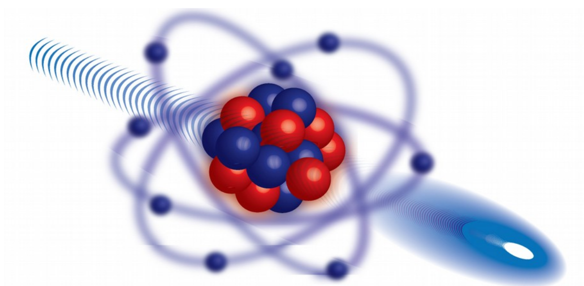
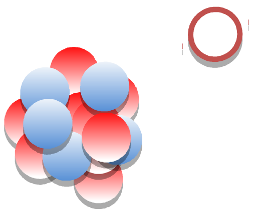
Nuclear ground-state properties from laser spectroscopy

Ronald Fernando Garcia Ruiz

CERN





1st APCTP-TRIUMF Joint Workshop

"Understanding Nuclei from Different Theoretical Approaches"

Pohang, South Korea 2018

The COLLAPS Collaboration

Collinear Laser Spectroscopy

M. Bissell, K. Blaum, B. Cheal, N. Frommgen, R.F. Garcia Ruiz, C. Gorges, M.Hammen, M. Kowalska, K. Kreim, S. Malbrunot-Ettenauer, R.Neugart, G. Neyens, W. Nortershauser, J. Papuga, X. Yang, D.Yordanov

The CRIS Collaboration

Collinear Resonance Ionization Spectroscopy

J. Billowes, C. Binnersley, T.E. Cocolios, G. Farooq-Smith, K.T. Flanagan, W. Gins, K.M. Lynch, S. Franchoo, V. Fedosseev, B.A. Marsh, M. Bissell, R.P. De Groote, R.F. Garcia Ruiz, A. Koszorus G. Nevens, C. Ricketts, H.H. Stroke, A. Vernon, K. Wendt, S. Wilkins, X. Yang

European Research Council

Established by the European Commission

Nuclear ground-state properties from laser spectroscopy

Contents

- Motivation
- Laser spectroscopy
  → Nuclear ground-state properties
- Recent results
  → Nuclear physics: ^{40,48,52,54}Ca, ^{56,68,78}Ni, ^{100,132}Sn regions
- Charge radii vs properties of nuclear matter
- Summary and outlook

Nuclear theory:
"Ab-initio";

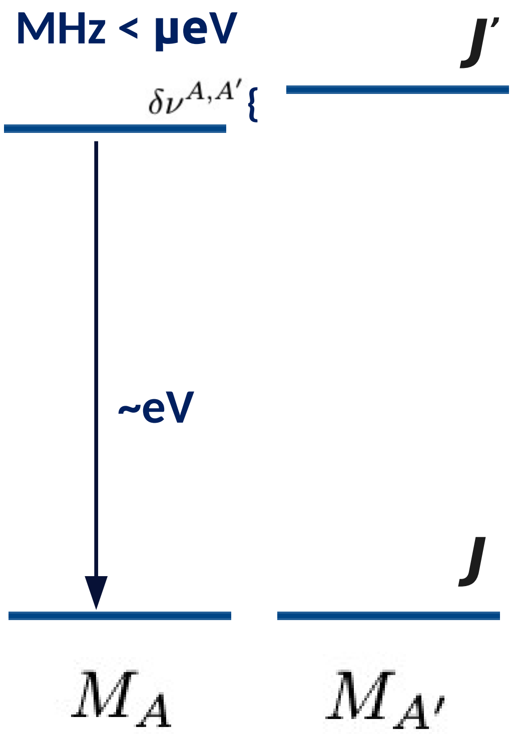
→ G. Hagen (ORNL)
→ J. Holt (TRIUMF)

Atomic theory:
-> B.K. Sahoo (PRL, India, Wuhan Inst., China)

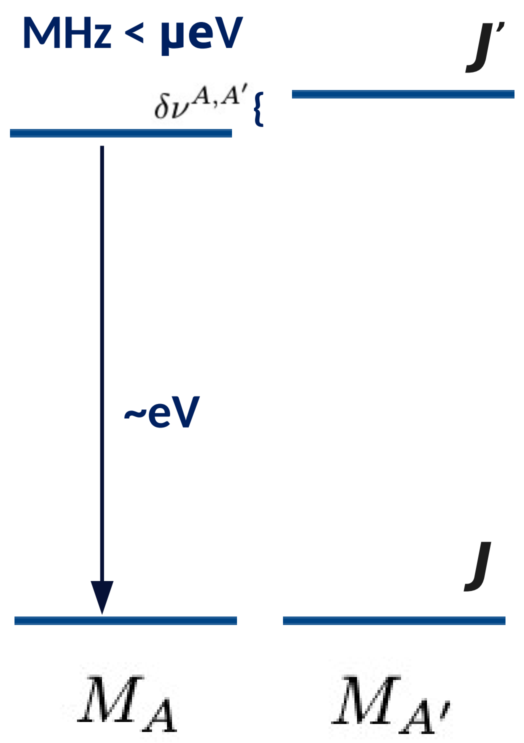
Quantum chemistry (RaF):
-> R. Bergerger (U. Marburg, Germany)

[Garcia Ruiz et al. Accepted in Phys. Rev. X (2018)]

Atomic hyperfine structure



Atomic hyperfine structure

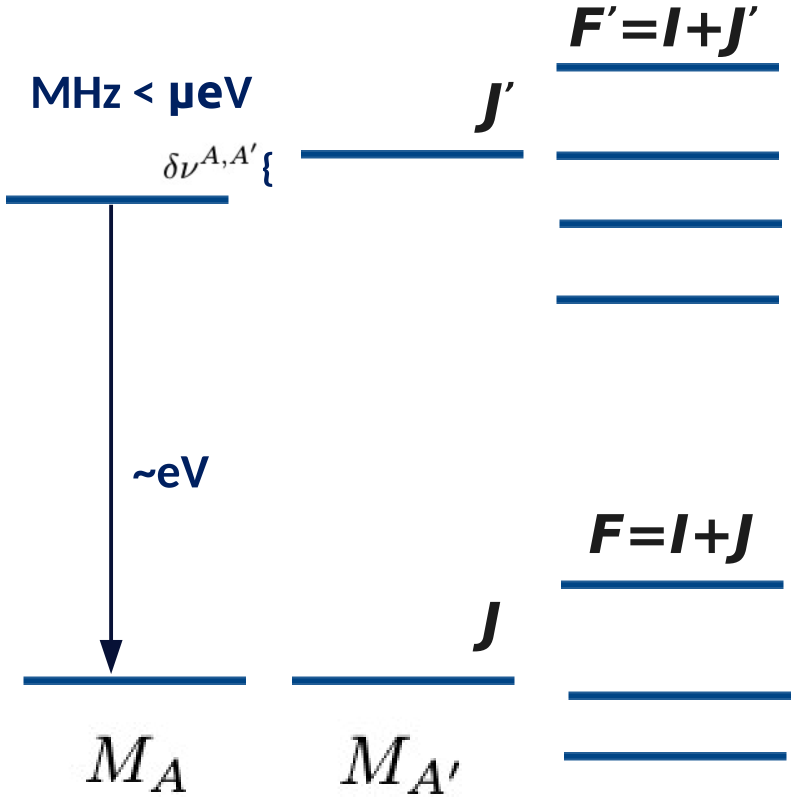


Atomic parameters

$$\delta\nu^{A,A'} = K_{MS}\frac{M_{A'} - M_A}{M_{A'}M_A} + F\delta\langle r^2\rangle^{A,A'}$$

Nuclear charge radius

Atomic hyperfine structure



$$\hat{H}_{\mathrm{dip}} = -\hat{\boldsymbol{\mu}} \cdot \hat{\boldsymbol{B}}(0)$$

Nucleus

Electrons

$$\hat{H}_{\mathrm{quad}} = -\hat{\boldsymbol{Q}} \cdot \nabla \boldsymbol{E}$$

Atomic parameters

$$\delta\nu^{A,A'} = K_{MS}\frac{M_{A'} - M_A}{M_{A'}M_A} + F\delta\langle r^2\rangle^{A,A'}$$

Nuclear charge radius

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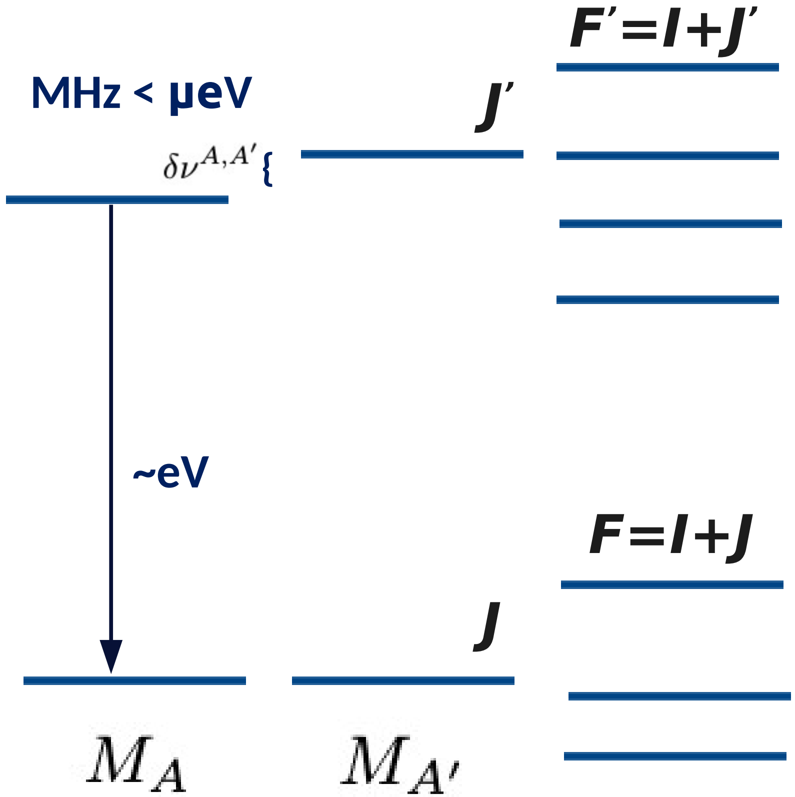


$$\hat{H}_{\mathrm{dip}} = -\hat{\boldsymbol{\mu}} \cdot \hat{\boldsymbol{B}}(0)$$

Nucleus

Electrons

$$\hat{H}_{\mathrm{quad}} = -\hat{\boldsymbol{Q}} \cdot \nabla \boldsymbol{E}$$

$$\} \sim C_1(I,J)A_{hfs} + C_2(I,J)B_{hfs}$$

Atomic parameters

$$\delta\nu^{A,A'} = K_{MS}\frac{M_{A'} - M_A}{M_{A'}M_A} + F\delta\langle r^2\rangle^{A,A'}$$

$$A_{hfs} = \frac{\mu_I B_e(0)}{IJ}$$

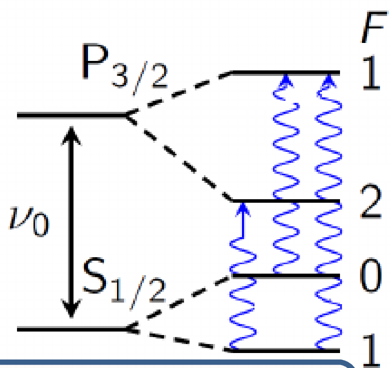
$$B_{hfs} = eQ_s\frac{\partial^2 V}{\partial^2 z}$$

Nuclear magnetic moment

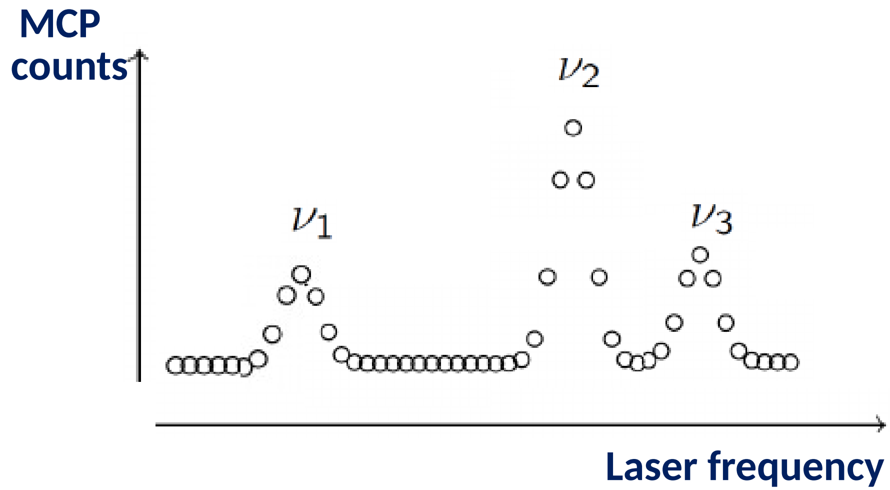
Nuclear charge radius

Nuclear quadrupole moment

Laser spectroscopy



Atomic hyperfine structure



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

Nuclear observables → $I \quad \delta\langle r^2\rangle \quad \mu_I \quad Q_s$

$$\delta\nu^{A,A'} = K_{MS}\frac{M_{A'} - M_A}{M_{A'}M_A} + F\delta\langle r^2\rangle^{A,A'} \qquad A = \frac{\mu_I B_e(0)}{IJ} \qquad B = eQ_s\frac{\partial^2 V}{\partial^2 z}$$

Atomic parameters

Motivation

Laser spectroscopy → $I \quad \delta\langle r^2\rangle \quad \mu \quad Q_s$

Nuclear Many-Body Problem

H

$H|\Psi\rangle = E|\Psi\rangle$

$\langle\Psi|\,\mu\,|\Psi\rangle$
$\langle\Psi|\,Q\,|\Psi\rangle$ **?**

Nuclear force
- Phenomenology
- Chiral effective field theory

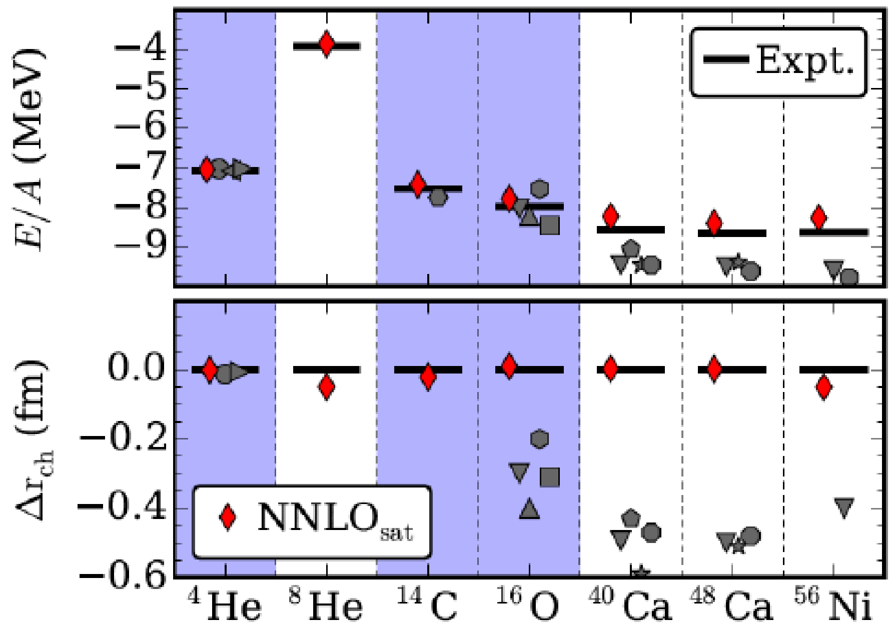
Many-body methods
- Ab-initio
- Shell-model
- DFT, ...

Electro-weak currents
- Effective neutron/proton charges
- Microscopic description of effective operators

Charge radii

Laser spectroscopy ➡ **I , $\langle r^2 \rangle$, μ , Q**

Simultaneous reproduction of charge radii and binding energies has been a long-standing challenges for nuclear theory.



