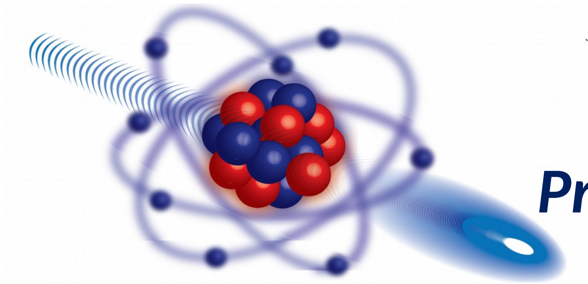
Laser spectroscopy of exotic nuclei: Recent results and future perspectives

Ronald Fernando Garcia Ruiz
CERN



Probing exotic structure of short-lived nuclei by electron scattering

ECT* Meeting, Trento 2018

Laser spectroscopy of exotic nuclei: Recent results and future perspectives

Contents

- Motivation
- Laser spectroscopy at ISOLDE
  → Recent developments
- Recent results
  → Nuclear physics: Ca, Ni, Sn regions
- Outstanding issues
  → Need of electron scattering data
- New opportunities
  Summary and outlook

Electron scattering
+
Laser spectroscopy

→ Nuclear physics

→ Atomic physics

→ Fundamental symmetries

CERN

The COLLAPS Collaboration

Collinear Laser Spectroscopy

MAX-PLANCK-GESELLSCHAFT

KU LEUVEN

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

TECHNISCHE UNIVERSITÄT DARMSTADT

M. Bissell, K. Blaum, B. Cheal, N. Frommgen, R.F. Garcia Ruiz, C. Gorges, H. Heylen, M.Hammen, S. Kaufmann, M. Kowalska, S. Malbrunot-Ettenauer, R.Neugart, G. Neyens, W. Nortershauser, L. Vazquez-Rodriguez, 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. Neyens, C. Ricketts, H.H. Stroke, A. Vernon, K. Wendt, S. Wilkins, X. Yang

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European Research Council
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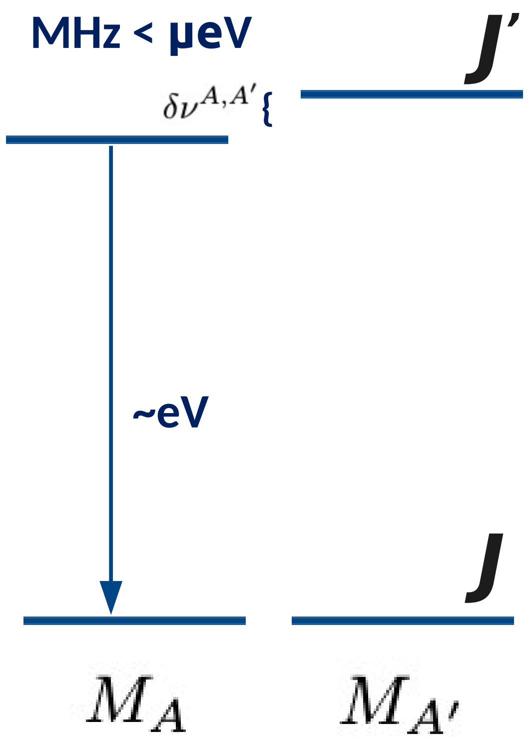
LPSC Grenoble

IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

ISOLDE

Atomic hyperfine structure



Isotope shift

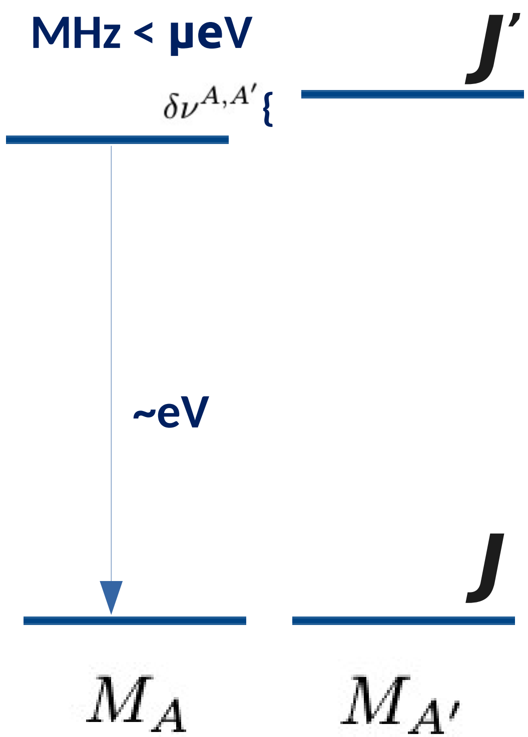
Atomic parameters

Usually main source of uncertainties
→ From atomic theory
→ Comparing with electron scattering experiments (King's plot)

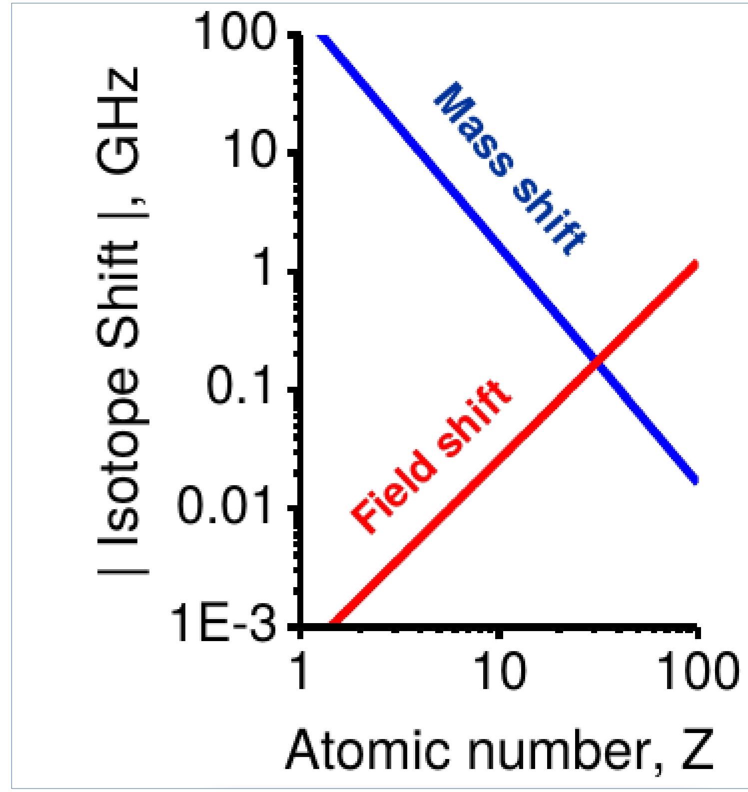
$$\delta\nu^{A,A'} = K_{MS}\frac{M_{A'} - M_A}{M_{A'}M_A} + F\delta\langle r^2\rangle^{A,A'}$$

