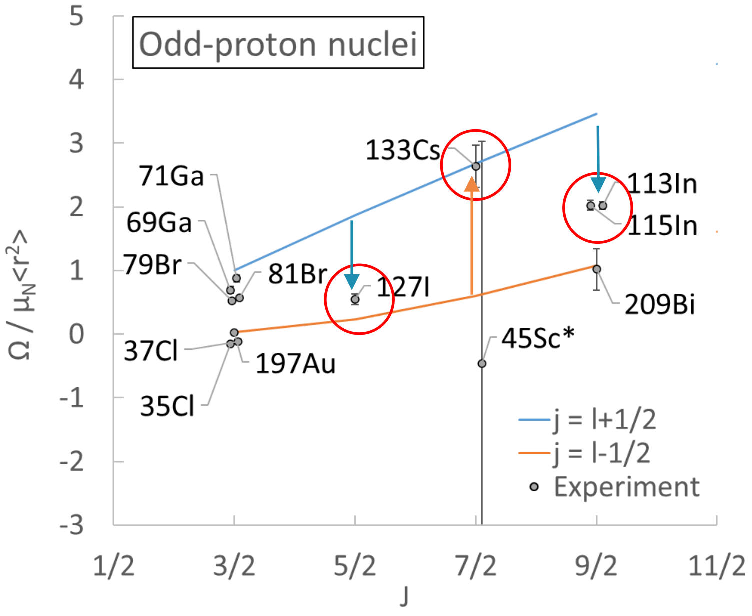
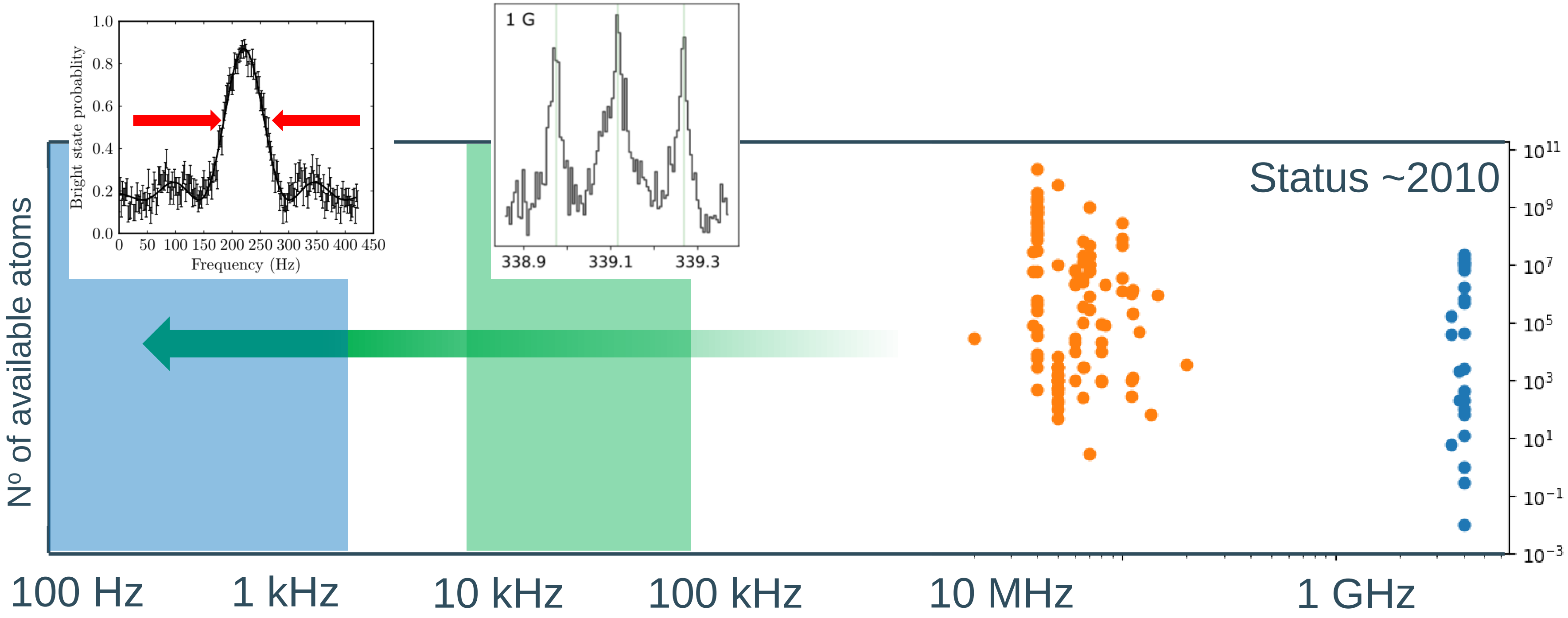