- Phys. Rev. Lett. 99 042501 (2007)
- Phys. Lett. B 736 119 (2014)
- Phys. Rev. Lett. 112 102501 (2014)
- Phys. Rev. Lett. 109 252501 (2012)
- Phys. Rev. C 90 014314 (2014)
- Phys. Rev. Lett. 94 212501 (2005)
- Phys. Rev. Lett. 108 242501 (2012)
- Phys. Rev. C 90 064619 (2014)
- Phys. Rev. Lett. 106 202502 (2011)
- Phys. Rev. C 89 061301 (2014)
- Phys. Rev. C 90 041302 (2014)
- Phys. Rev. C 91, 051301(R) (2015)
  Nature Physics 12, 186 (2016)

Many-body methods

- Ab-initio
- Shell-model
- DFT, RNFT, …

Nuclear force

- Phenomenology
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Electro-weak currents

- Effective neutron/proton charges
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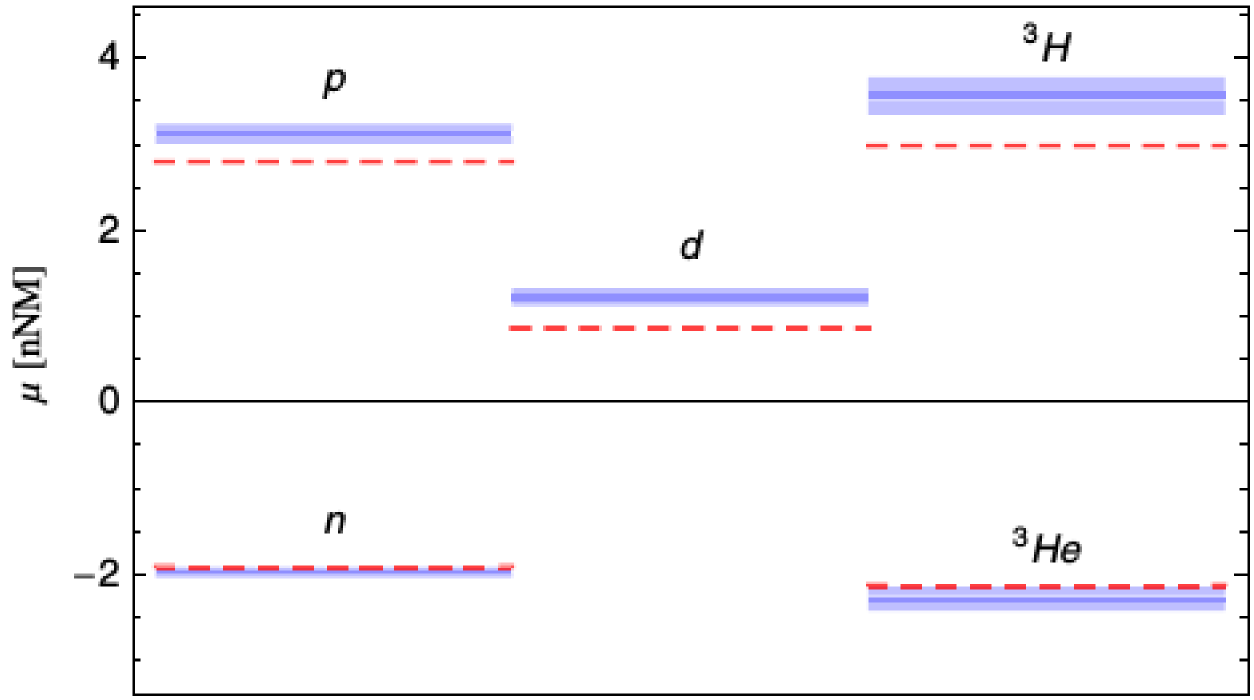
Electromagnetic moments

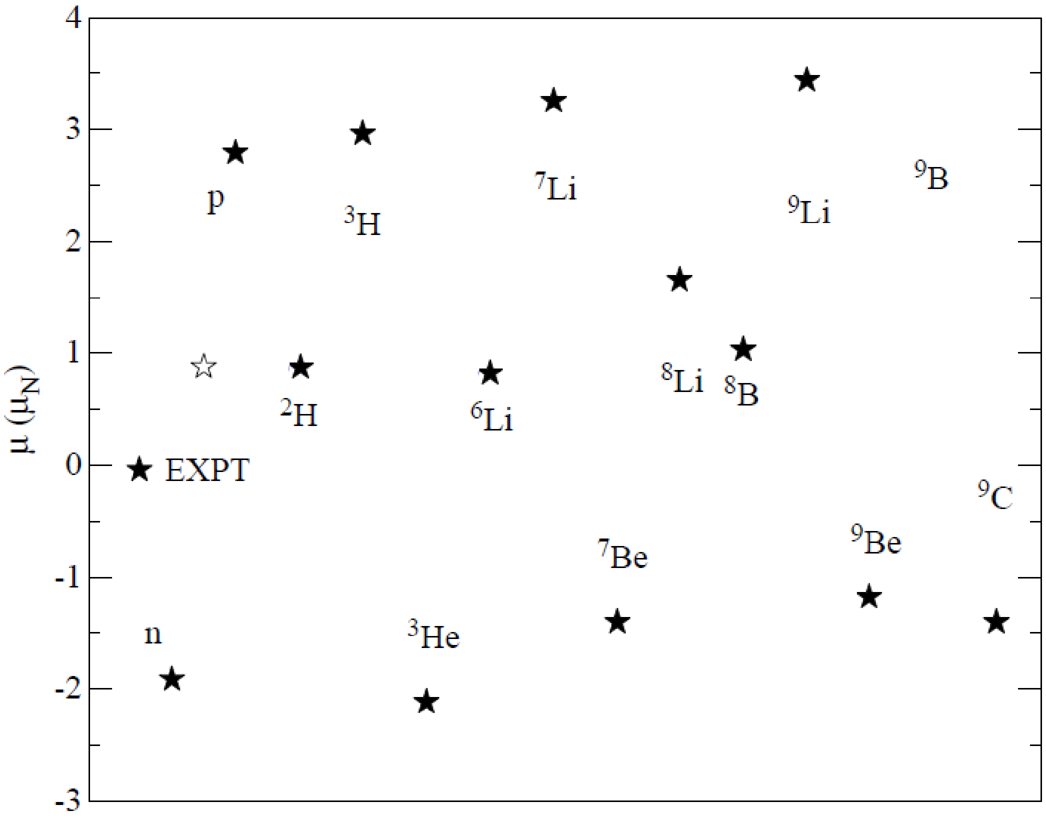
Beane et al. PRL 113, 252001 (2014)

(NPLQCD Collaboration)



Lattice QCD
Exp

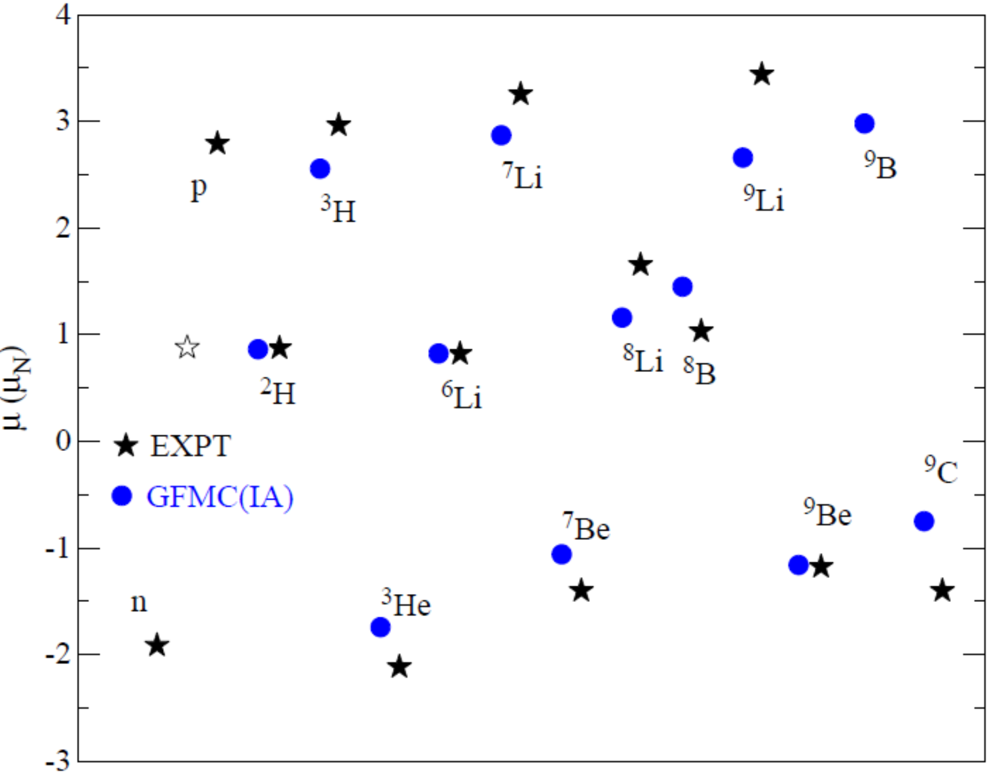
Electromagnetic moments



Electromagnetic moments

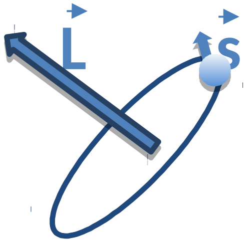
[Pastore et al. PRC 87, 035503 (2013)]
[Carlson et al. RMP 87, 1067 (2015)]

Ab-initio calculations (QMC)



-> Magnetic moments are highly sensitive to MEC:

Impulse approximation (IA):



$$\hat{\mu} = \frac{\mu_N}{\hbar}\left(\sum^{A} g_L^i \vec{L}^i + \sum^{A} g_S^i \vec{S}^i\right)$$

$$Q_2 = e\sum_{i=1}^{A} g_L^{(i)} r_i^2 P_2(\theta_i)$$

Many-body methods
- Ab-initio
- Shell-model
- DFT, RNFT, ...

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Electromagnetic moments

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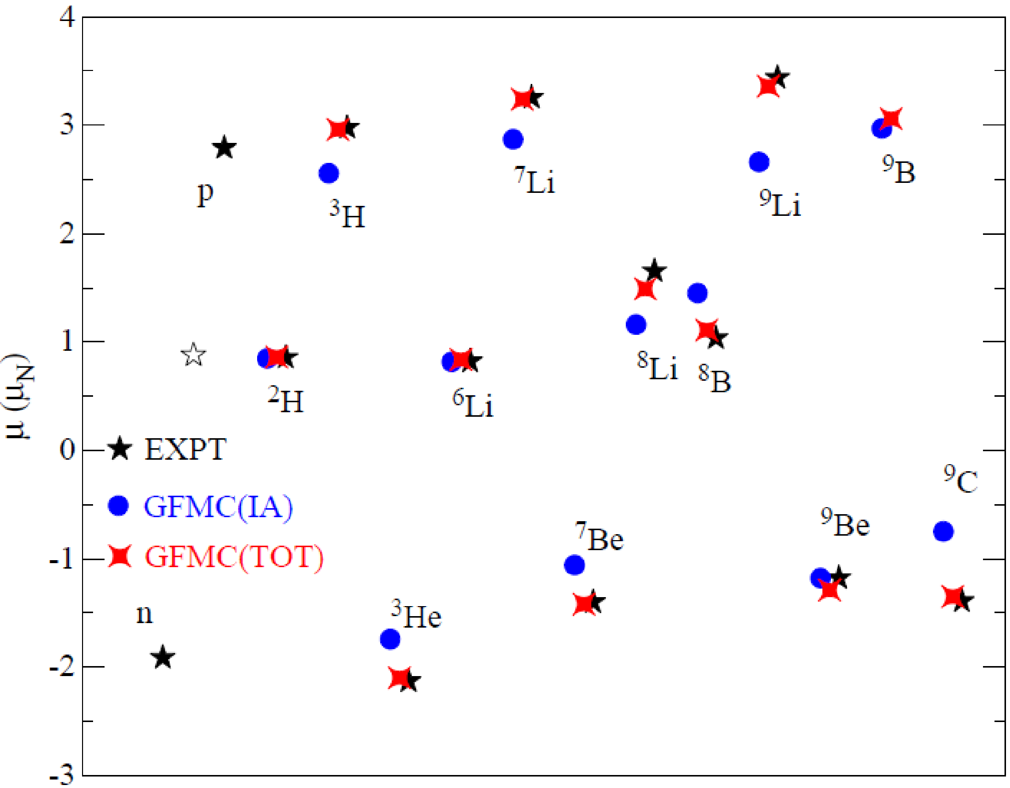
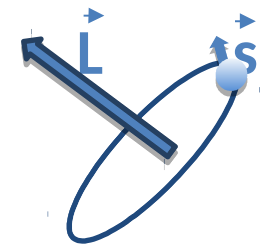
Ab-initio calculations (QMC)



-> Magnetic moments are highly sensitive:
changes up to MEC ~40% for ^{9}C

Impulse approximation (IA):



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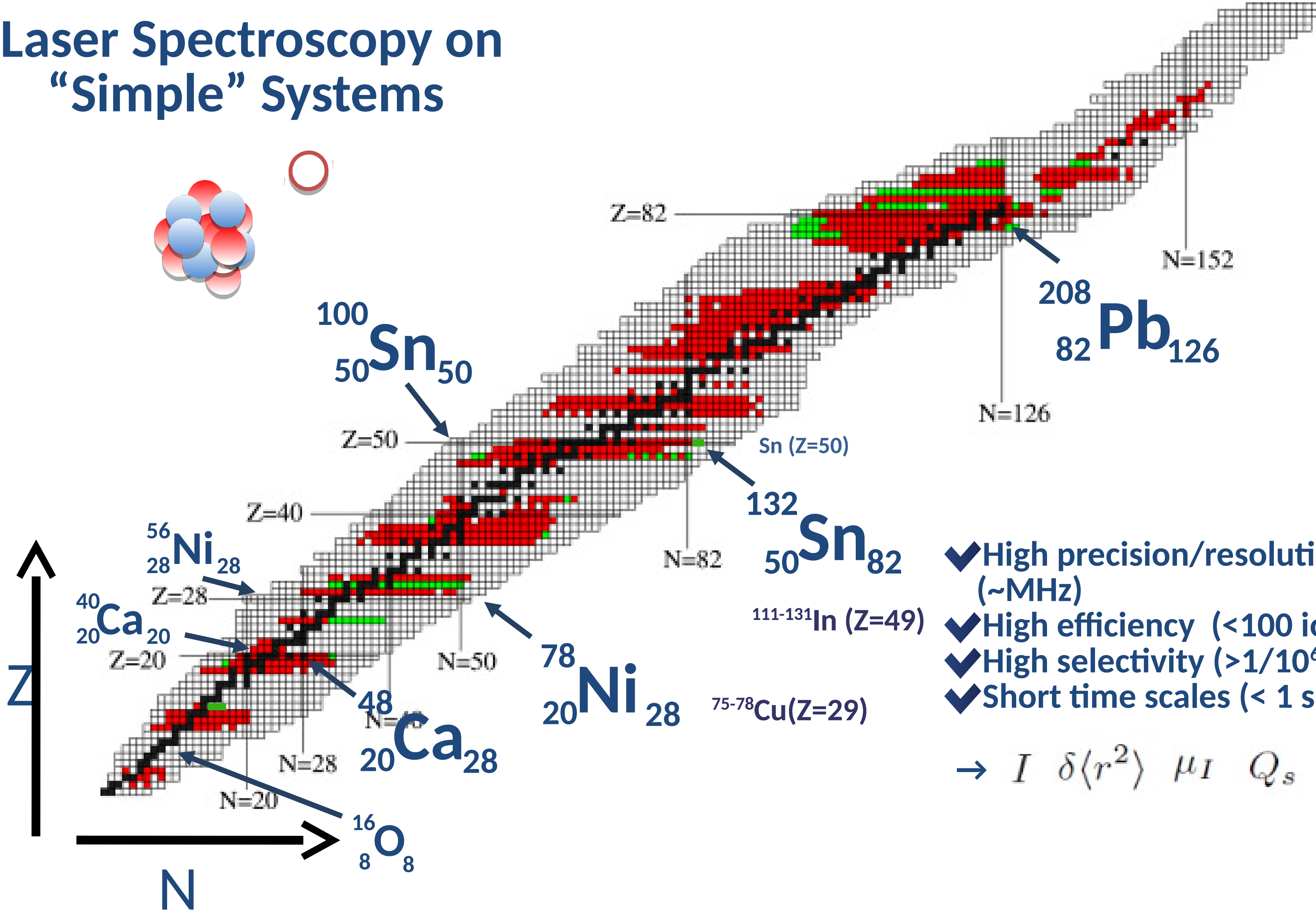
Motivation

Laser Spectroscopy on "Simple" Systems

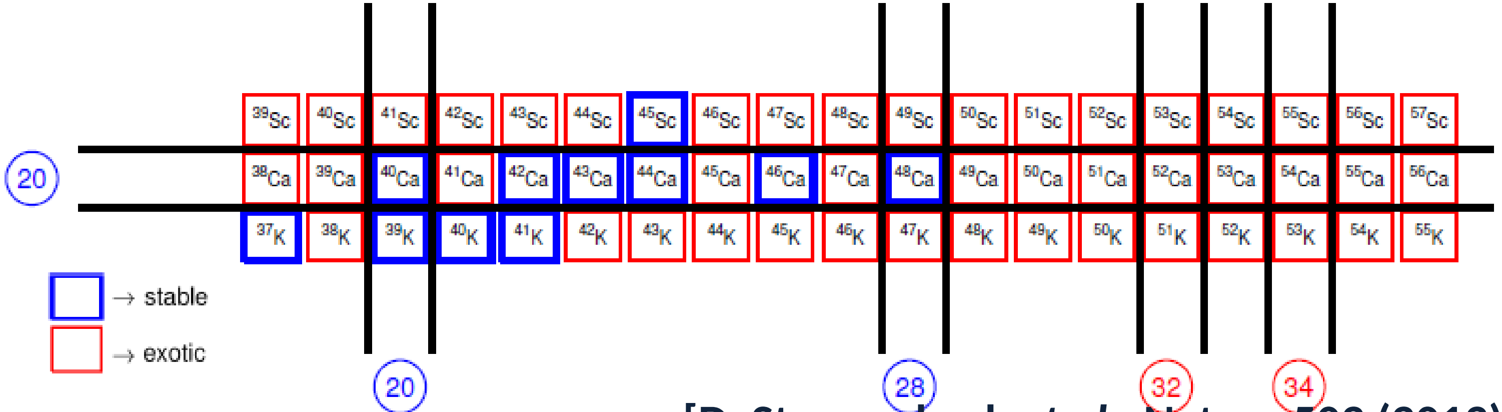


- ✔ High precision/resolution (~MHz)
- ✔ High efficiency (<100 ions/s)
- ✔ High selectivity (>1/10^6)
- ✔ Short time scales (< 1 s)

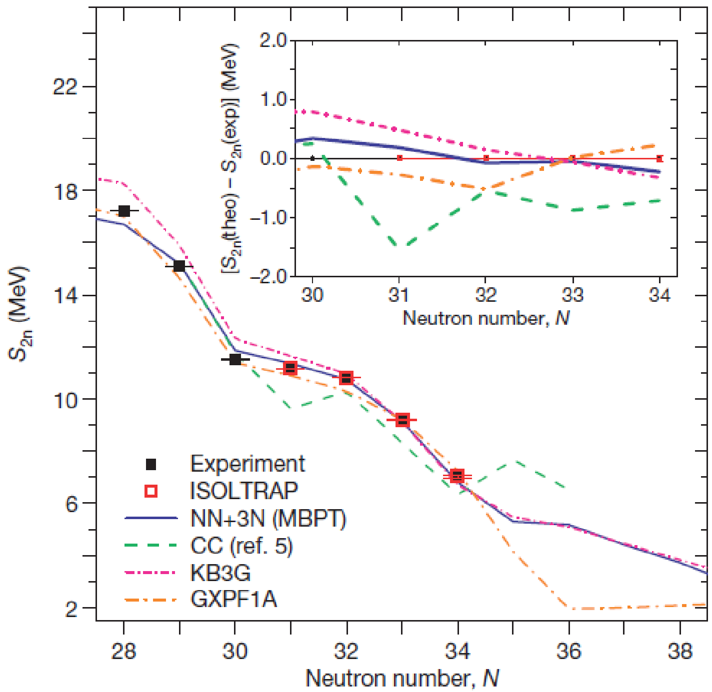
$\rightarrow \; I \quad \delta\langle r^2\rangle \quad \mu_I \quad Q_s$

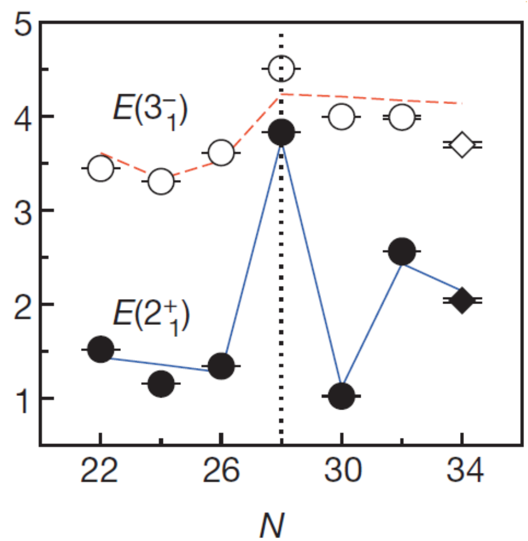
Calcium (Z=20) region

Calcium (Z=20)-> Appearance of multiple shell structures?