Nuclear charge radius

Atomic hyperfine structure



Isotope shift



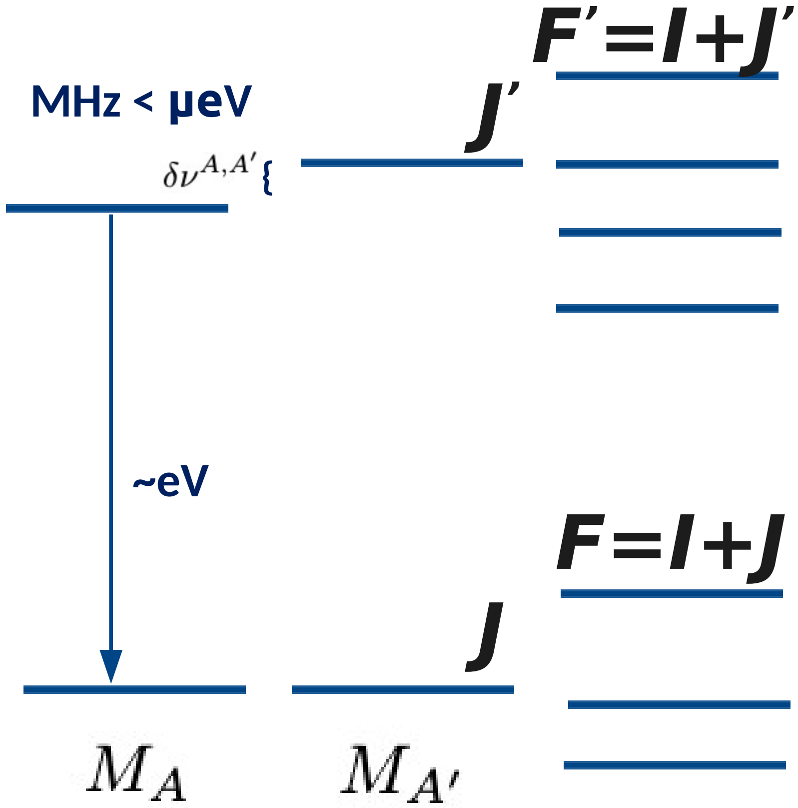
Atomic parameters

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

Involves many electron correlations

Nuclear charge radius

Atomic hyperfine structure



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

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

Nucleus

Electrons

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

Atomic parameters

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

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

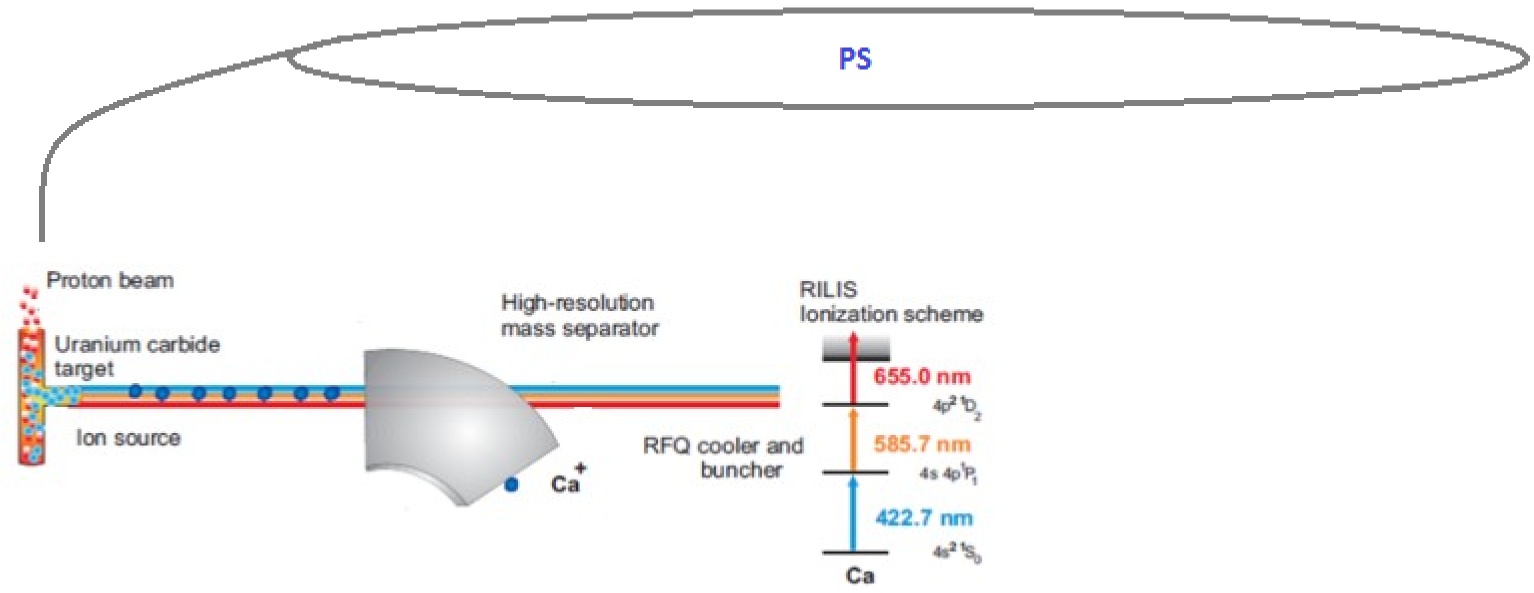
$$B_{hfs} = eQ_s\frac{\partial^2 V}{\partial^2 z}$$