O. Becker et al, PRA vol 45, 5, 1993

In conclusion…



- Higher-order moments have only scarcely been explored
- Significant potential for new information on the nucleus
- Lots of experimental opportunity
- Nuclear theory ready for the challenge(?)
- Atomic theory required for accurate results and to find most sensitive states to probe



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Atomic theory is warming up…

PHYSICAL REVIEW A **92**, 052506 (2015)

Appraising nuclear-octupole-moment contributions to the hyperfine structures in ^{211}Fr

B. K. Sahoo*
Theoretical Physics Division, Physical Research Laboratory, Ahmedabad-380009, India

(Received 10 July 2015; published 3 November 2015)

Hyperfine structure of ^{173}Yb^{+}: Toward resolving the ^{173}Yb nuclear-octupole-moment puzzle

Di Xiao,[1] Jiguang Li (李冀光),[2] Wesley C. Campbell,[3] Thomas Dellaert,[3] Patrick McMillin,[3] Anthony Ransford,[3] Conrad Roman,[3] and Andrei Derevianko[1,*]
[1]*Department of Physics, University of Nevada, Reno, Nevada 89557, USA*
[2]*Institute of Applied Physics and Computational Mathematics, Beijing 100088, China*
…lifornia,

Hyperfine structure of the metastable $^3P_2$ state of alkaline-earth-metal atoms as an accurate probe of nuclear magnetic octupole moments