[D. Steppenbeck *et al*., Nature 502 (2013)]





Evidence of magic numbers(?)

$^{54}_{20}\mathrm{Ca}_{34}$

[F. Wienholtz *et al*., Nature 498 (2013)]

$^{52}_{20}\mathrm{Ca}_{32}$

Charge radii	$\delta\langle r^2\rangle^{A,A'}$
Quadrupole moment	Q_s
Magnetic moment	μ_I
Nuclear spin	I

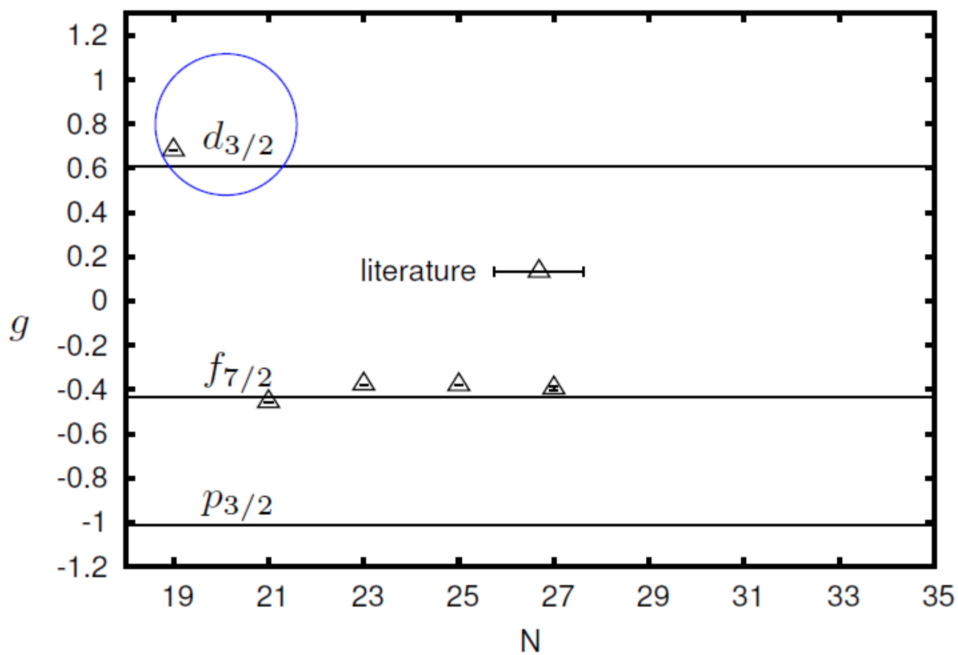
?

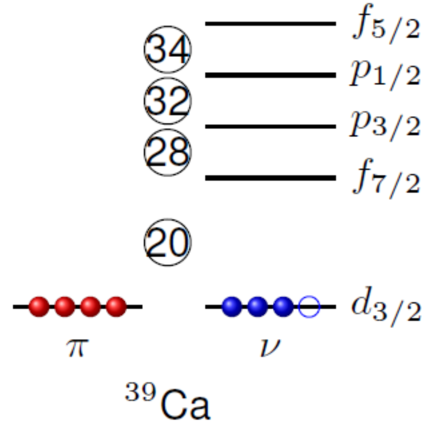
Results: Electromagnetic moments

[R.F. Garcia Ruiz *et al.* PRC 91, 041304(R) (2015)]

$$\hat{\mu} = \frac{\mu_N}{\hbar}\left(\sum_i^A g_L^i \hat{L}^i + \sum_i^A g_S^i \hat{S}^i\right)$$

g=μ/I





[R.F. Garcia Ruiz *et al.* PRC 91, 041304(R) (2015)]

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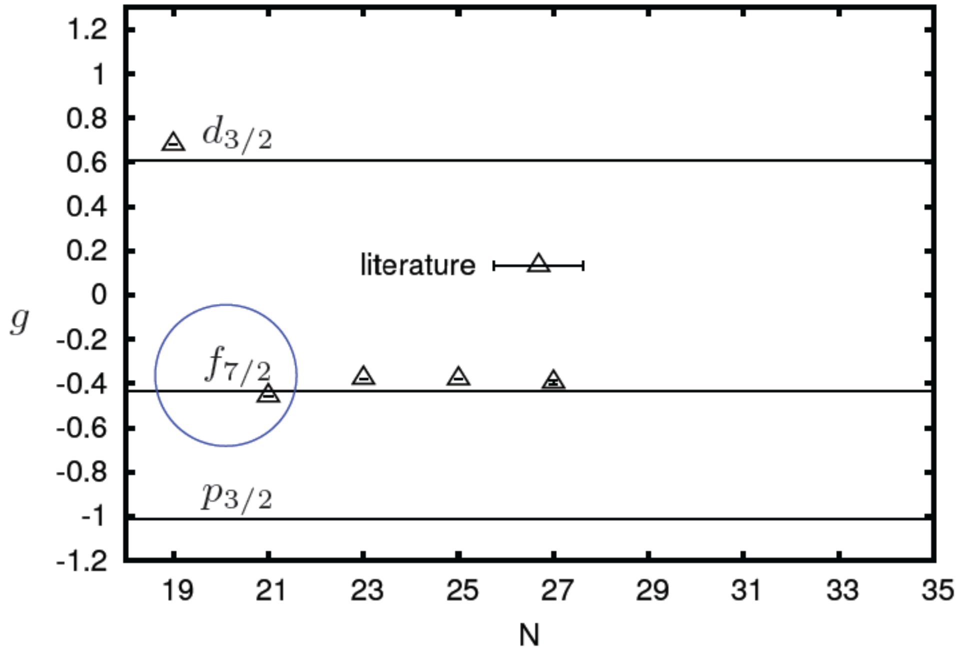

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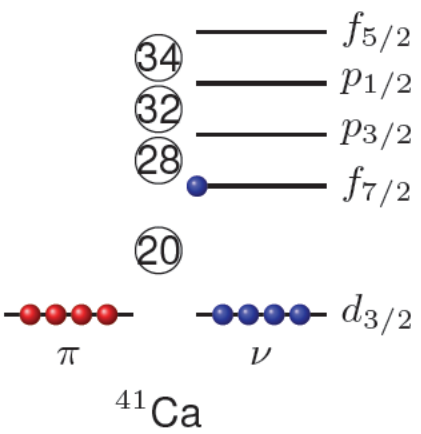

[R.F. Garcia Ruiz *et al.* PRC 91, 041304(R) (2015)]

Results: Electromagnetic moments

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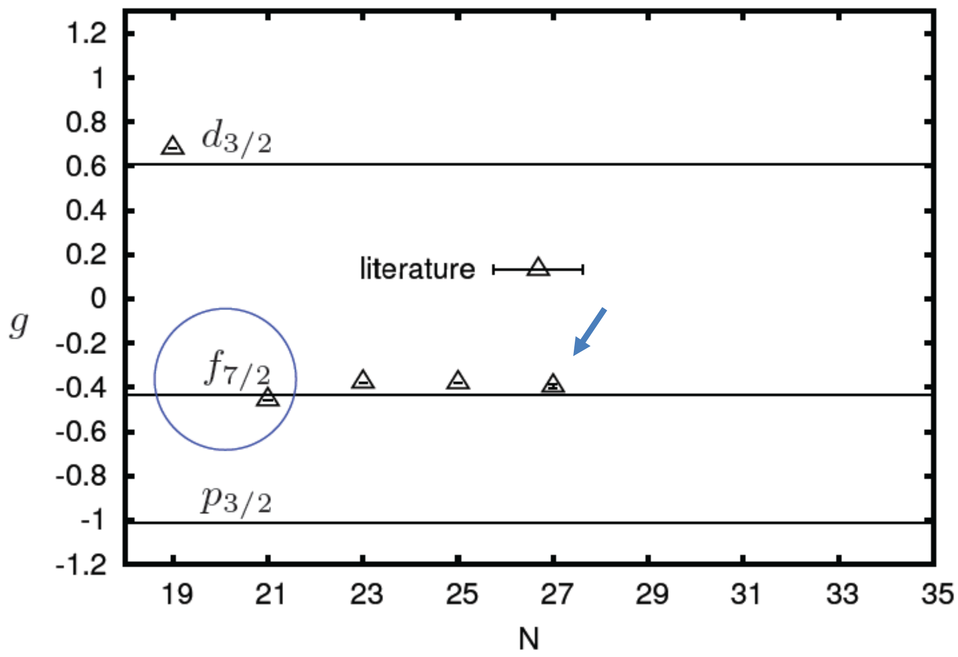

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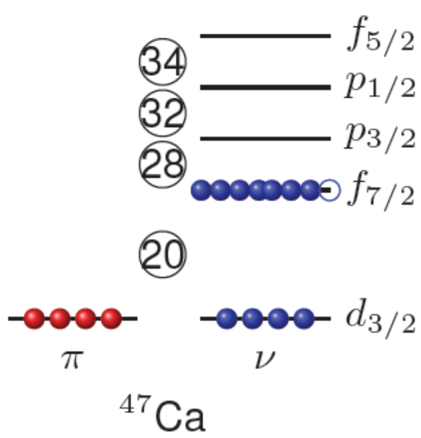

[R.F. Garcia Ruiz *et al.* PRC 91, 041304(R) (2015)]

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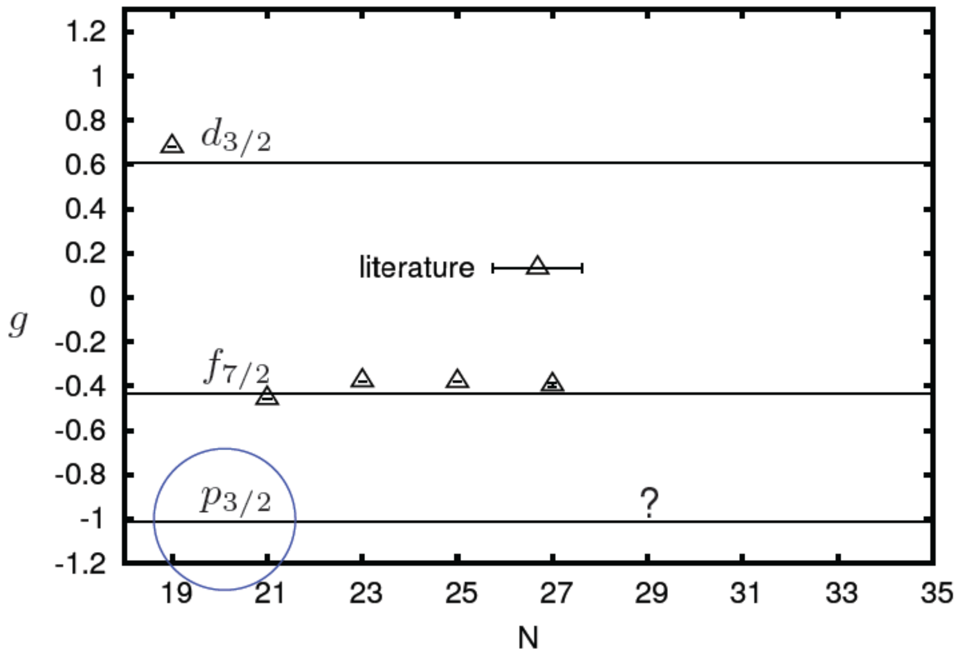

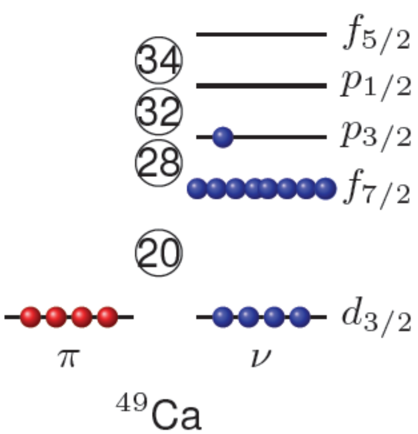

[R.F. Garcia Ruiz *et al.* PRC 91, 041304(R) (2015)]

Results: Electromagnetic moments

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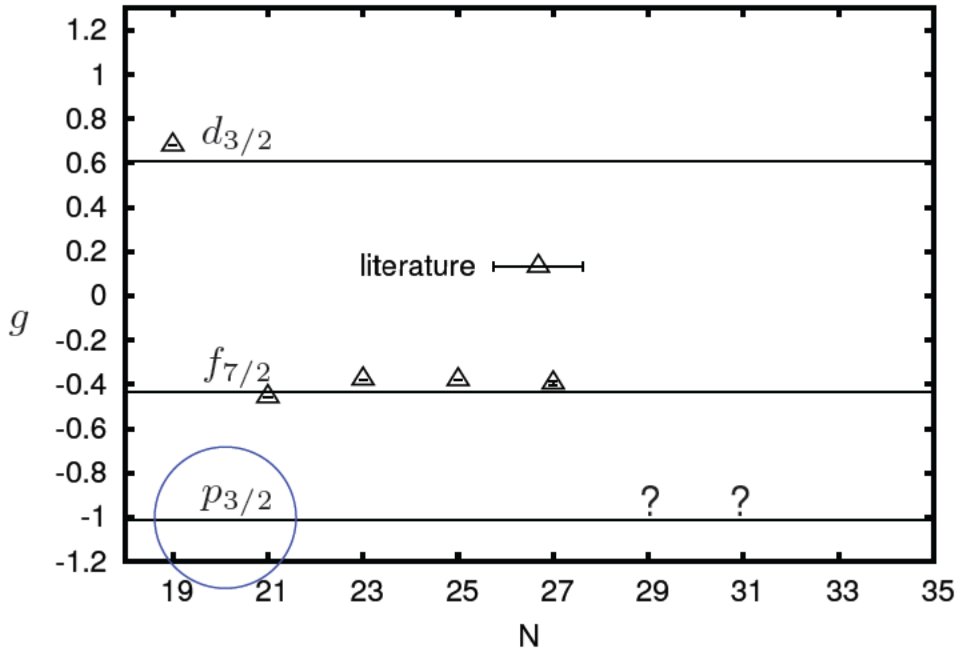

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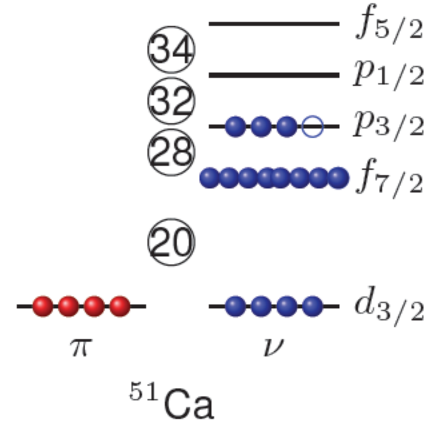