Nuclear charge radius

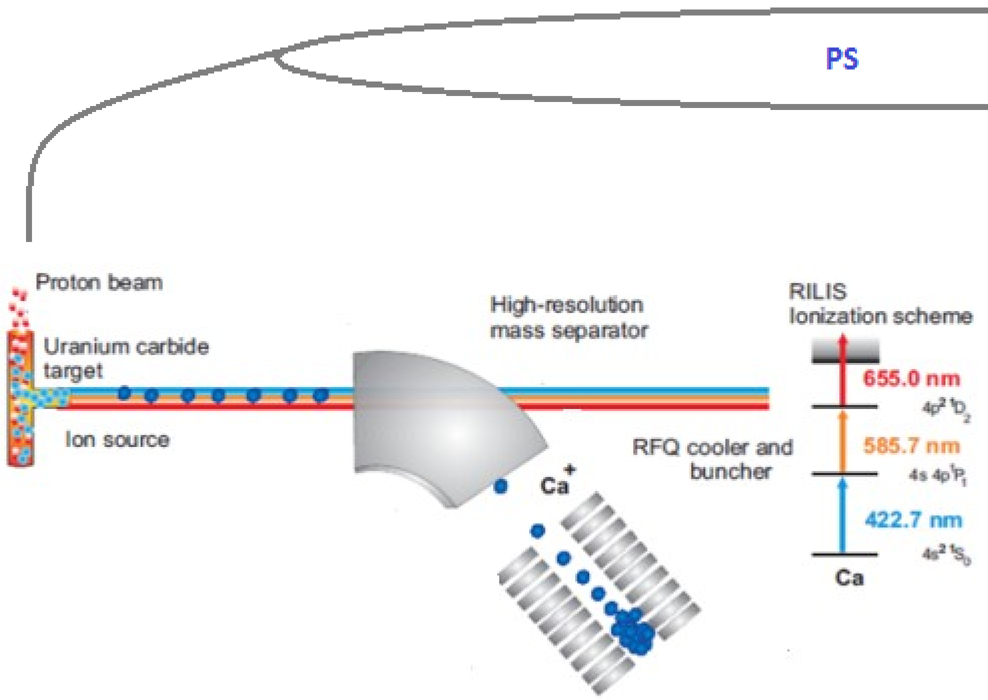
Nuclear magnetic moment

Nuclear quadrupole moment

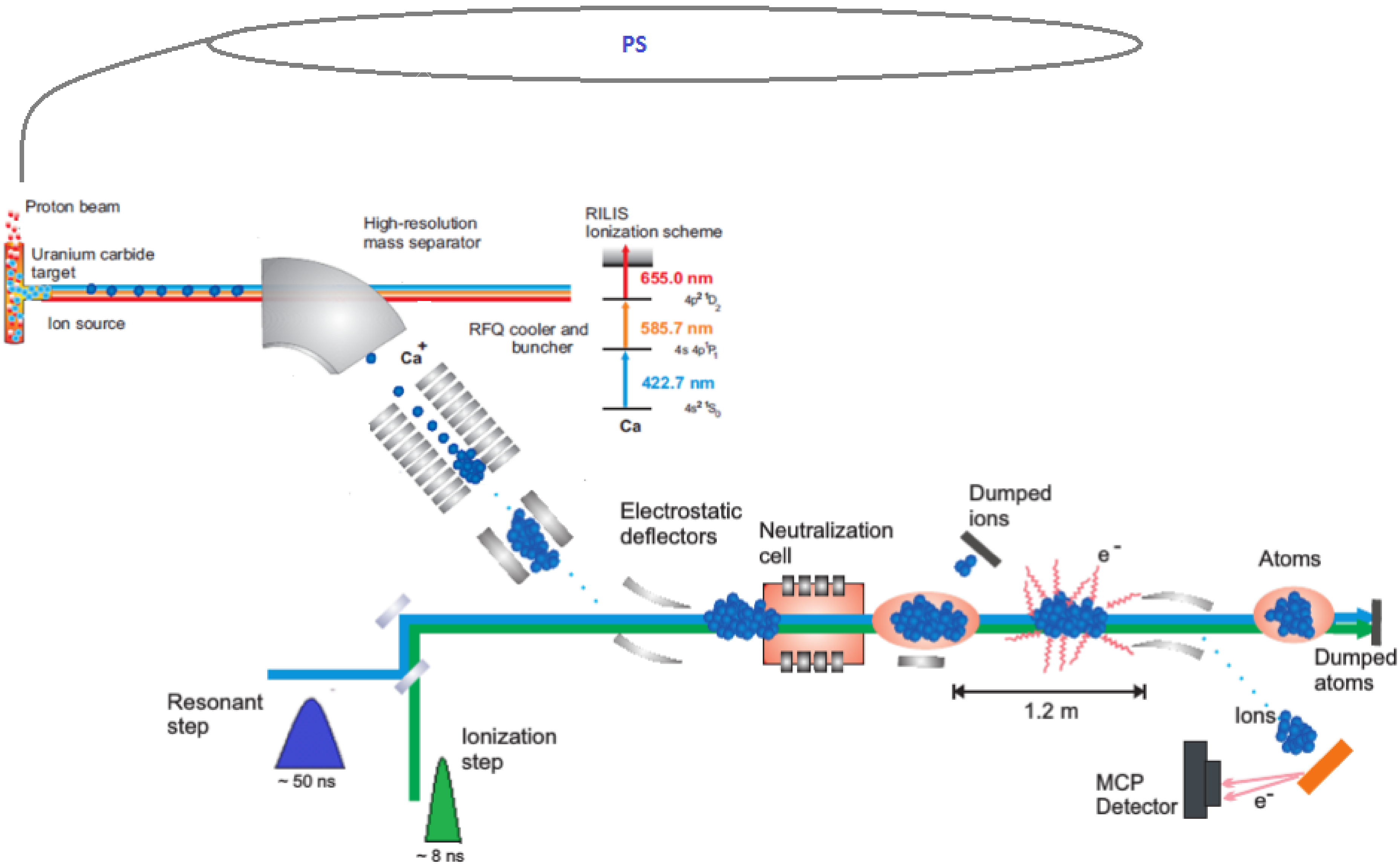
Collinear laser spectroscopy at ISOLDE



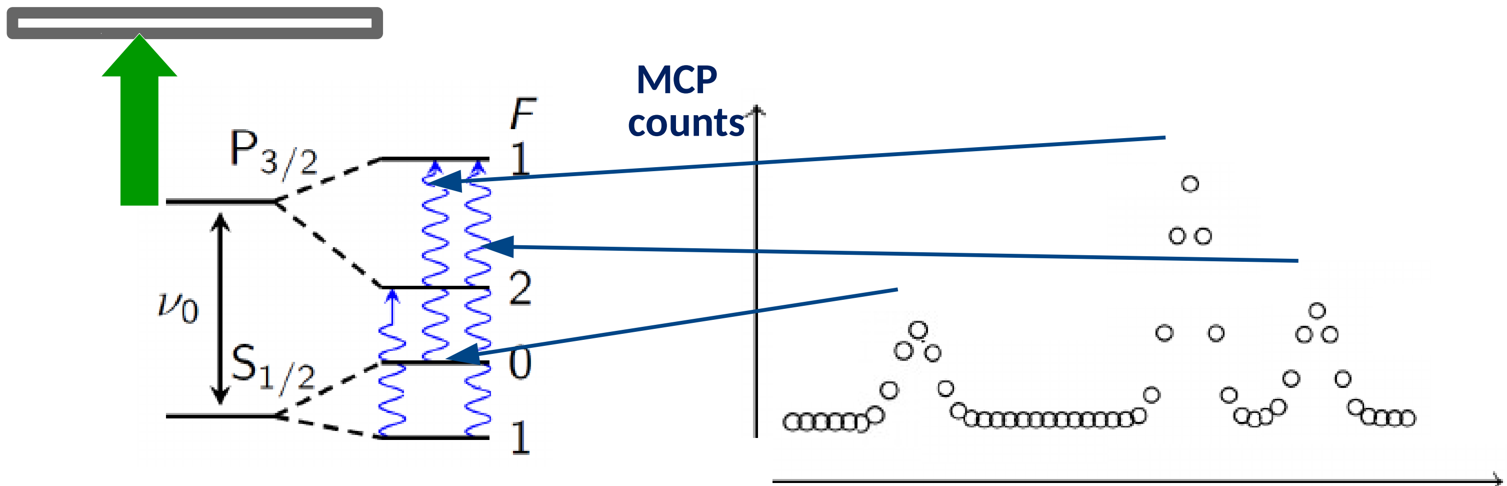
Collinear laser spectroscopy at ISOLDE

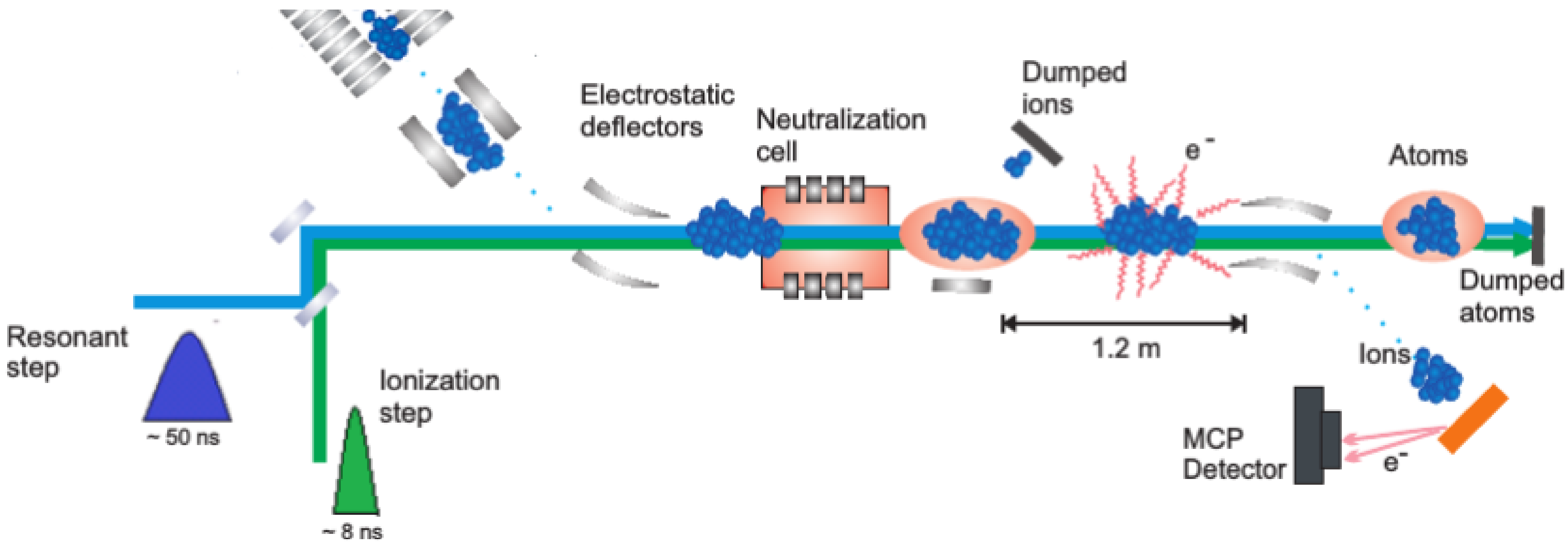


Collinear laser spectroscopy at ISOLDE

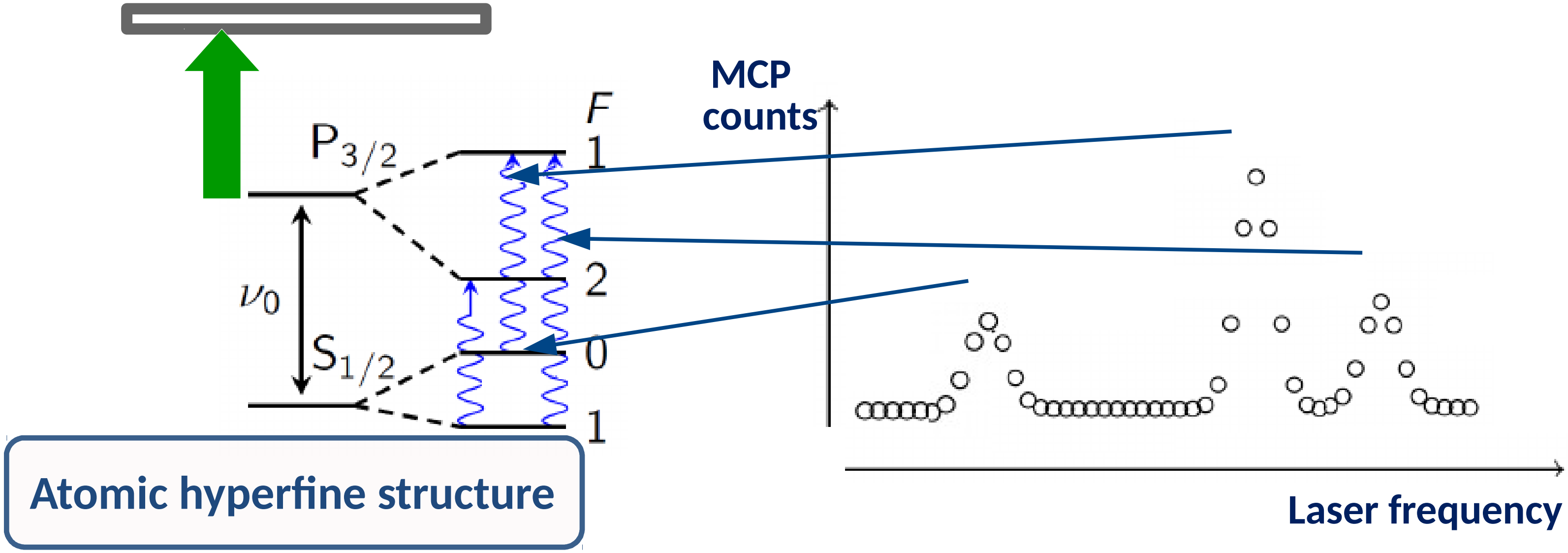


Collinear laser spectroscopy at ISOLDE





Motivation



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

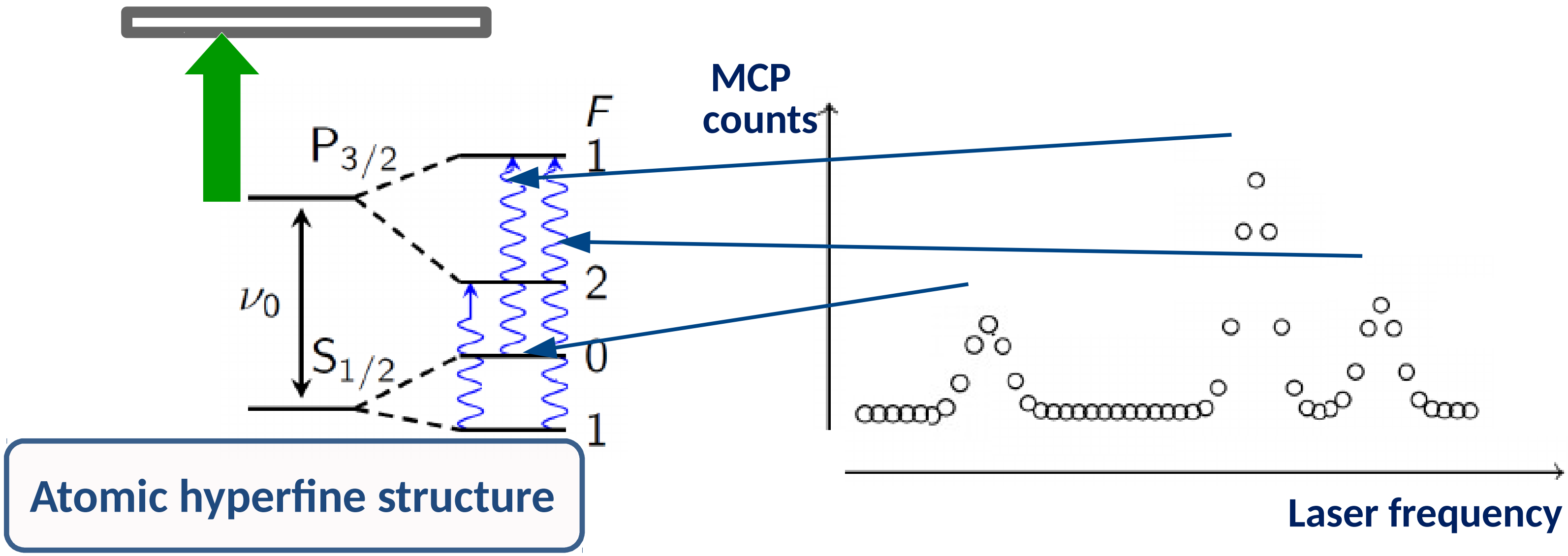
$$\delta\nu^{A,A'} = K_{MS}\frac{M_{A'} - M_A}{M_{A'}M_A} + F\delta\langle r^2\rangle^{A,A'}$$