K. Beloy and A. Derevianko
Physics Department, University of Nevada, Reno, Nevada 89557, USA

W. R. Johnson
Physics Department, University of Notre Dame, Notre Dame, Indiana 46566, USA

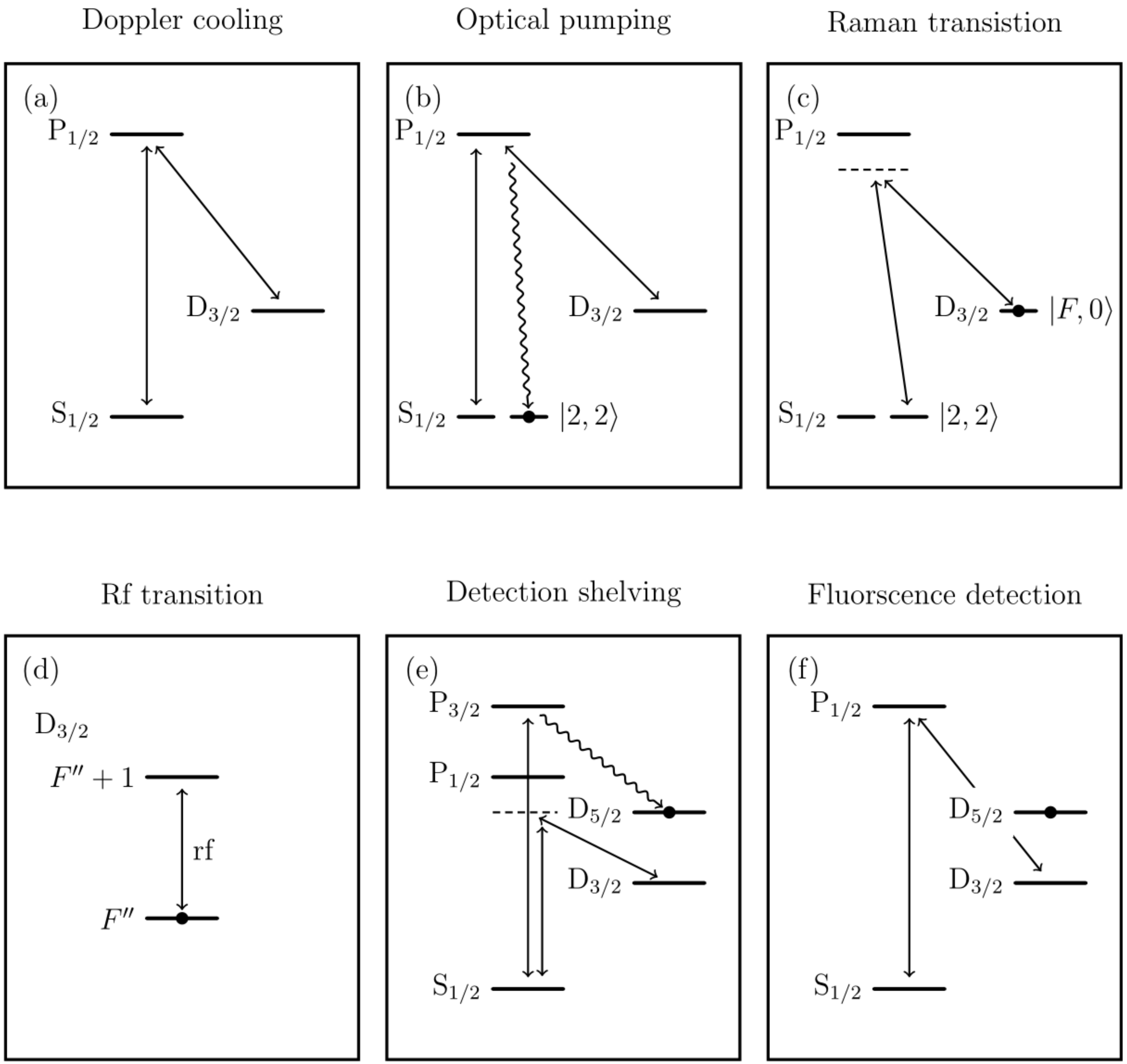
Relativistic coupled-cluster-theory analysis of the hyperfine interaction of Ra^{+} isotopes

Fei-Chen Li,[1,3] Yong-Bo Tang,[2,*] Hao-Xue Qiao,[1,*] and Ting-Yun Shi[3]
[1]*Department of Physics, Wuhan University, Wuhan, 430072, China*
[2]*College of Engineering Physics, Shenzhen Technology University, Shenzhen, 518118, China and*
[3]*State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences, Wuhan, 430071, China**

(Dated: March 16, 2021)

Hyperfine-structure constants of odd Ra^{+} due to the interactions of nuclear magnetic dipole, electric quadrupole, and magnetic octupole moments with the electrons are investigated in the frame-

Thanks for your attention!


Doppler cooling
Optical pumping
Raman transistion
(a)
$P_{1/2}$
$D_{3/2}$
$S_{1/2}$
(b)
$P_{1/2}$
$D_{3/2}$
$S_{1/2}$
$|2, 2\rangle$
(c)
$P_{1/2}$
$D_{3/2}$
$|F, 0\rangle$
$S_{1/2}$
$|2, 2\rangle$
Rf transition
Detection shelving
Fluorscence detection
(d)
$D_{3/2}$
$F'' + 1$
rf
F''
(e)
$P_{3/2}$
$P_{1/2}$
$D_{5/2}$
$D_{3/2}$
$S_{1/2}$
(f)
$P_{1/2}$
$D_{5/2}$
$D_{3/2}$
$S_{1/2}$