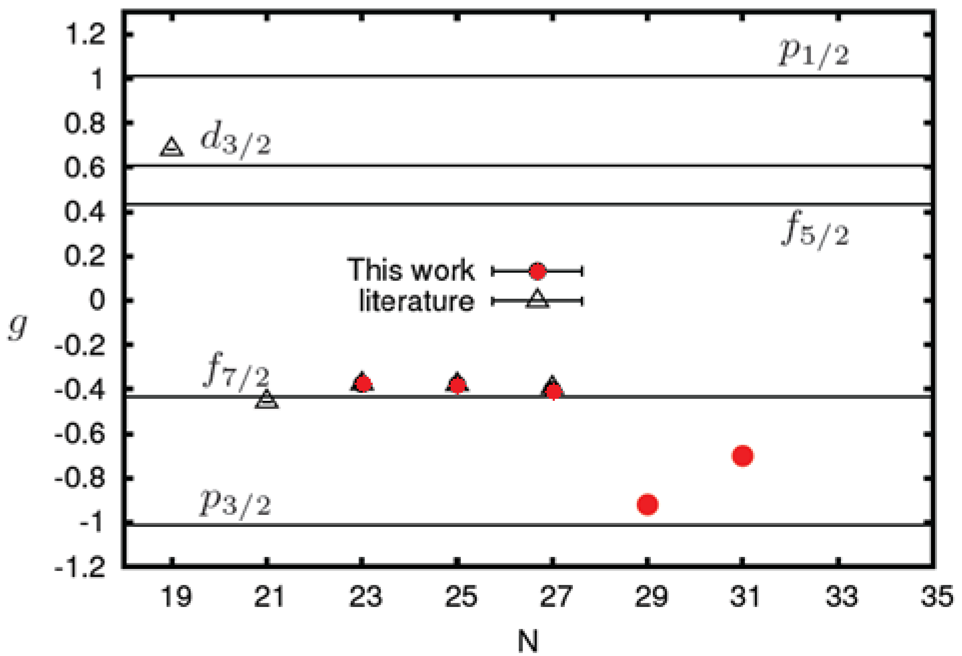
[R.F. Garcia Ruiz *et al.* PRC 91, 041304(R) (2015)]

Results: Electromagnetic moments

[R.F. Garcia Ruiz *et al.* PRC 91, 041304(R) (2015)]

k

g=μ/I



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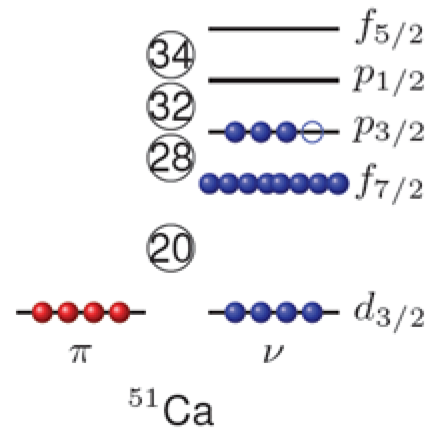
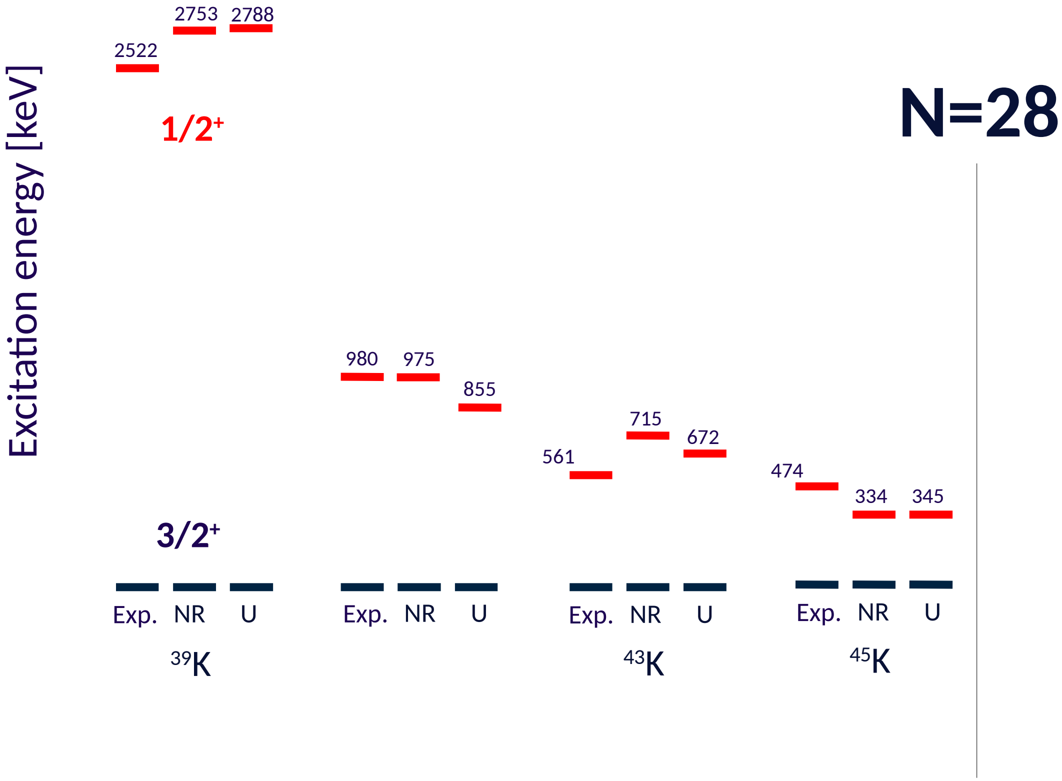
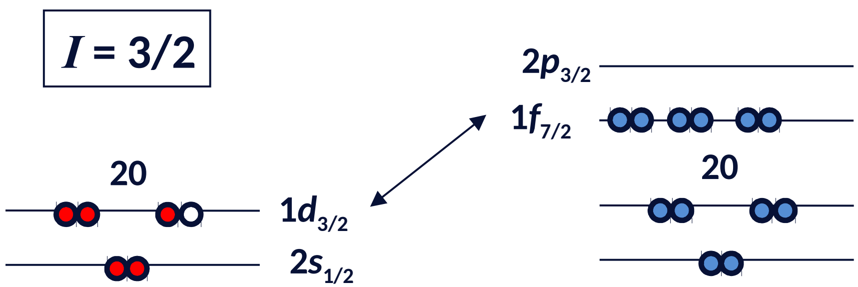


[R.F. Garcia Ruiz *et al.* PRC 91, 041304(R) (2015)]

-> cross shell excitations across N=32 are important!

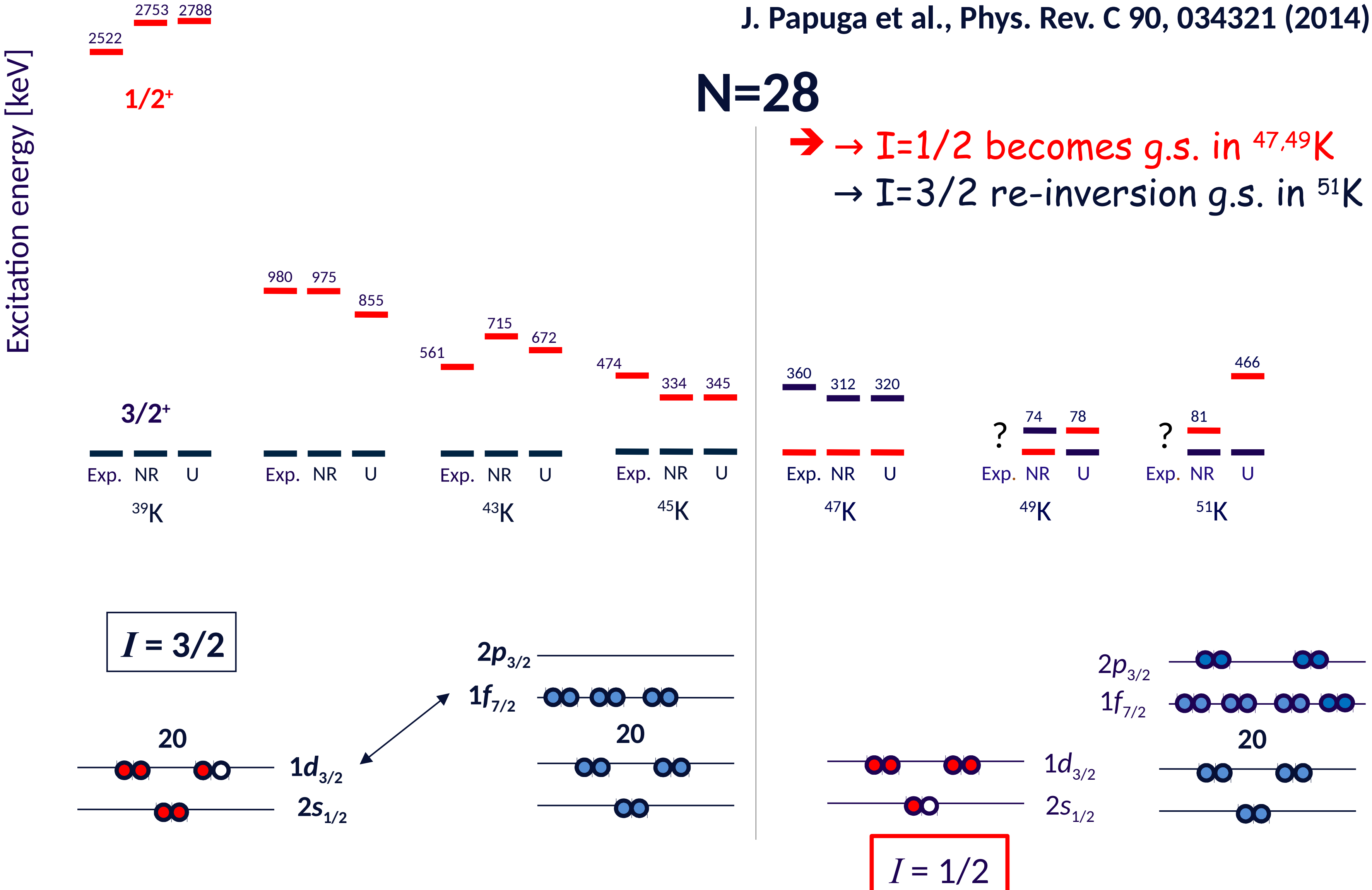
K-isotopes: Evolution of proton orbits



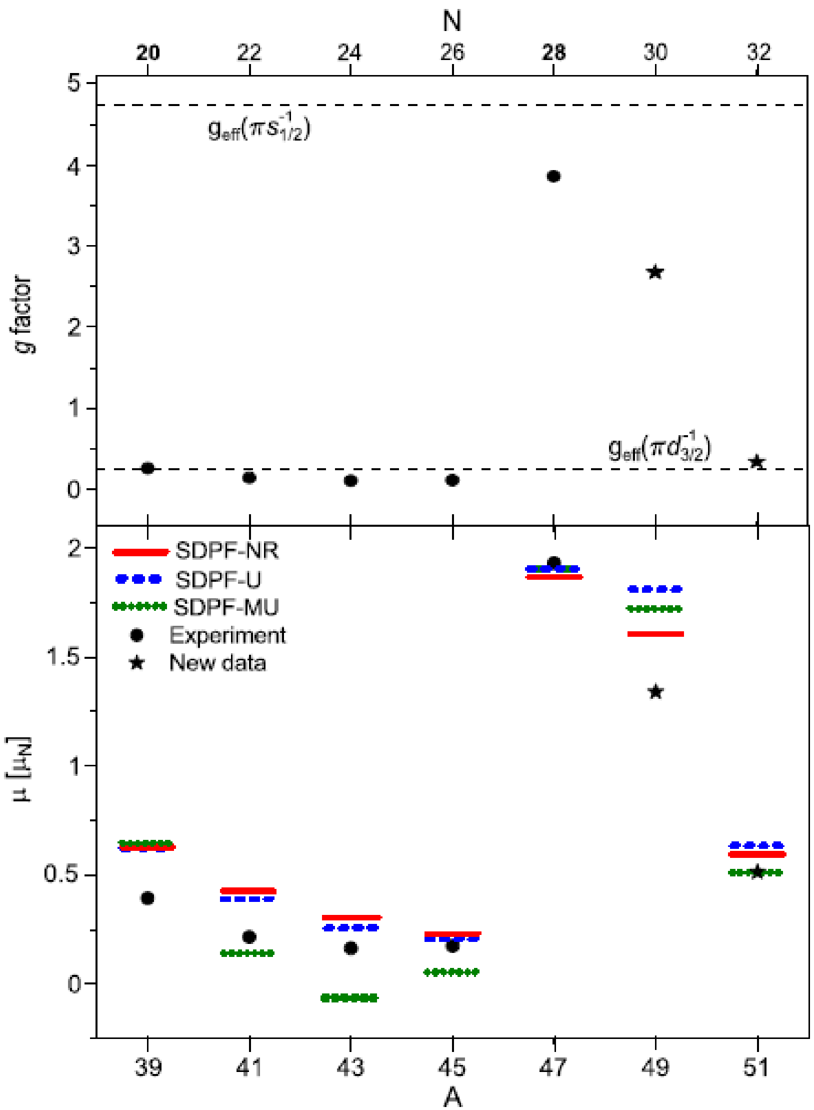


K-isotopes: Evolution of proton orbits

J. Papuga et al., Phys. Rev. Lett. 110, 172503 (2013)
J. Papuga et al., Phys. Rev. C 90, 034321 (2014)



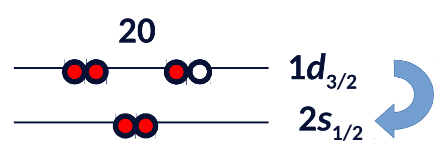
Magnetic moments and g-factors of odd K

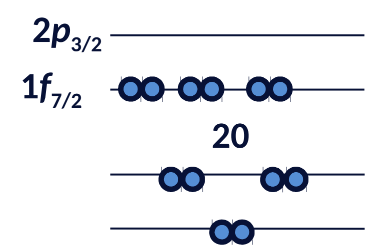


J. Papuga et al., Phys. Rev. Lett. 110, 172503 (2013)
J. Papuga et al., Phys. Rev. C 90, 034321 (2014)

→ ^{47,49}K dominated by hole in $s_{1/2}$ orbit

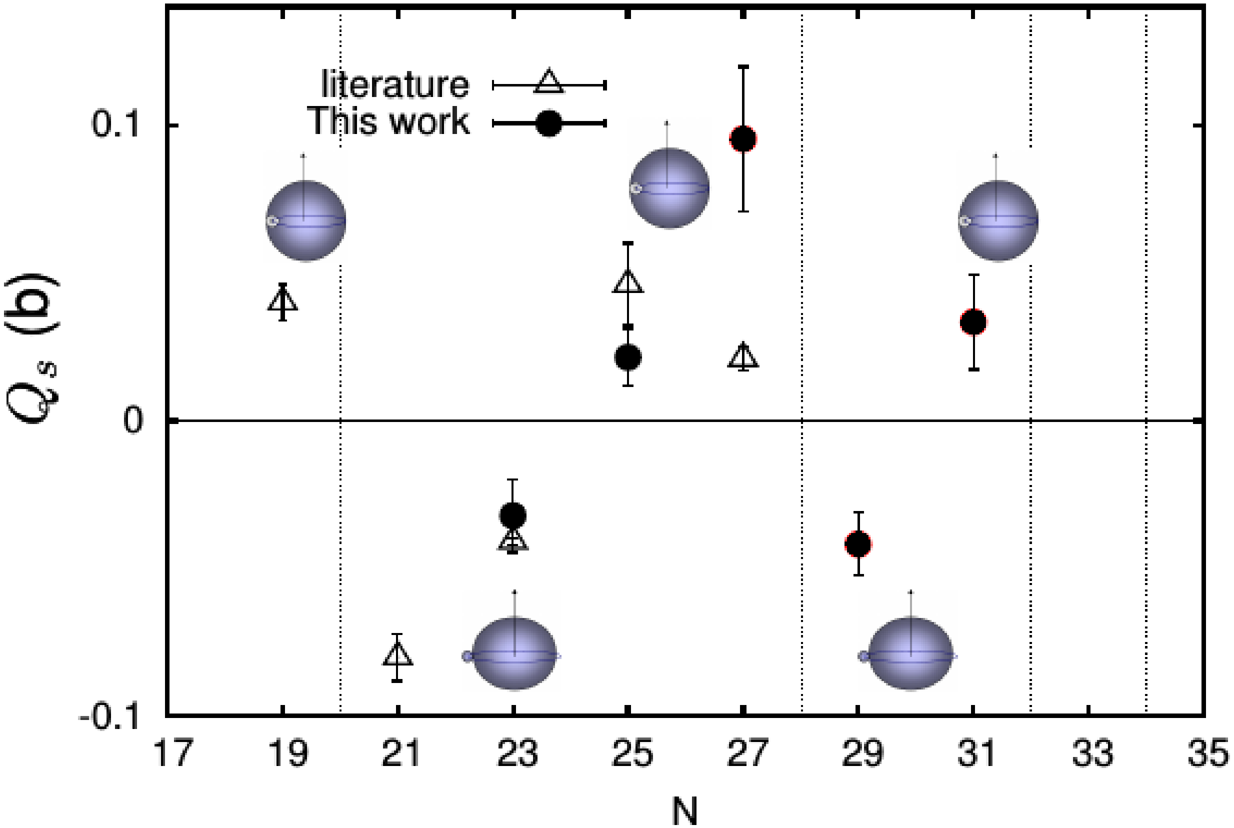
→ ^{49}K wave function strongly mixed with $d_{3/2}$