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

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

Atomic parameters

Motivation



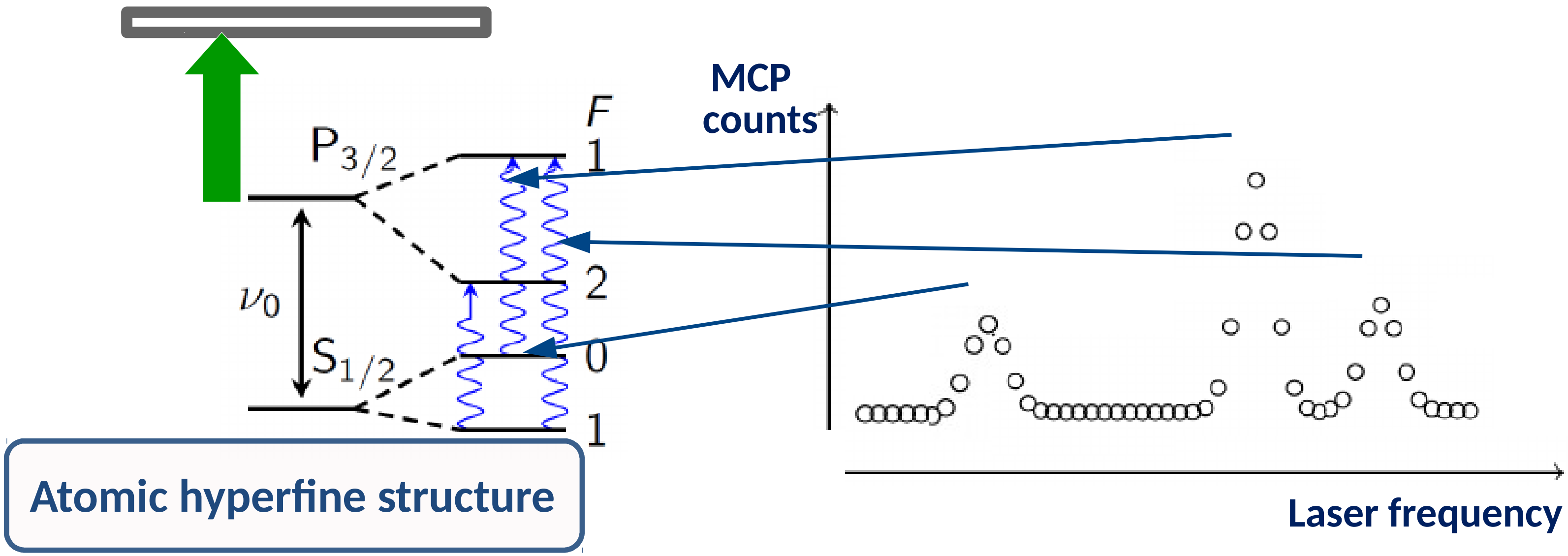
$$h\nu = \nu_0 + A\frac{C}{2} + B\frac{1}{4}\frac{(3/2)C(C+1) - 2I(I+1)J(J+1)}{I(2I-1)J(2J-1)}$$

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



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

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

Many-body methods

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

Nuclear force

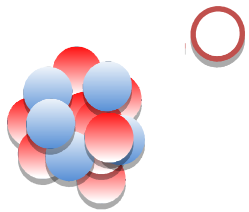
- Phenomenology
- Chiral effective field theory

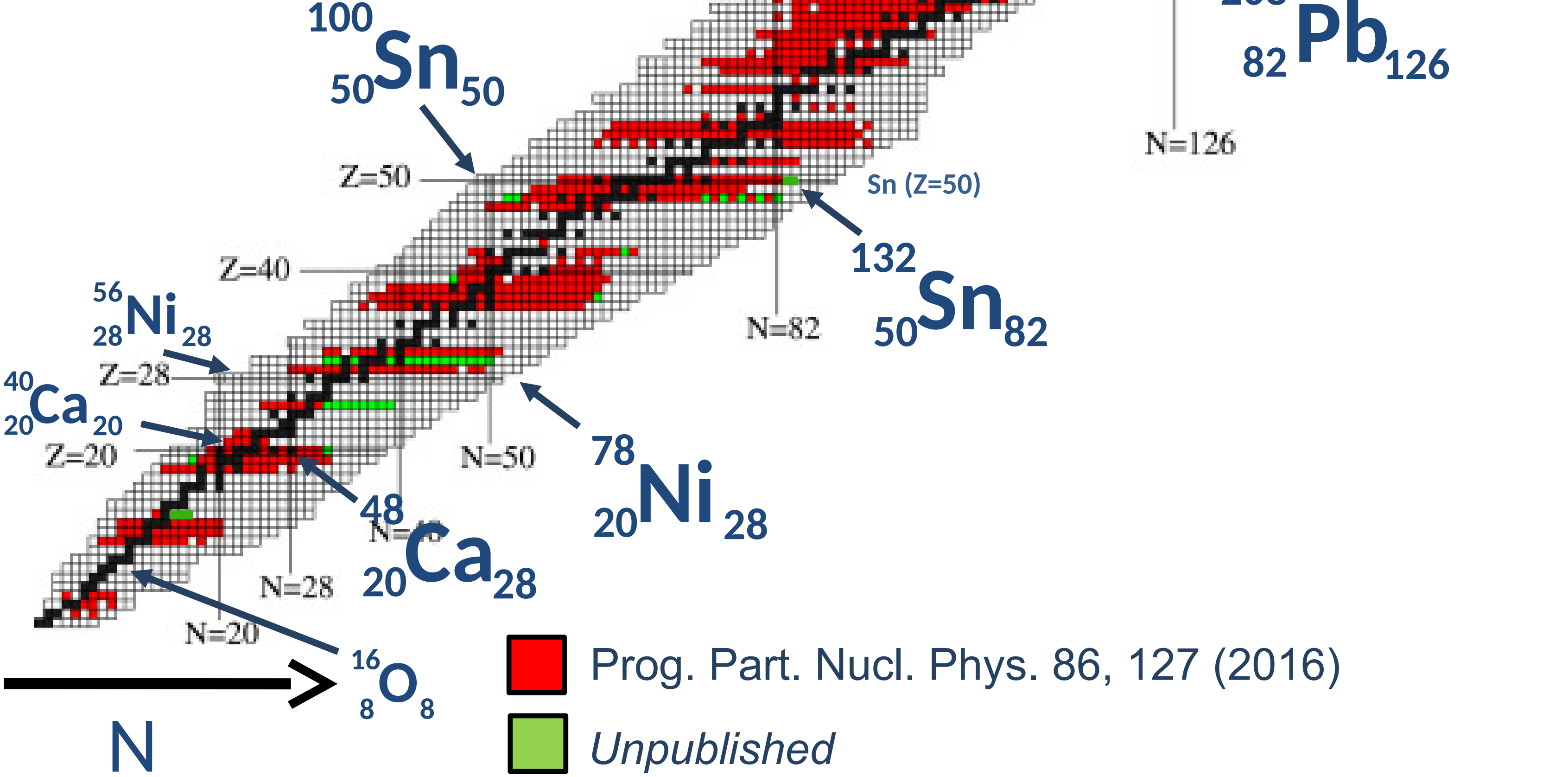
Electro-weak currents

- Effective neutron/proton charges
- Microscopic description of effective operators

Motivation

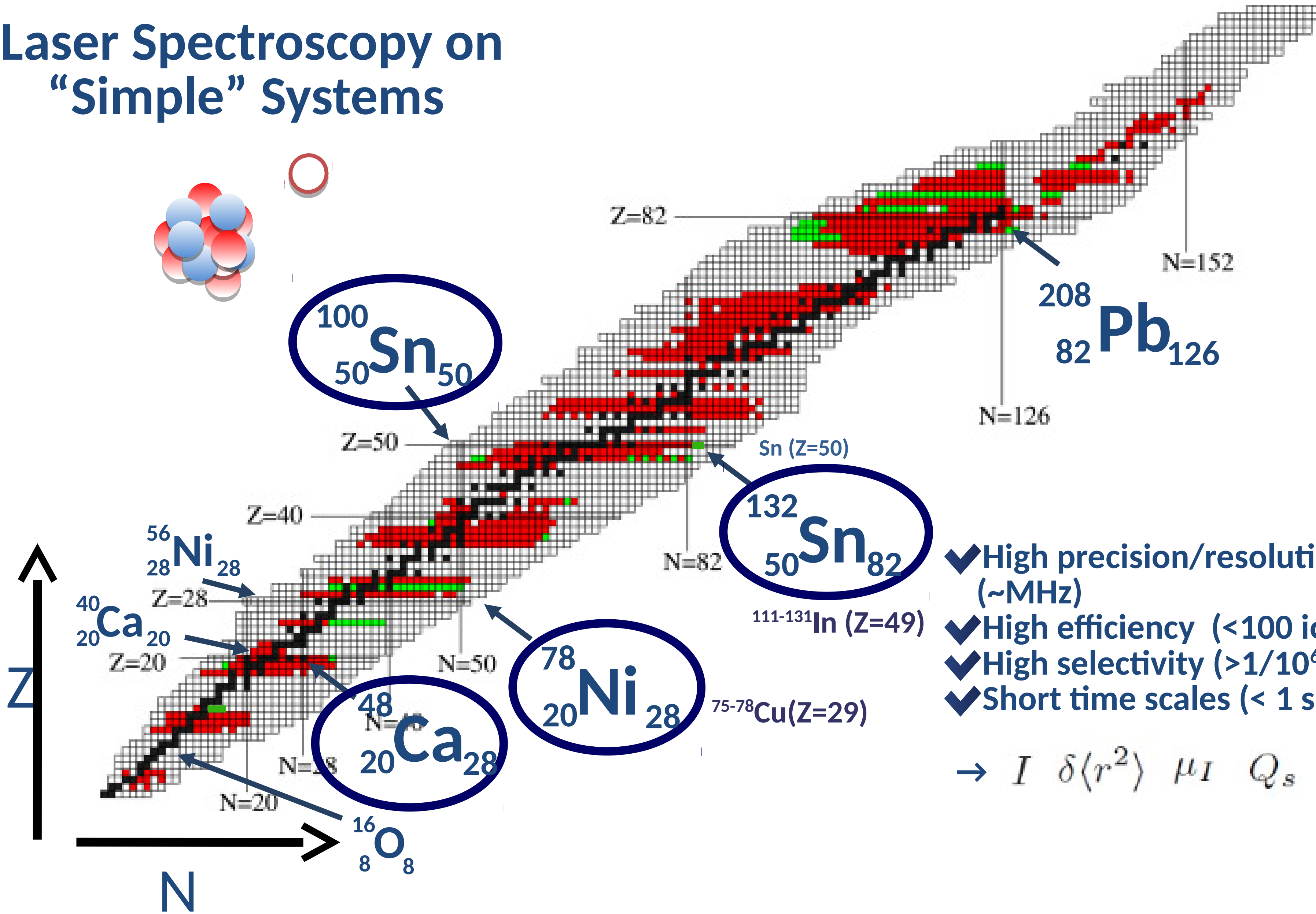
Laser Spectroscopy on "Simple" Systems





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)

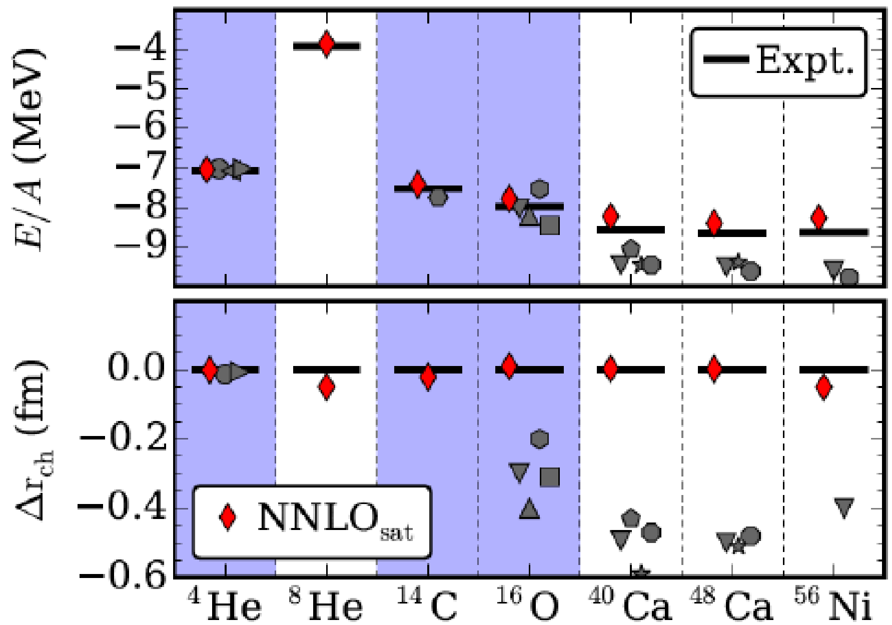
$$\rightarrow \; I \quad \delta\langle r^2\rangle \quad \mu_I \quad Q_s$$

RESULTS

Charge radii

Laser spectroscopy ➡ ***I* , $<r^2>$, *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
- Chiral effective field theory

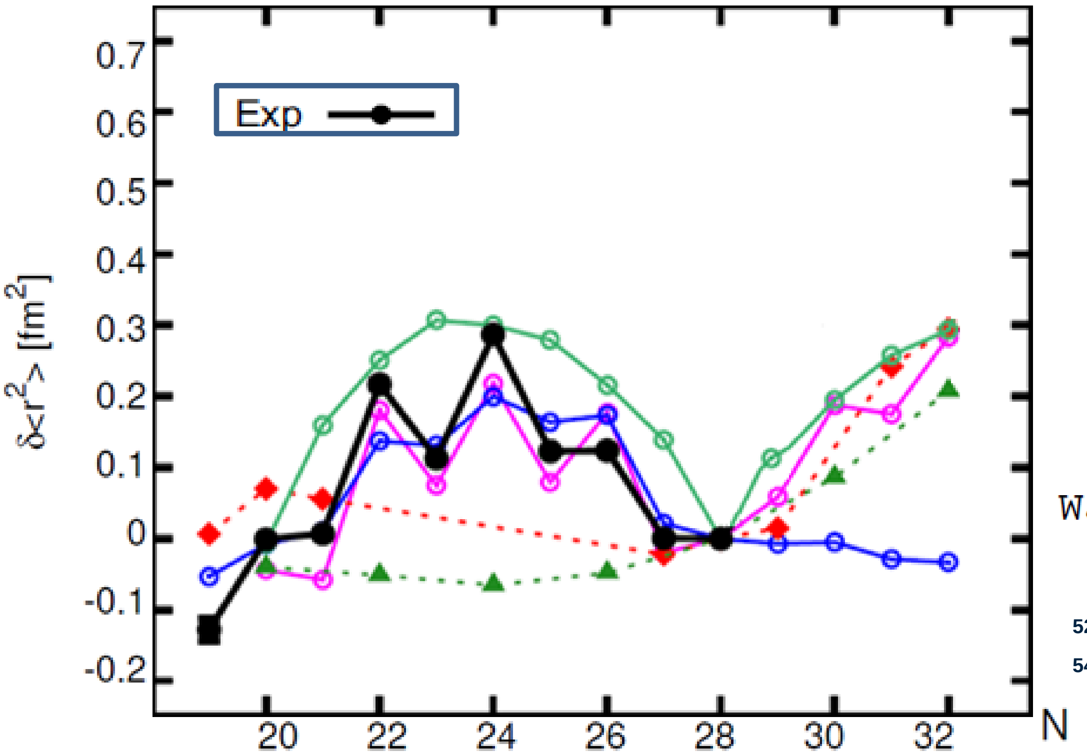
Electro-weak currents

- Effective neutron/proton charges
- Microscopic description of effective operators

Charge radii: Ca(Z=20) isotopes

[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)

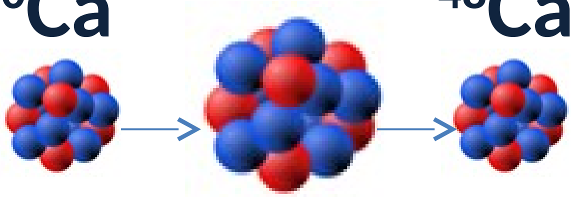
UNEDF0 — Nature 486, 509 (2012)

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)]

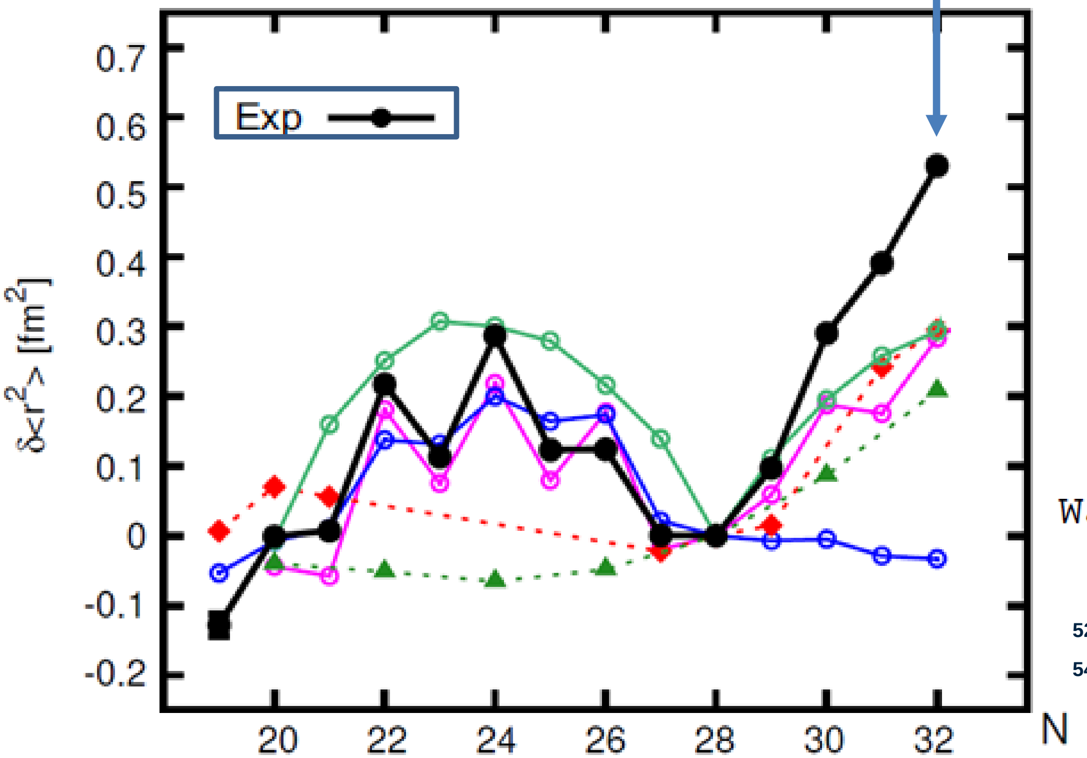
^{40}Ca **^{48}Ca** **^{52}Ca**



Charge radii: Ca(Z=20) isotopes

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

Much larger than expected!



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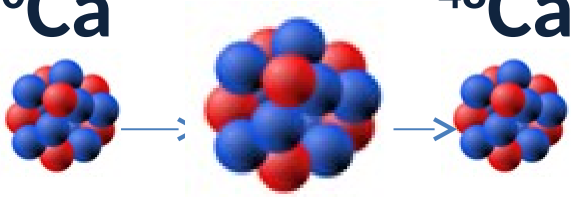