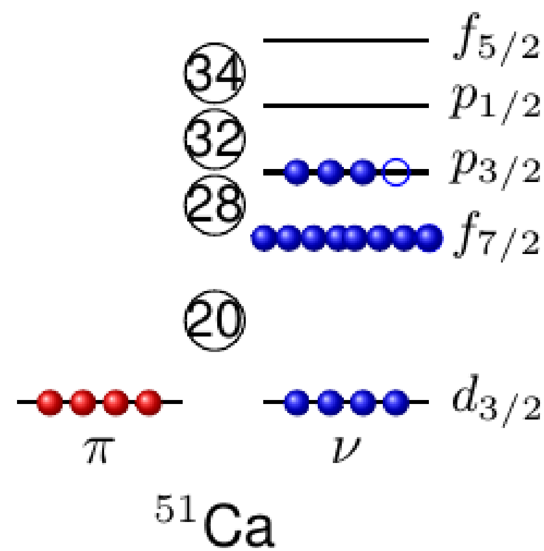




Quadrupole moments of Ca isotopes

[R.F. Garcia Ruiz *et al.* PRC 91, 041304(R) (2015)]

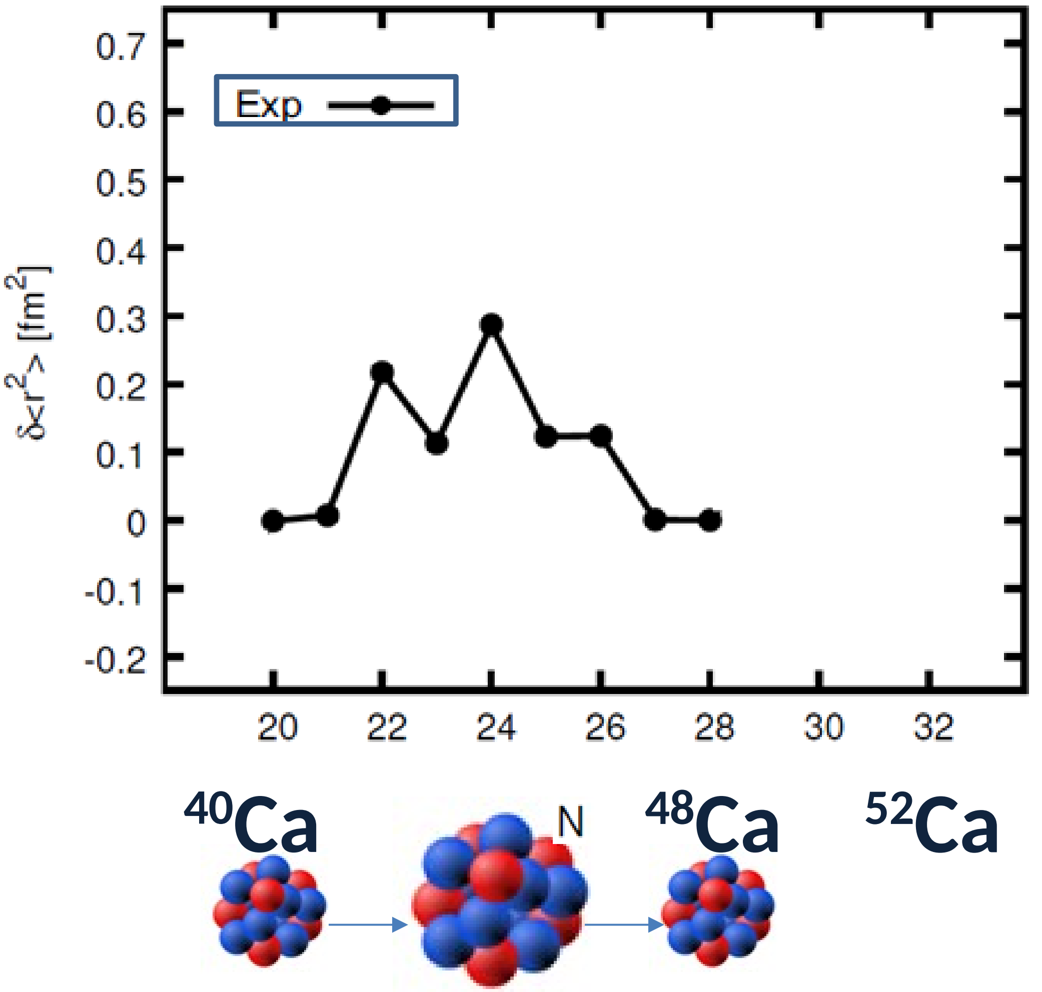




Charge radii of calcium isotopes

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

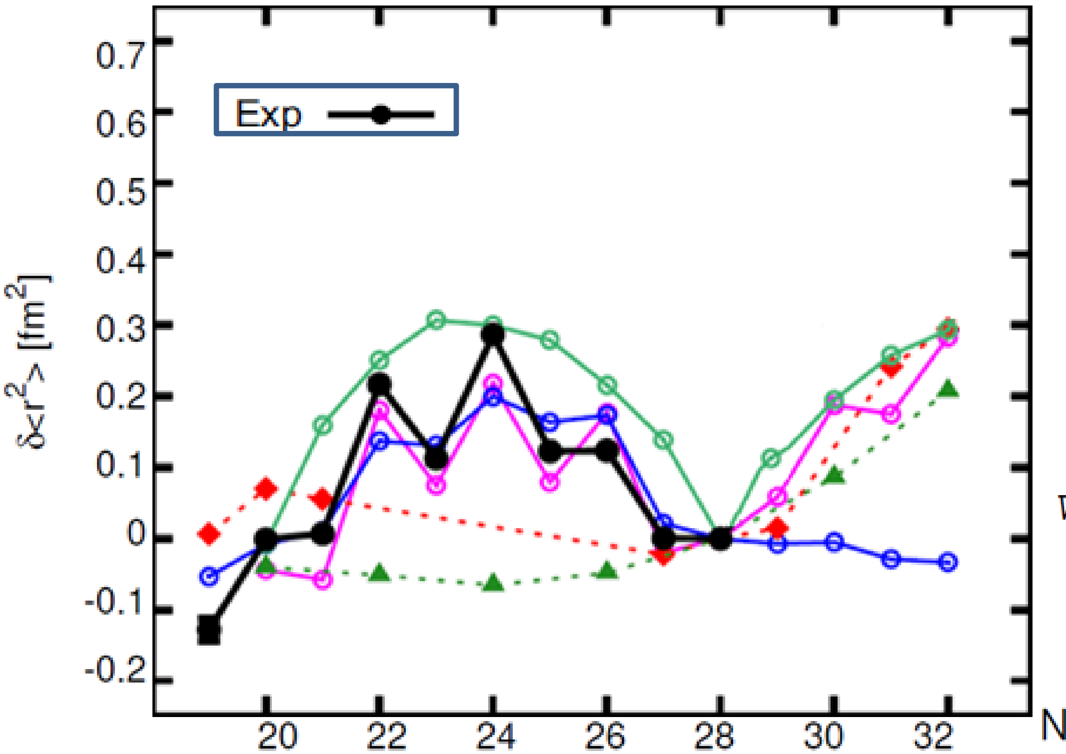
Charge radii of Ca isotopes: A challenge for nuclear theory!



Charge radii: Ca(Z=20) isotopes

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

The charge radii of Ca isotopes present additional challenges



$NNLO_{sat}$ PRC 91, 051301 (2015)
Nature Physics 12, 180 (2016)

ZBM2 PLB 522, 240 (2001)
PRL 113, 052502 (2014)
PRC 92, 014305 (2015)

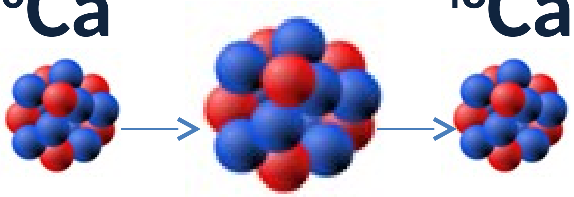
DF3-a NPA 676, 49 (2000)

UNEDF0 Nature 486, 509 (2012)

Wang et al. PRC 88, 011301(R) (2013)

^{52}Ca [Wienholtz et al. Nature 498, 346 (2013)]
^{54}Ca [Steppenbeck et al. Nature 502, 207 (2013)]

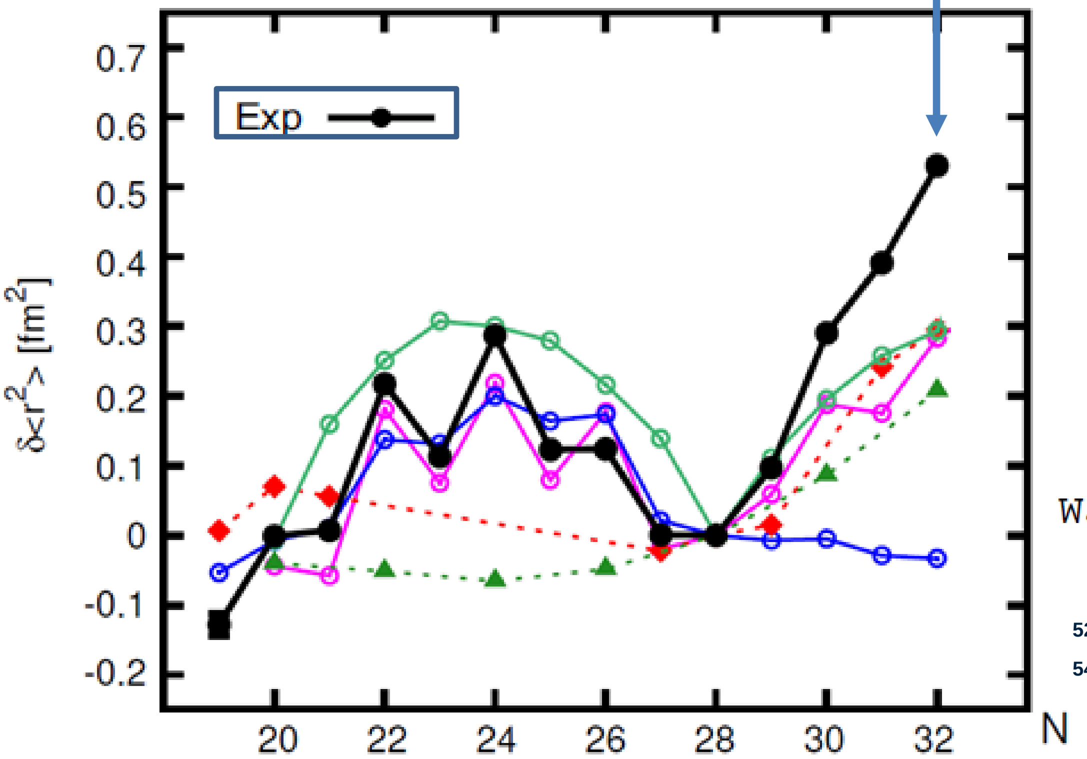
^{40}Ca **^{48}Ca** **^{52}Ca**



Charge radii: Ca(Z=20) isotopes

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

Much larger than expected!



NNLO$_{sat}$ PRC 91, 051301 (2015)
Nature Physics 12, 180 (2016)

ZBM2 PLB 522, 240 (2001)
PRL 113, 052502 (2014)
PRC 92, 014305 (2015)

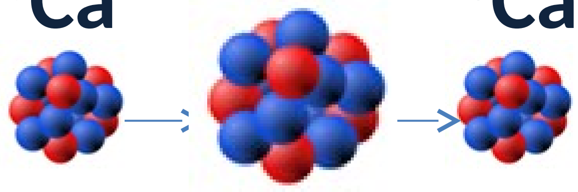
DF3-a NPA 676, 49 (2000)

UNEDF0 Nature 486, 509 (2012)

Wang et al. PRC 88, 011301(R) (2013)

^{52}Ca [Wienholtz et al. Nature 498, 346 (2013)]
^{54}Ca [Steppenbeck et al. Nature 502, 207 (2013)]

^{40}Ca ^{48}Ca ^{52}Ca

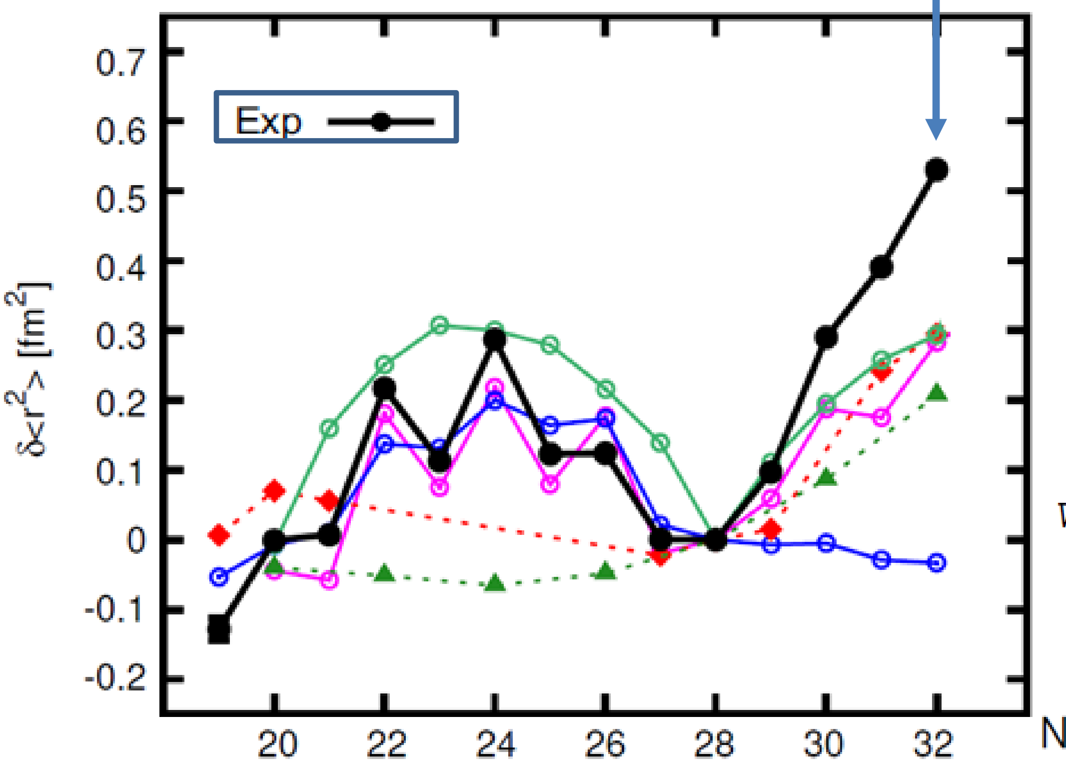


Charge radii: Ca(Z=20) isotopes

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

Max sensitivity ~250 ions/s

Much larger than expected!



NNLO$_{sat}$ — PRC 91, 051301 (2015); Nature Physics 12, 180 (2016)

ZBM2 — PLB 522, 240 (2001); PRL 113, 052502 (2014); PRC 92, 014305 (2015)

DF3-a — NPA 676, 49 (2000)

UNEDF0 — Nature 486, 509 (2012)

Wang et al. — PRC 88, 011301(R) (2013)

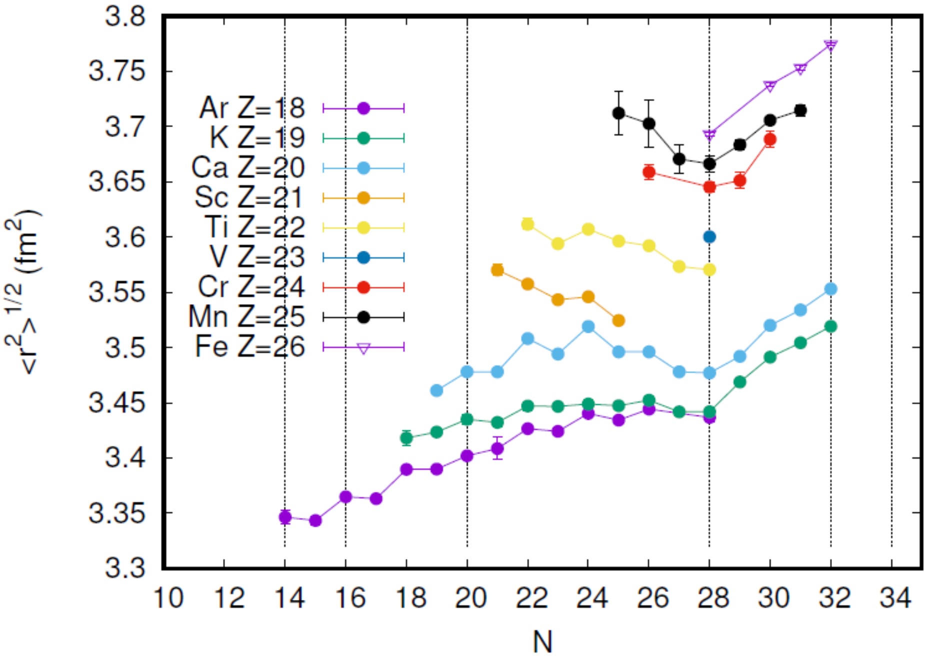
^{40}Ca ^{48}Ca ^{52}Ca

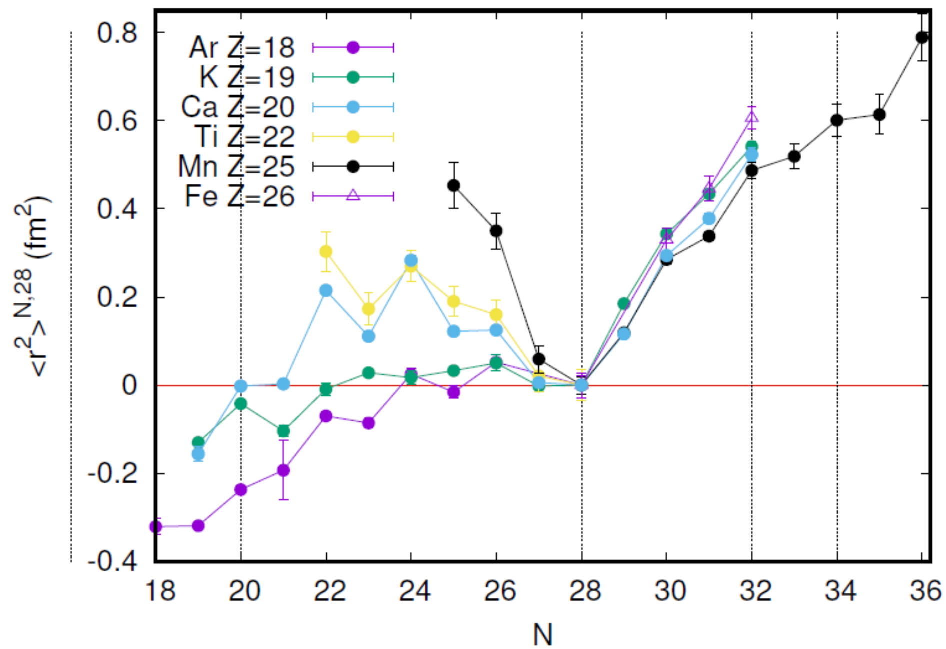
Beyond ^{52}Ca: Sensitivity -> ~1 ion/s

Radioactive detection of Collinear-laser optical pumping after Charge exchange

[R.F. Garcia Ruiz *et al.* J. Phys. G. 44, 044003 (2017)]