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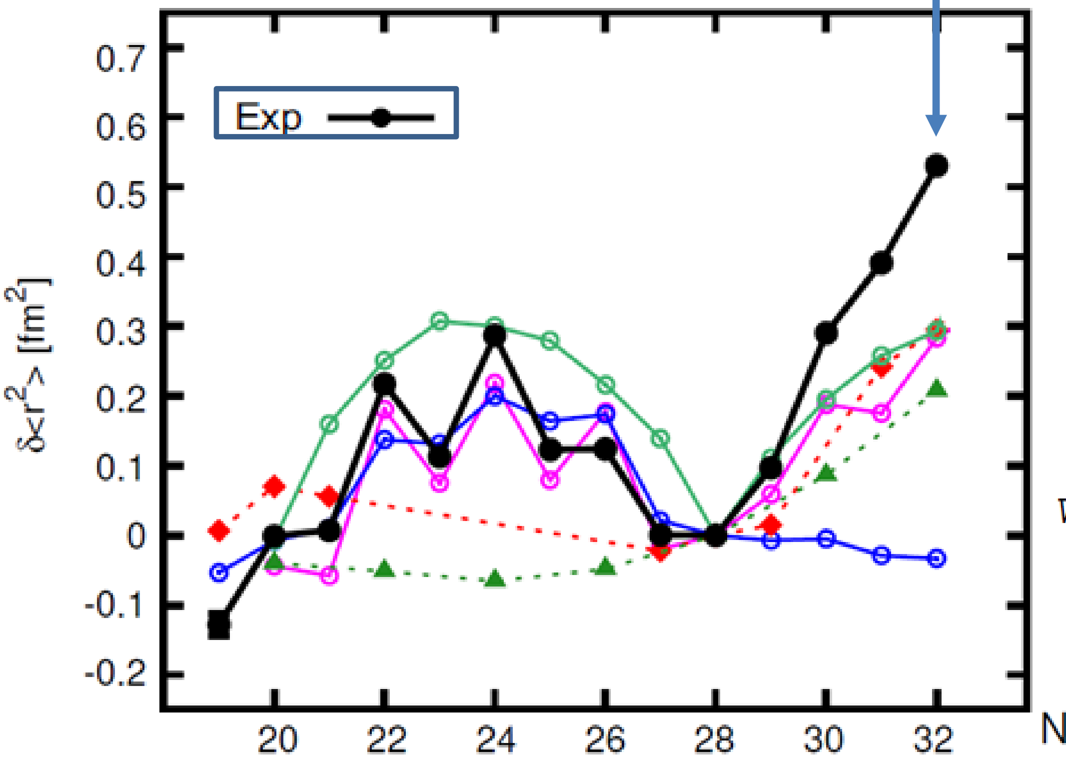

Max sensitivity ~250 ions/s

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

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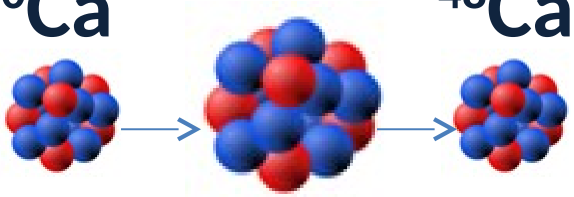
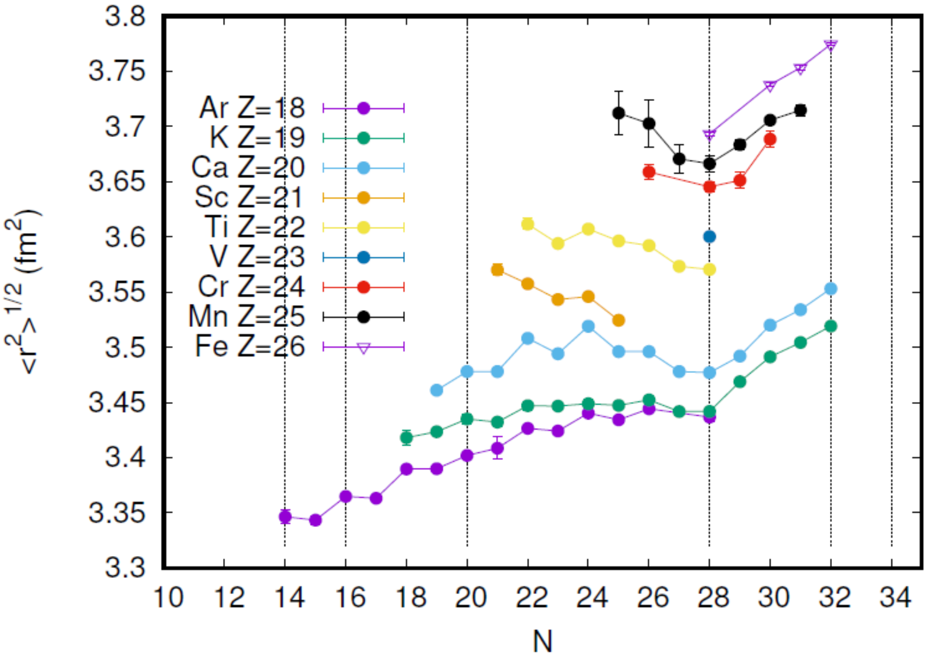


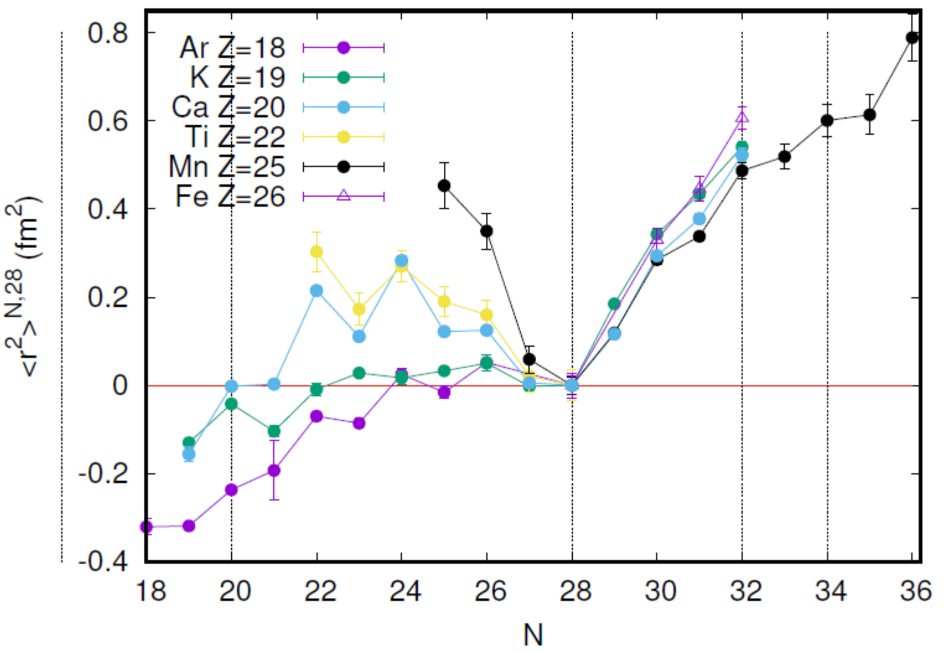
Beyond ^{52}Ca: Sensitivity -> ~1 ion/s

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





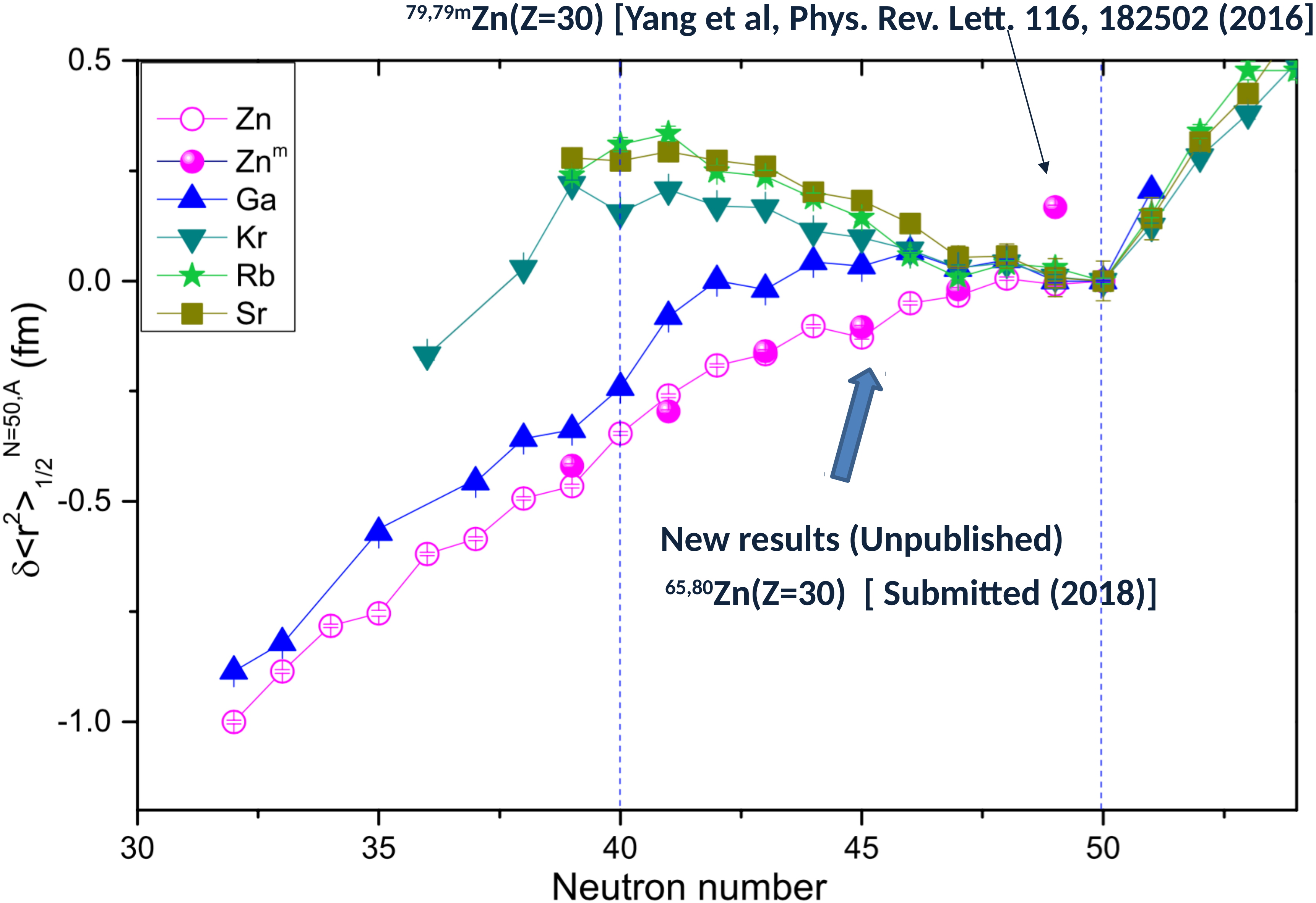
K (Z=19) → [K. Kreim et al, Phys. Lett. B 731, 97 (2014)]
Ca (Z=20) → [R.F. Garcia Ruiz et al., Nature Physics 12, 594 (2016)]
Mn (Z=25) → [H. Heylen et al, Phys. Rev. C 94, 054321(2016)]
Sc (Z=21) → [In preparation (2018)]