Charge radii systematic around the Ca region





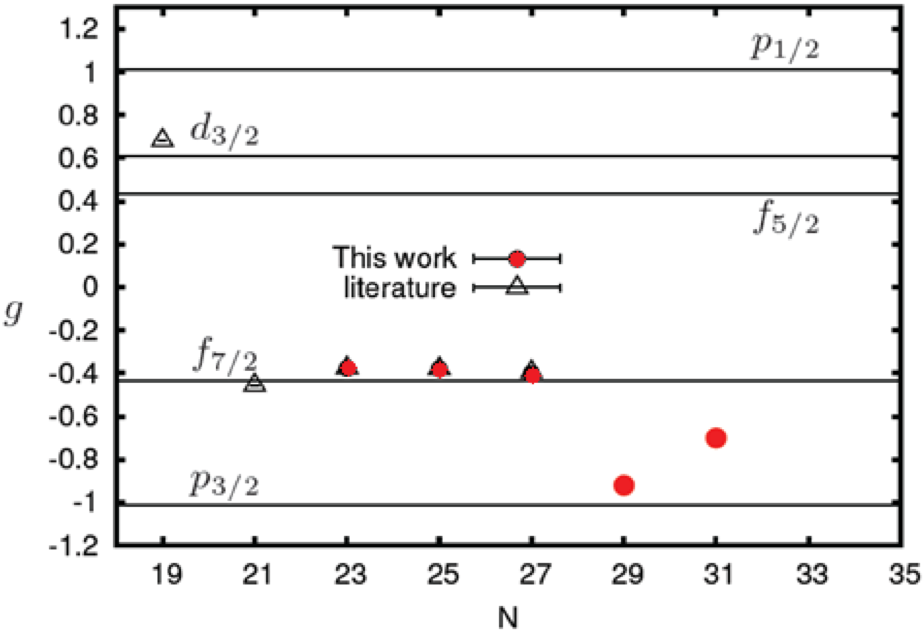
$^{50-61}$Mn (Z=25) → [H. Heylen et al, Phys. Rev. C 94, 054321(2016)]
$^{40-52}$Ca (Z=20) → [R.F. Garcia Ruiz et al., Nature Physics 12, 594 (2016)]
$^{38-51}$K (Z=19) → [K. Kreim et al, Phys. Lett. B 731, 97 (2014)]
$^{44-50}$Sc (Z=21) → [In preparation (2018)]

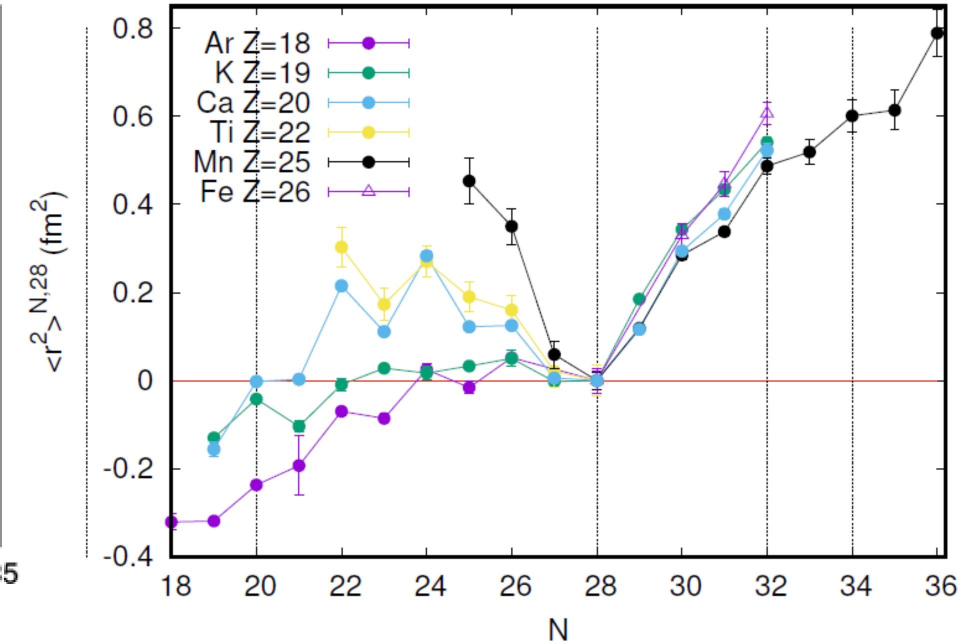
COLLAPS/ISOLDE

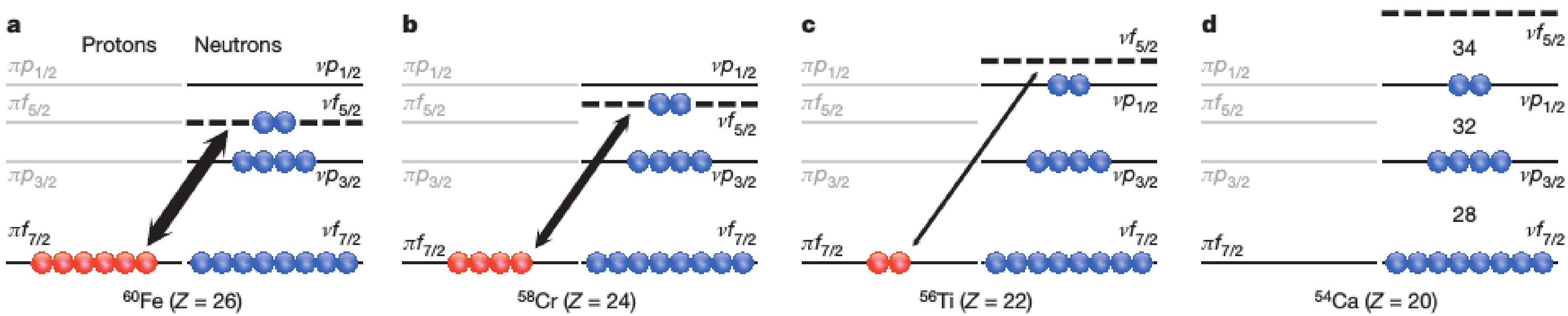
$^{48-42}$K(Z=19) → [In preparation (2018)]

CRIS/ISOLDE

Charge radii systematic around the Ca region

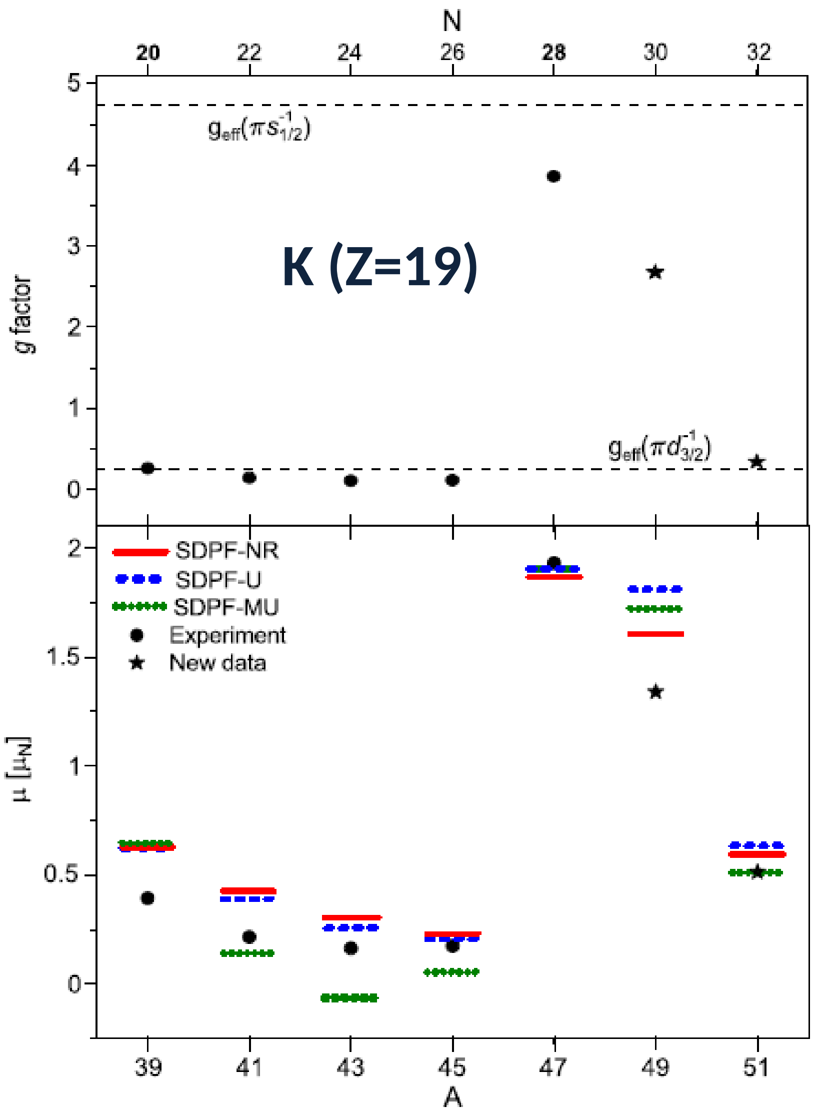


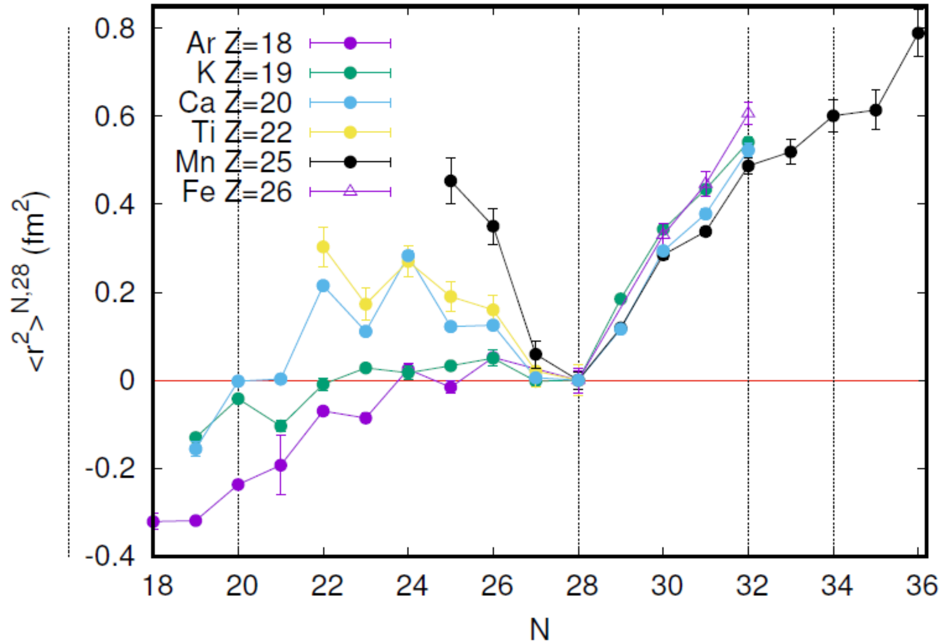




D. Steppenbeck *et al*., Nature 502 (2013)

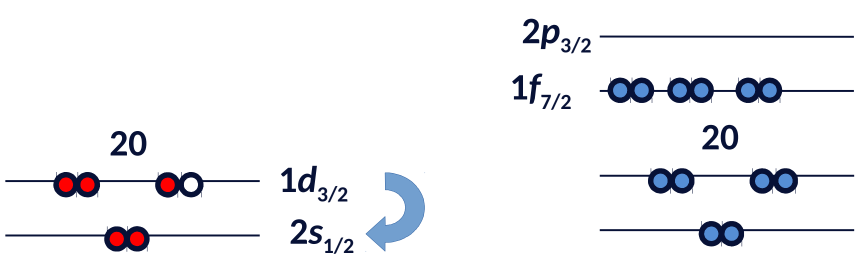
RESULTS: K(Z=19) Isotopes





→ I=1/2 becomes g.s. in ^{47,49}K

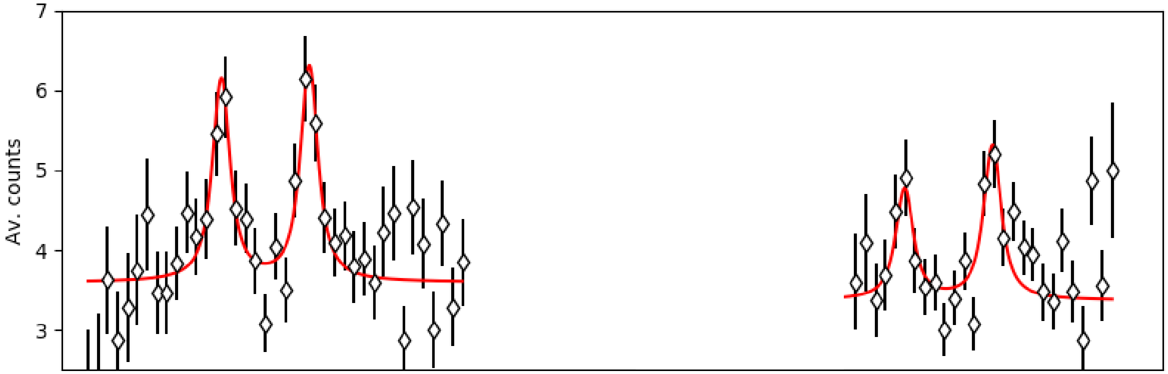
→ I=3/2 re-inversion g.s. in ^{51}K

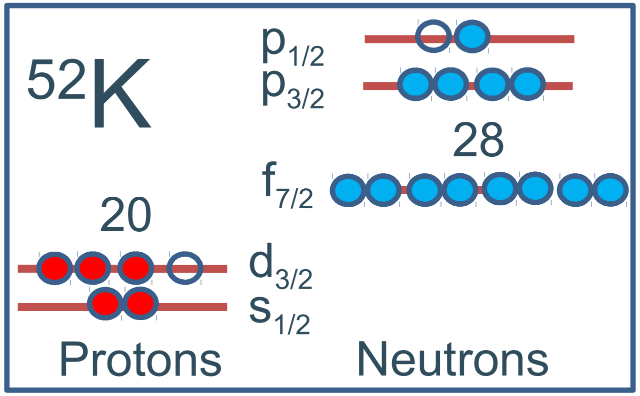


J. Papuga et al., Phys. Rev. Lett. 110, 172503 (2013)

J. Papuga et al., Phys. Rev. C 90, 034321 (2014)

Ground state structure of ^{52}K (N=33) from Collinear Resonance Ionization Spectroscopy CRIS



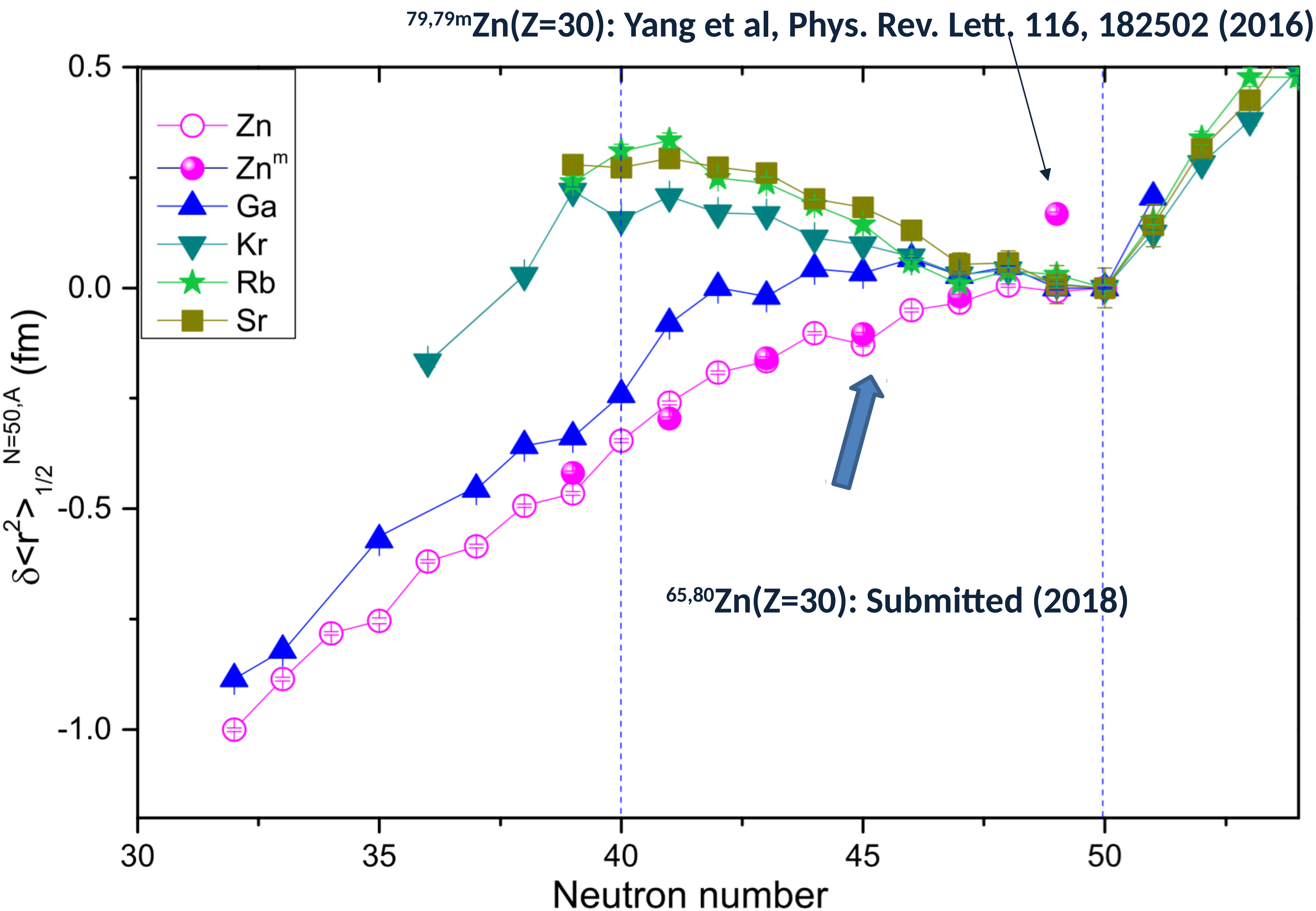


PRELIMINARY

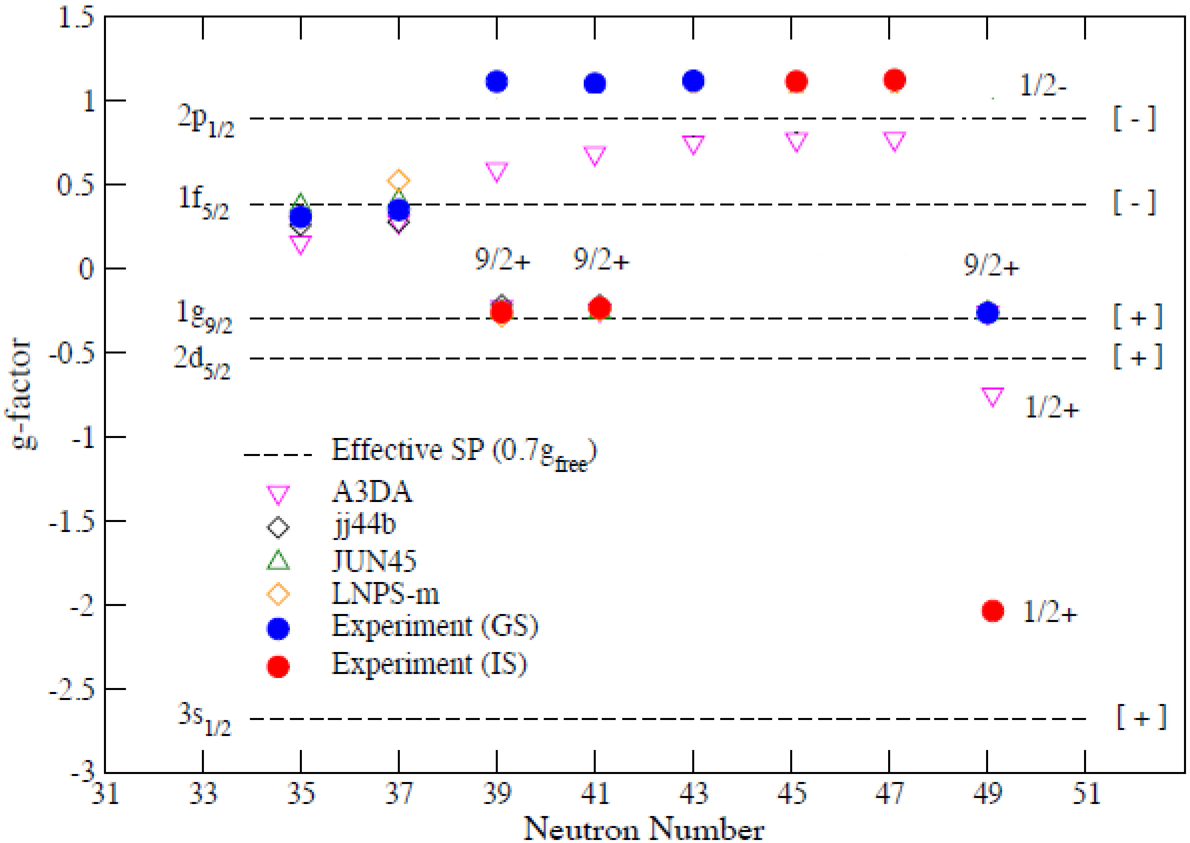
[Koszorus et al. In preparation]

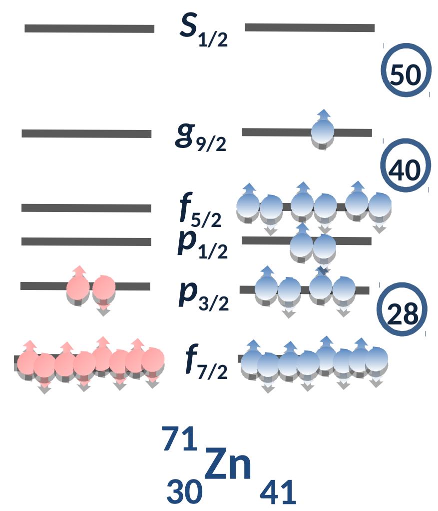
Nickel (Z=28) region

Charge radii systematic in the Ni region



EM: Zinc (Z=30) isotopes





^{65,79}Zn(Z=30): Wraith et al. Phys. Lett. B 771, 385 (2017)

Tin (Z=50) region

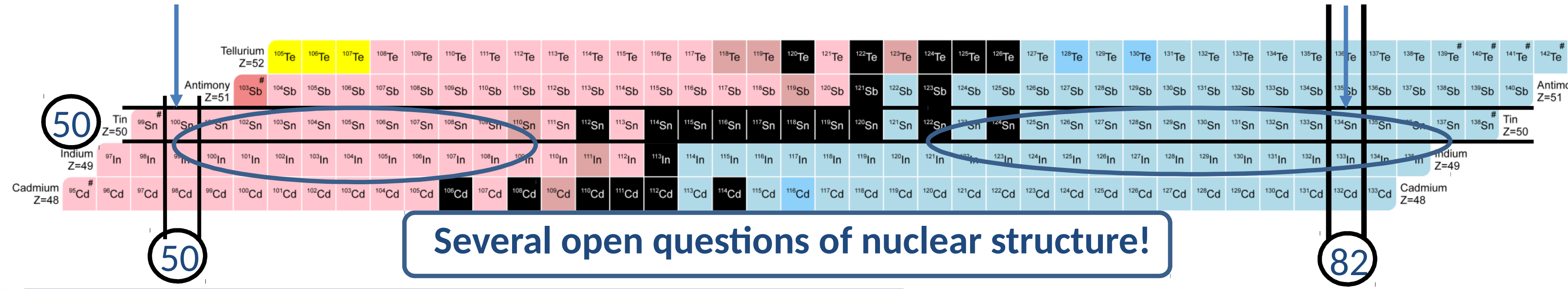
Nuclear structure around ^{100}Sn and ^{132}Sn

Doubly "magic" ^{100}Sn

[Hinke *et al.* Nature 486, 341 (2012)]

Doubly "magic" ^{132}Sn

[Jones *et al.* Nature 465, 454 (2010)]



Several open questions of nuclear structure!

$^{111-131}$In (Z=49): Garcia Ruiz et al. CERN-INTC-2017-025 (2017)
$^{100-111}$In (Z=49): Garcia Ruiz et al. CERN-INTC-2017-055 (2017)
$^{103-121}$Sn (Z=50): Garcia Ruiz et al. CERN-INTC-2016-037 (2016)

- Shell evolution towards N=Z=50 ?
- Ordering of shell model orbits ?
- Robustness of N=Z=50 shell closures?
- Proton-neutron correlations?

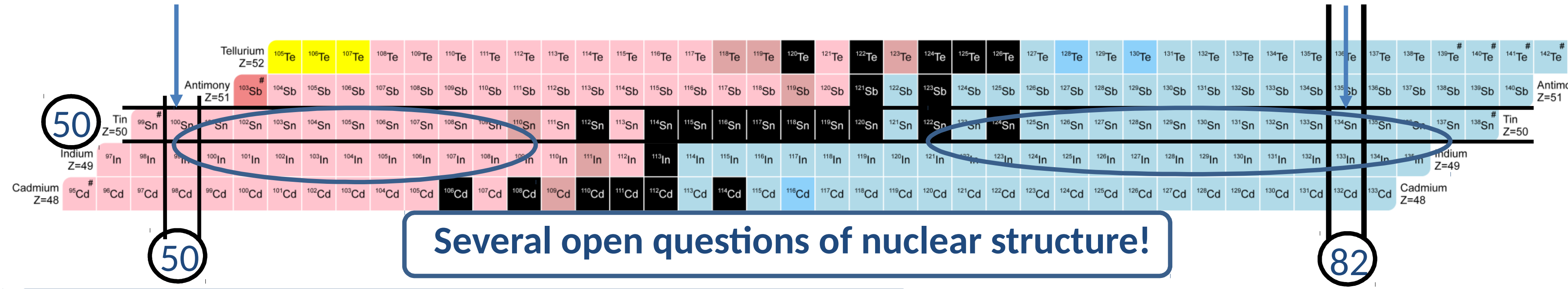
Nuclear structure around ^{100}Sn and ^{132}Sn

Doubly "magic" ^{100}Sn

[Hinke *et al*. Nature 486, 341 (2012)]

Doubly "magic" ^{132}Sn

[Jones *et al*. Nature 465, 454 (2010)]



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$^{103-121}$Sn (Z=50): Garcia Ruiz et al. CERN-INTC-2016-037 (2016)

Nuclear theory:
→ G. Hagen (ORNL)
→ J. Holt (TRIUMF)

INSANE effort→

○ In and Sn from Ab-initio Nuclear calculations and Experiments

Nuclear structure around ^{100}Sn and ^{132}Sn

Doubly "magic" ^{100}Sn

[Hinke *et al*. Nature 486, 341 (2012)]

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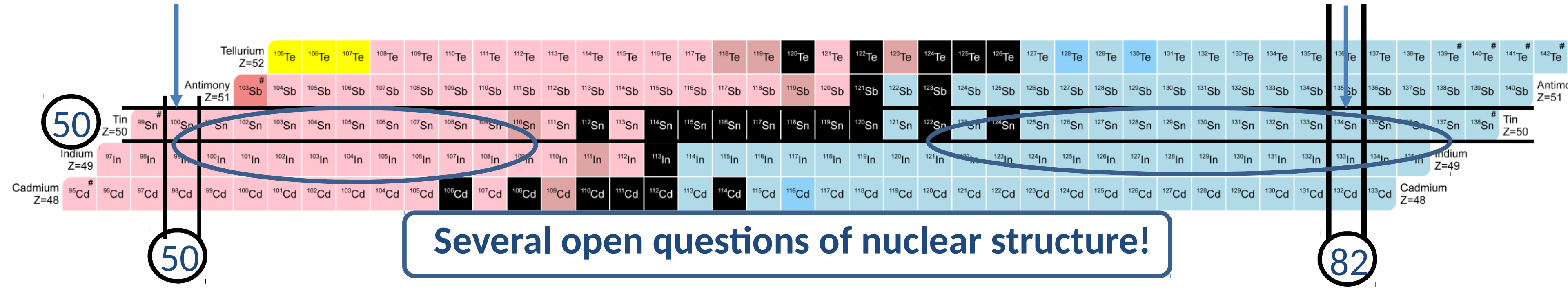

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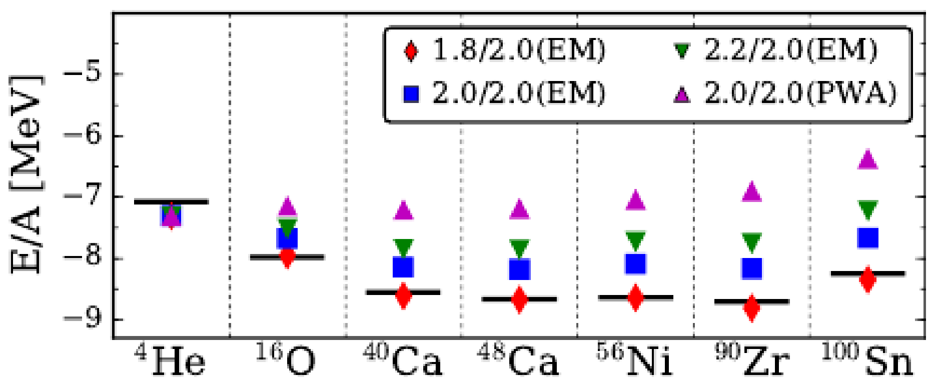
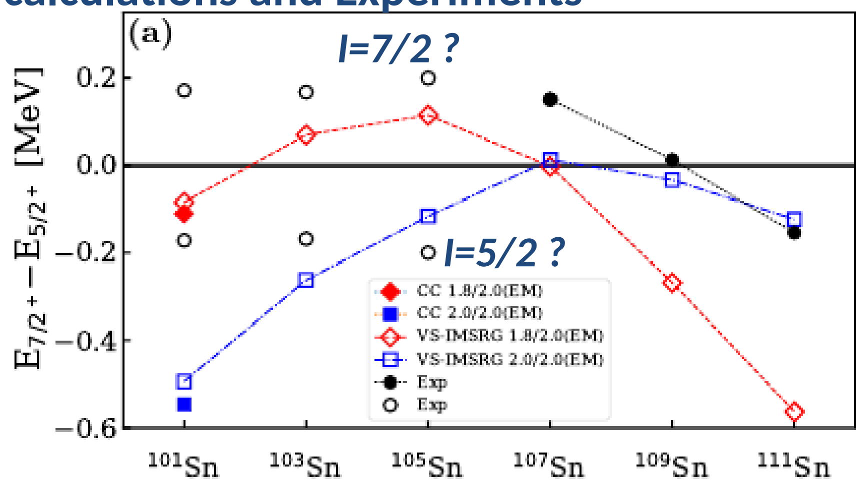
$^{103-121}$Sn (Z=50): Garcia Ruiz et al. CERN-INTC-2016-037 (2016)

INSANE effort-> In and Sn Ab-initio Nuclear calculations and Experiments

- Ab-initio calculations





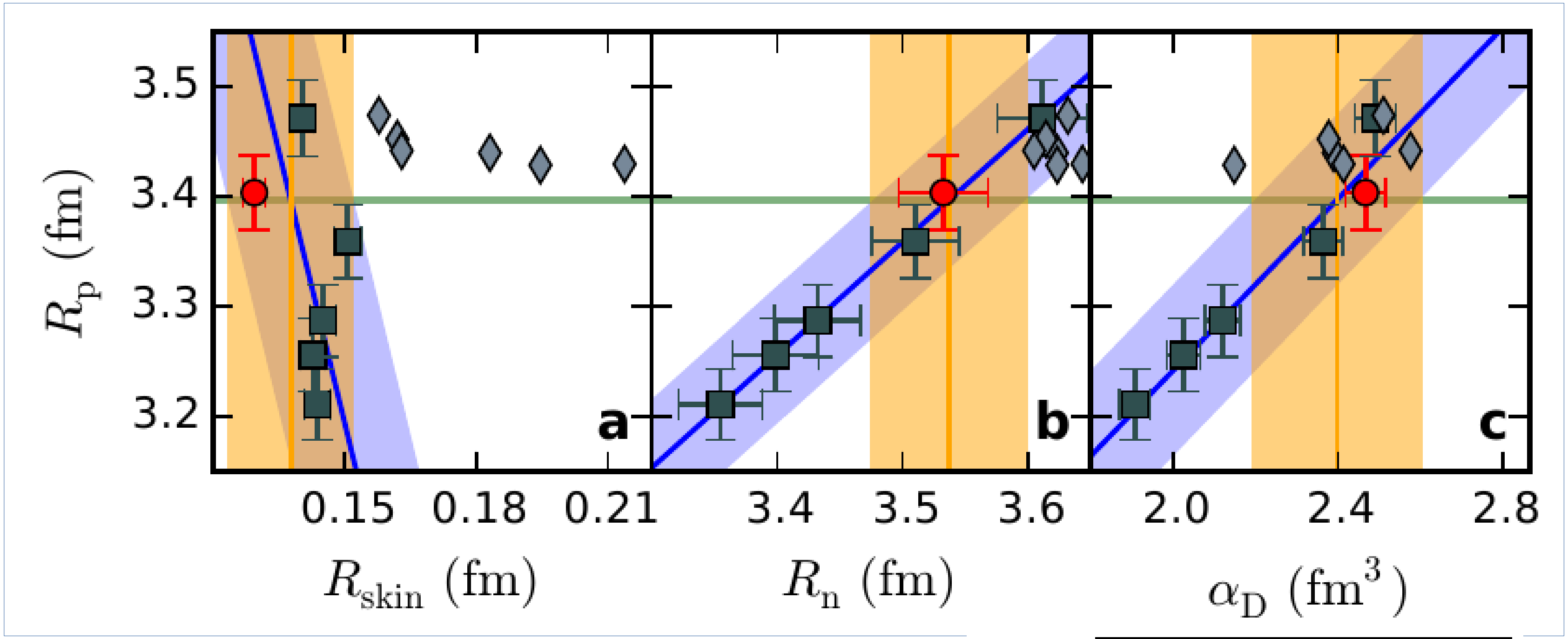
T. Morris et al. Phys. Rev. Lett. 120, 152503 (2018)