} COLLAPS/ISOLDE

$^{48-52}$K(Z=19) → [In preparation (2018)] } CRIS/ISOLDE

^{52,53}Fe(Z=26) → [Minamisono Phys. Rev. Lett. 117, 252501 (2016)] } BECOLA/NSCL

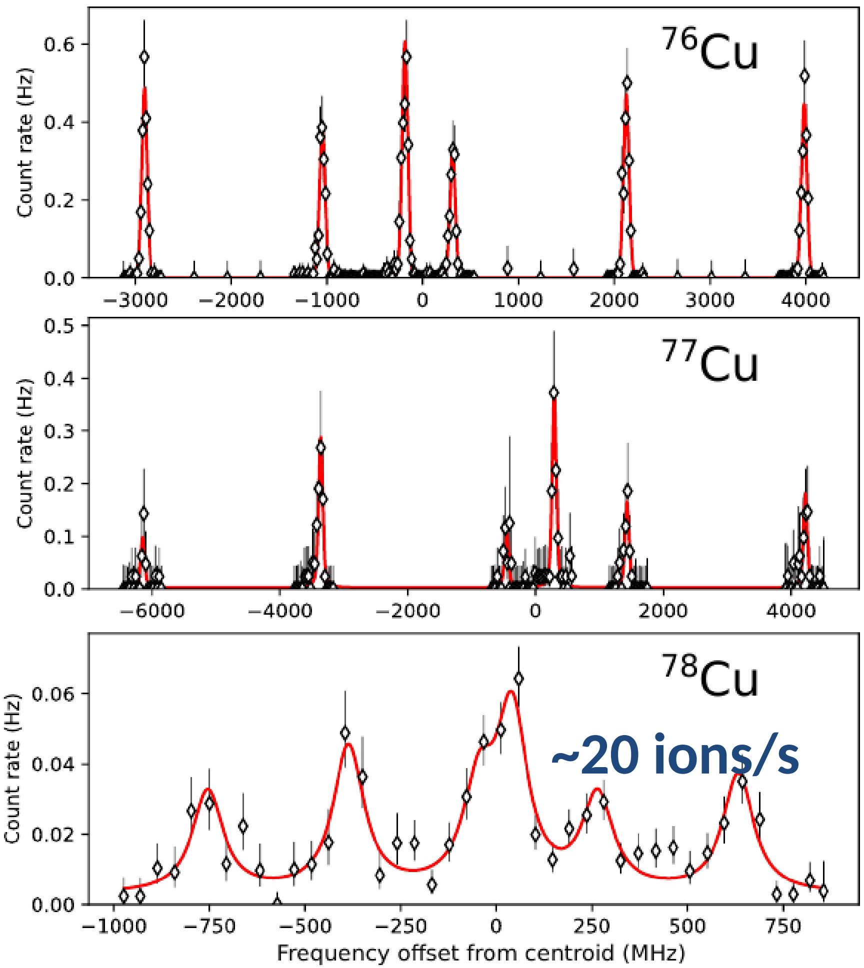
Charge radii systematic in the Ni region

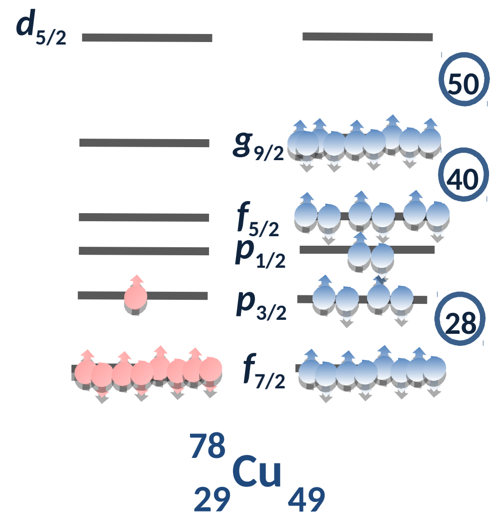


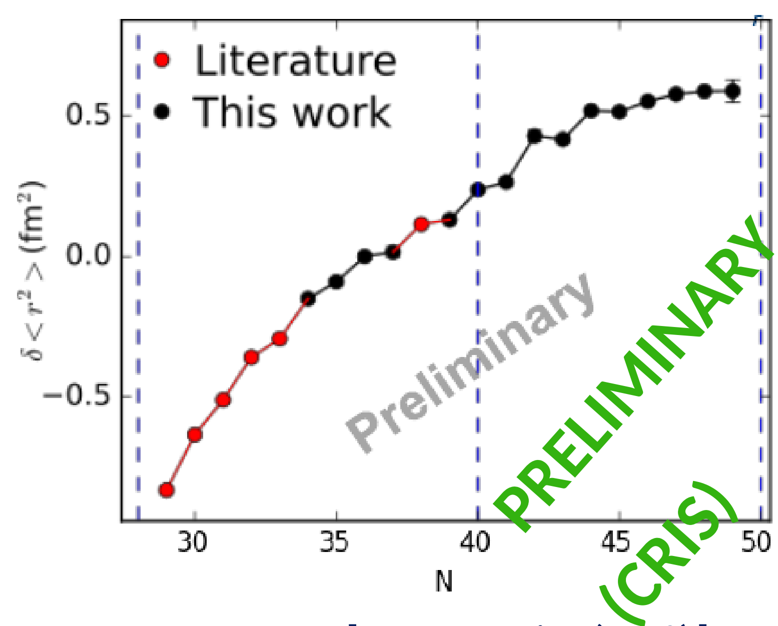
Results: Copper(Z=29) isotopes around ^{78}Ni

Dipole and quadrupole moments of $^{73-78}$Cu as a test of the robustness of the Z = 28 shell closure near ^{78}Ni

[De Groote et al. PRC 96, 041302 (R) (2017)]







[In preparation (2018)]

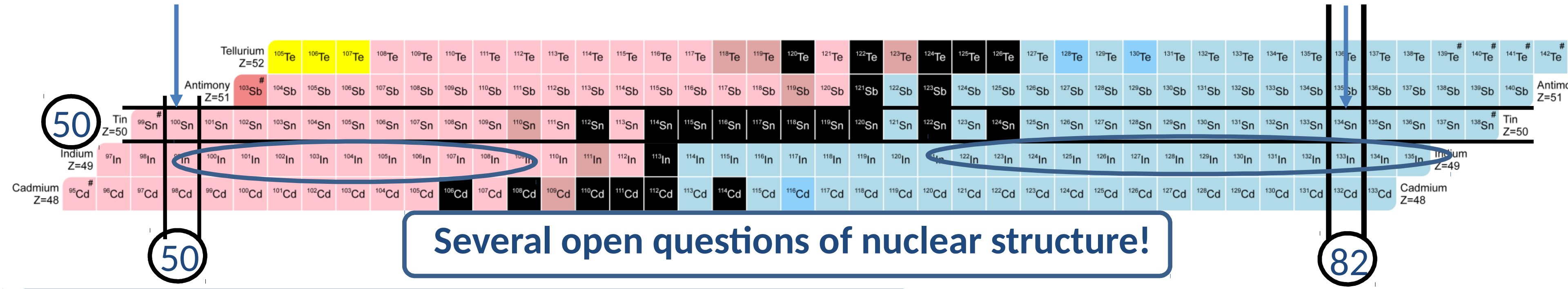
Nuclear structure around ^{100}Sn and ^{132}Sn

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)

- Heaviest self-conjugate (N = Z = 50) nucleus
- Largest strength in allowed β decay
- In the closest proximity to the proton dripline
- At the endpoint of the rapid proton capture process
- Biggest nuclei that can be accessed by *ab-initio* calculations
- Largest number of stable isotopes.
- ...

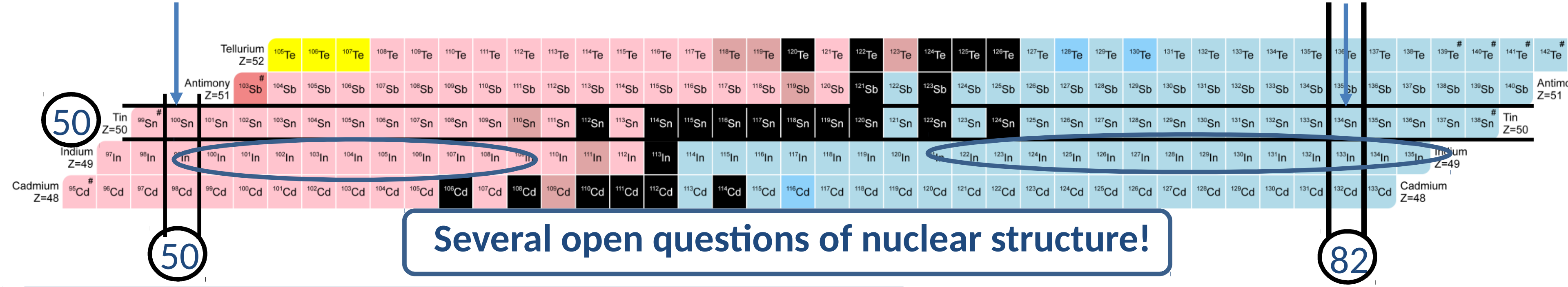
Nuclear structure around ^{100}Sn and ^{132}Sn