Nuclear chart taken from http://people.physics.anu.edu.au/~ecs103/chart/index.php

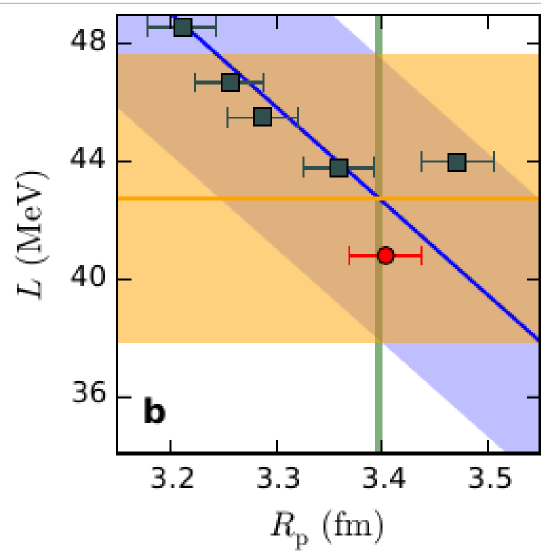
Nuclear ground-state properties
and
Properties of nuclear matter

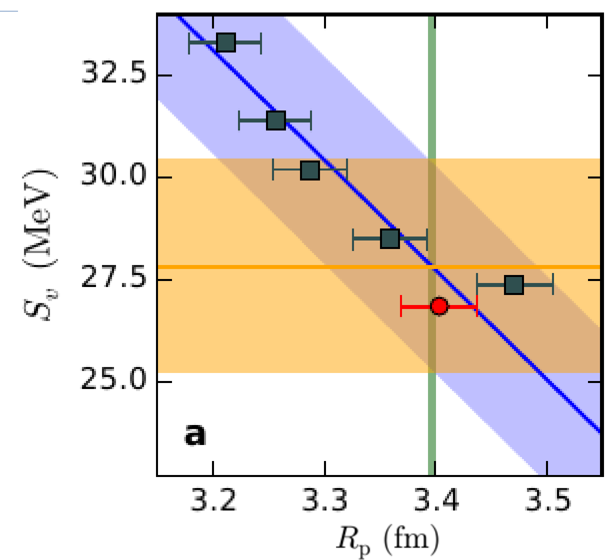
^{48}Ca: Charge radii vs properties of nuclear matter

G. Hagen et al. Nature Phys. 12, 180 (2016)



Constrain to properties of nuclear matter

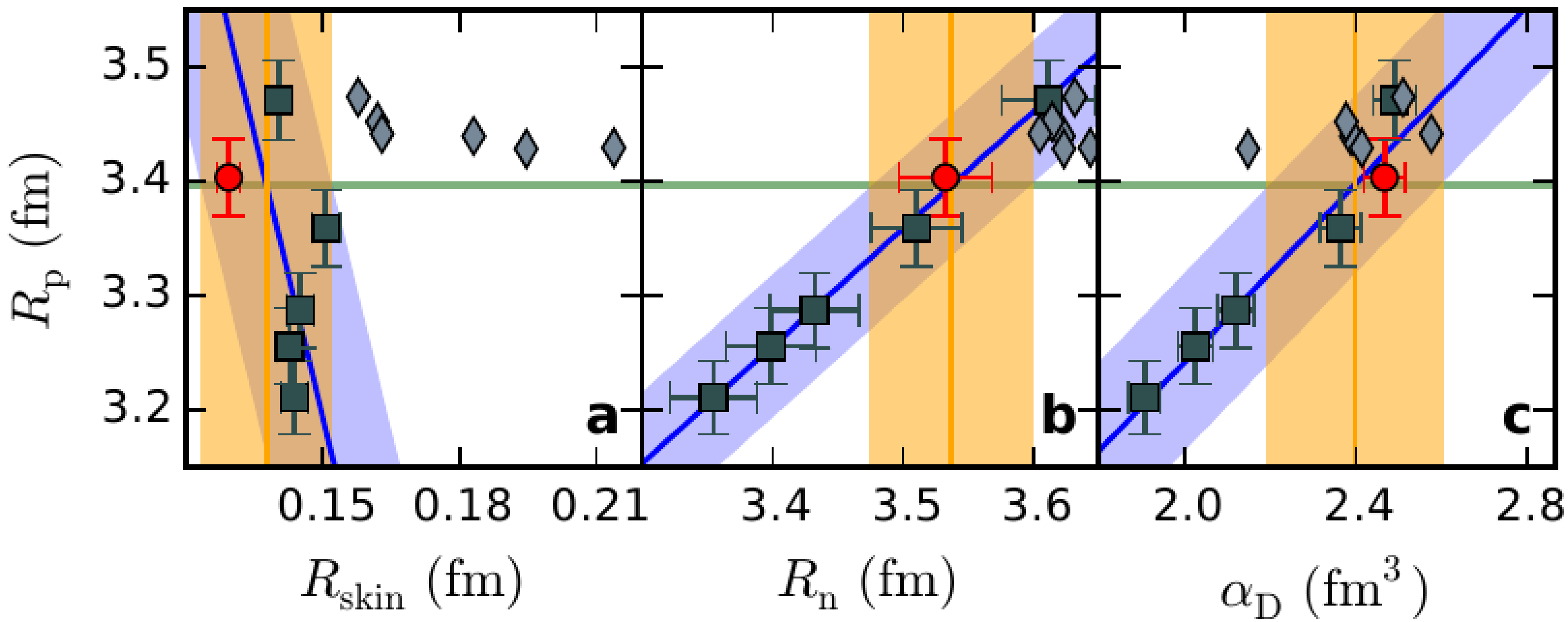


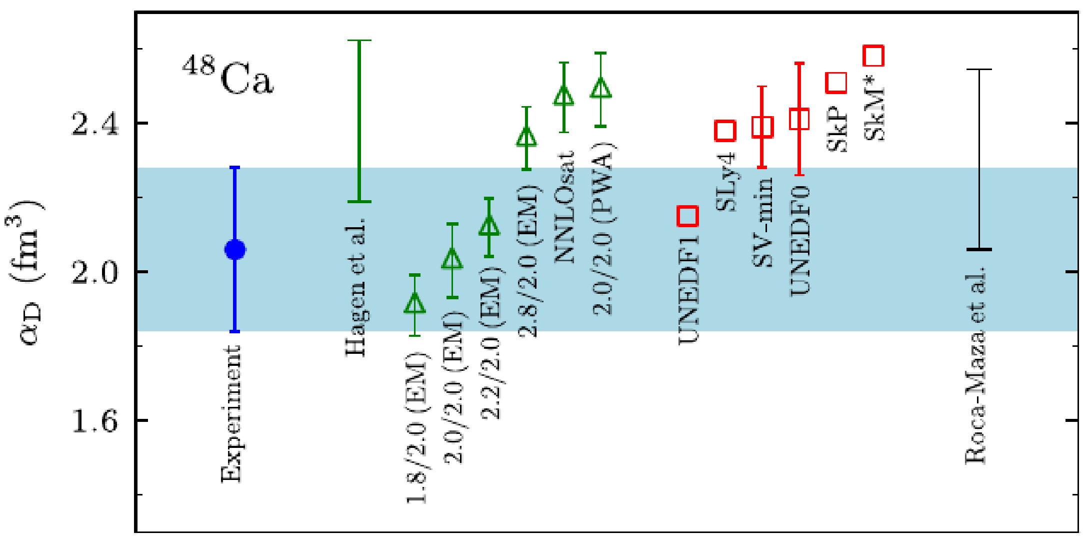


^{48}Ca: Charge radii vs properties of nuclear matter

G. Hagen et al. Nature Phys. 12, 180 (2016)

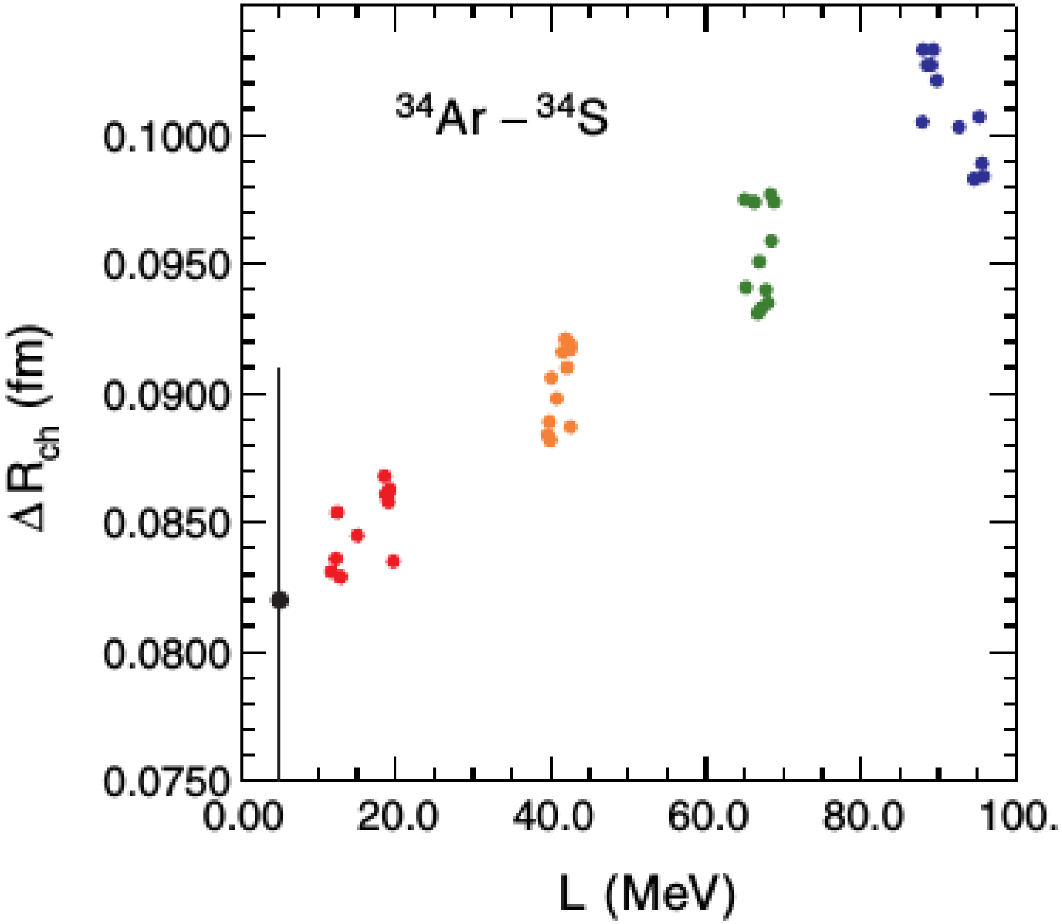
^{48}Ca





J. Birkhan et al.
Phys. Rev. Lett. 118, 252501 (2017)

Mirror charge radii vs L



Brown et al. Phys. Rev. Lett. 119, 122502 (2017)

Summary and Outlook

Charge radii measurements
-> Challenge for nuclear structure theory

$\delta \langle r^2 \rangle^{A,A'}$

Ground-state spin and electromagnetic moments

I Q_s μ_I

Unanswered question regarding the use of effective operators, importance of MEC currents?

[Ekstrom et al. PRL 113, 262504 (2014)]
[Carlson et al. RMP 87, 1067 (2015)]
[Pastore et al. PRC 87, 035503 (2013)]

The nuclear force

- Phenomenology
- Chiral Effective field theory

Many-body methods

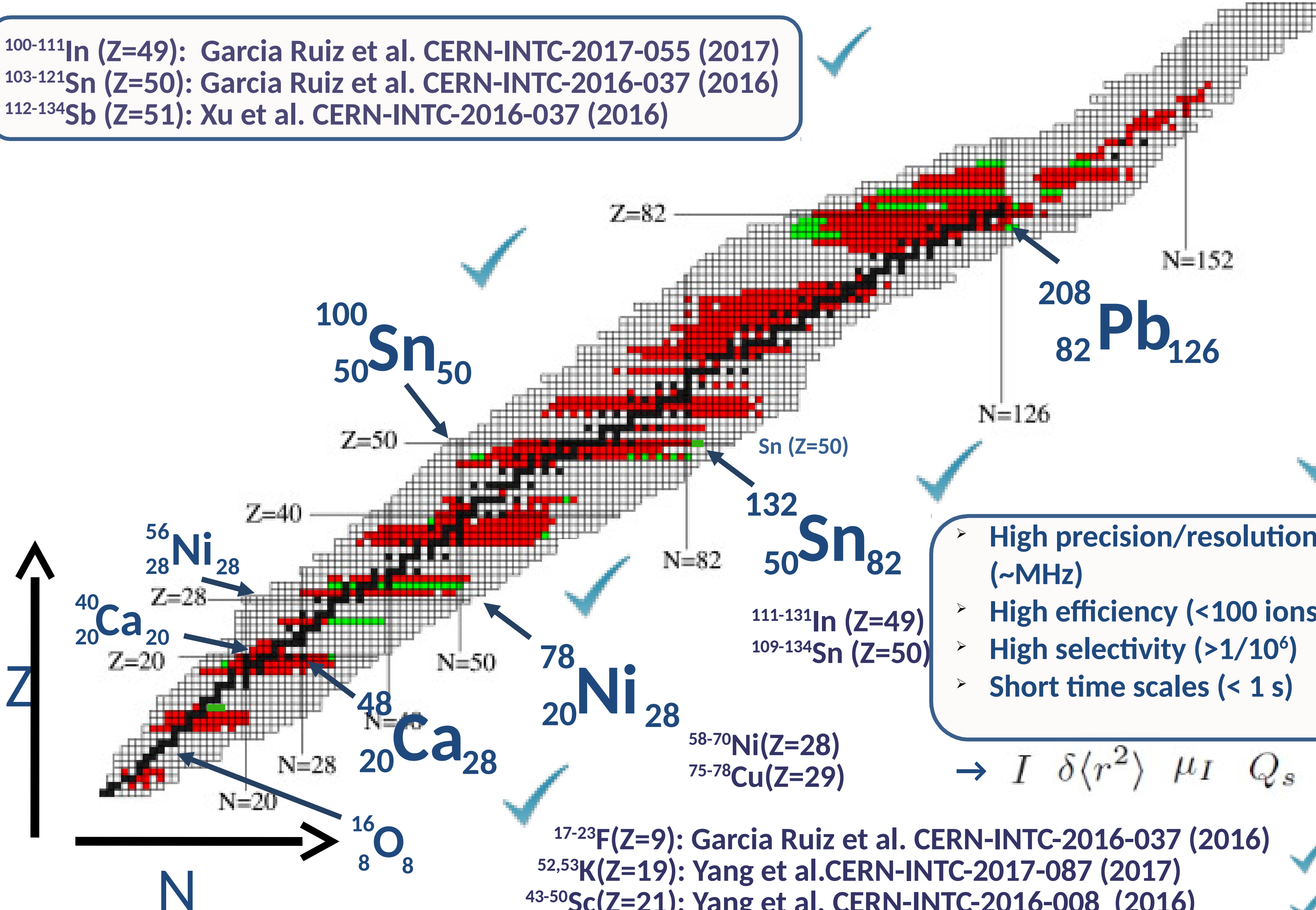
- Shell-model
- Ab-initio
- DFT

Electro-weak currents

- role of many-body currents
- effective operators

Summary and Outlook

$^{100-111}$In (Z=49): Garcia Ruiz et al. CERN-INTC-2017-055 (2017)
$^{103-121}$Sn (Z=50): Garcia Ruiz et al. CERN-INTC-2016-037 (2016)
$^{112-134}$Sb (Z=51): Xu et al. CERN-INTC-2016-037 (2016)



$^{111-131}$In (Z=49)
$^{109-134}$Sn (Z=50)

- High precision/resolution (~MHz)
- High efficiency (<100 ions/s)
- High selectivity (>1/10^6)
- Short time scales (< 1 s)

$\rightarrow \; I \quad \delta\langle r^2\rangle \quad \mu_I \quad Q_s$

$^{58-70}$Ni(Z=28)
$^{75-78}$Cu(Z=29)

$^{17-23}$F(Z=9): Garcia Ruiz et al. CERN-INTC-2016-037 (2016)
^{52,53}K(Z=19): Yang et al.CERN-INTC-2017-087 (2017)
$^{43-50}$Sc(Z=21): Yang et al. CERN-INTC-2016-008 (2016)

Thanks for your attention!