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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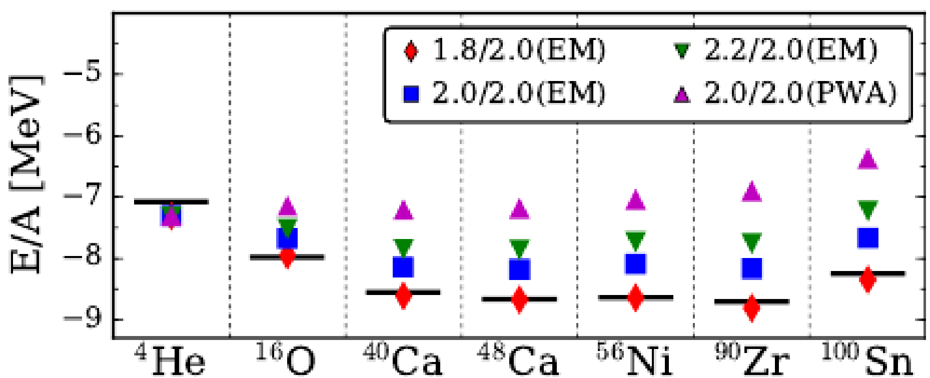
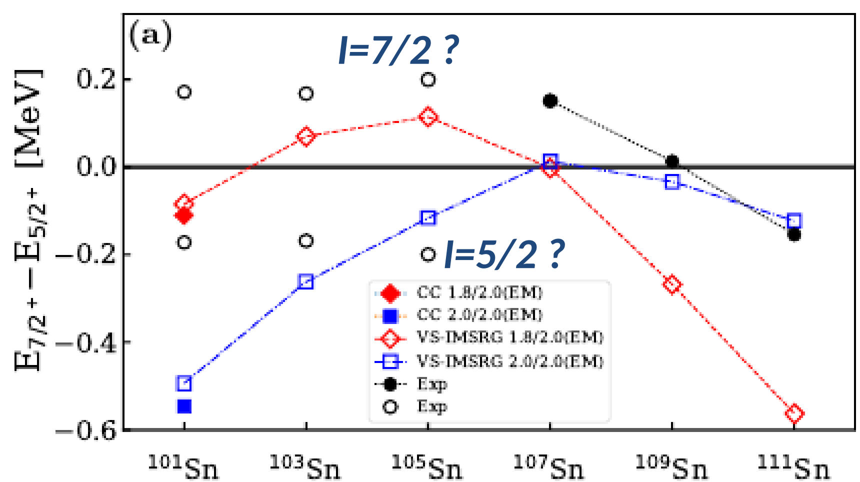
○ **Ab-initio calculations**

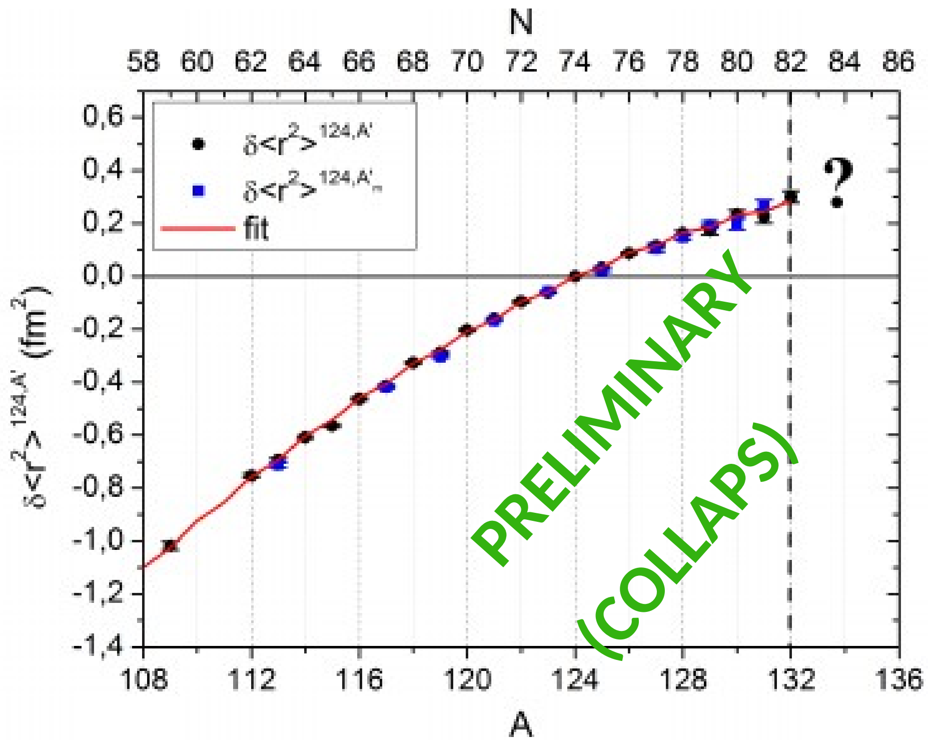


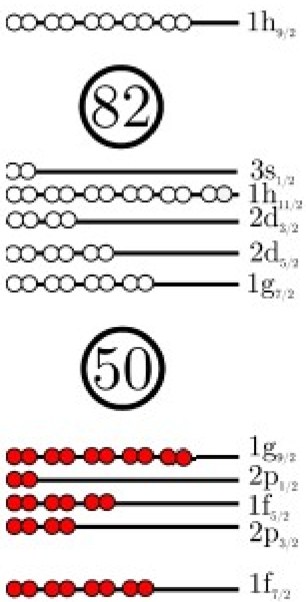


[T. Morris et al. Phys. Rev. Lett. 120, 152503 (2018)]

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

Results: Sn (Z=50) isotopes up to ^{134}Sn





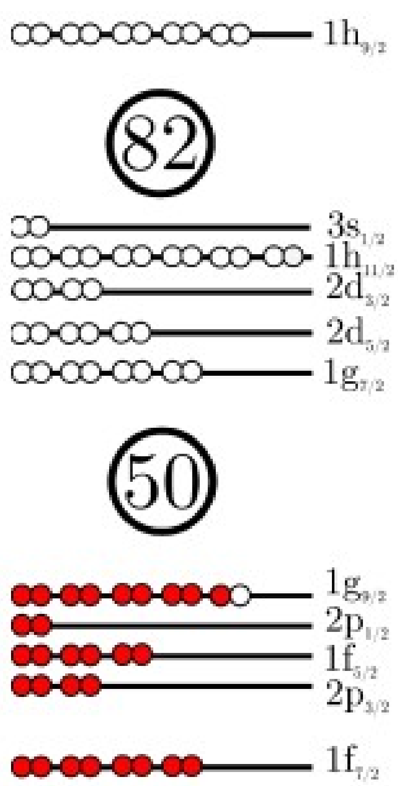
Charge radii and electromagnetic moments

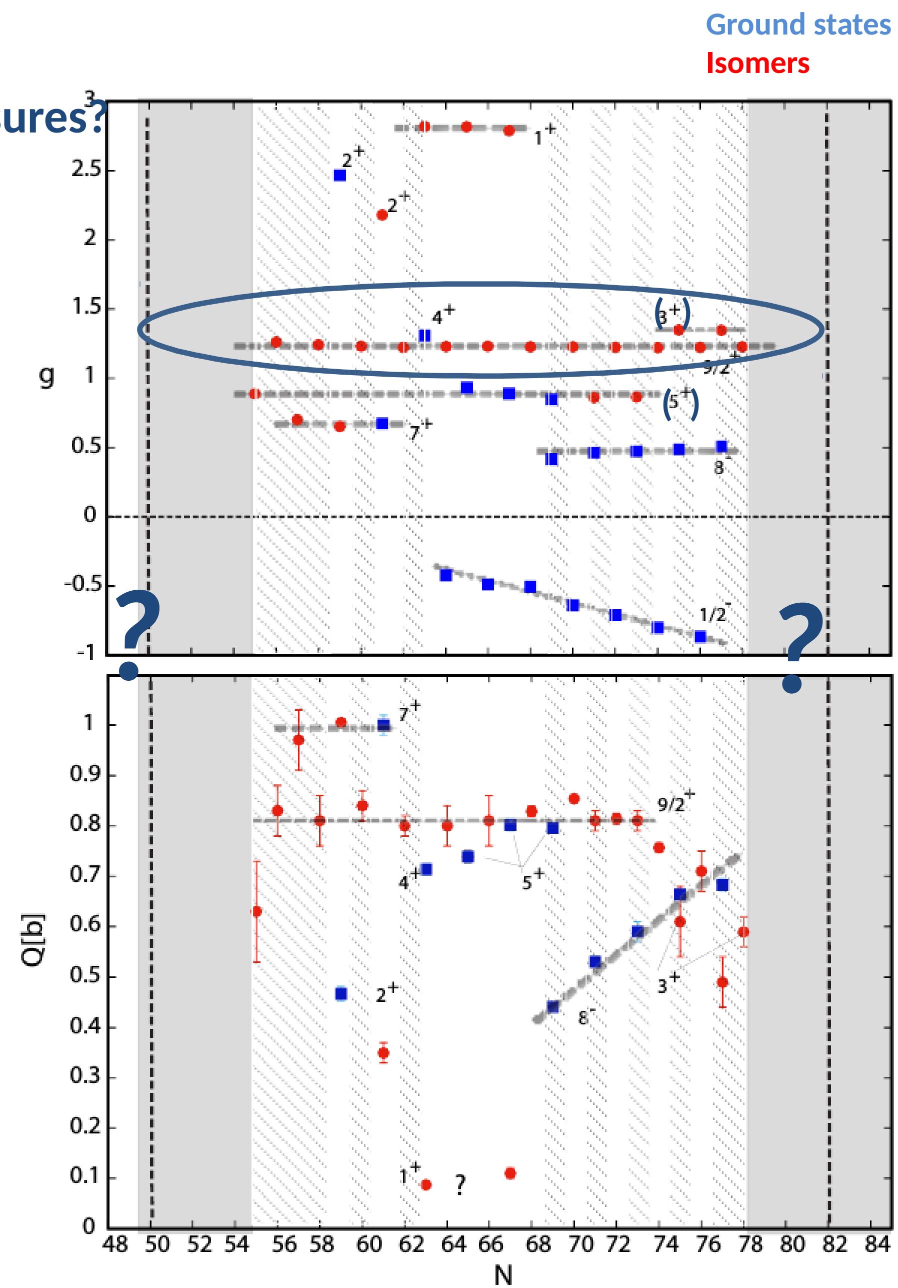
Evolution of collectivity / single particle

- approaching the N=Z=50 and N=82 shell closures?
- Role of correlations across N=Z=50 and N=82?

Role of electro-weak currents?

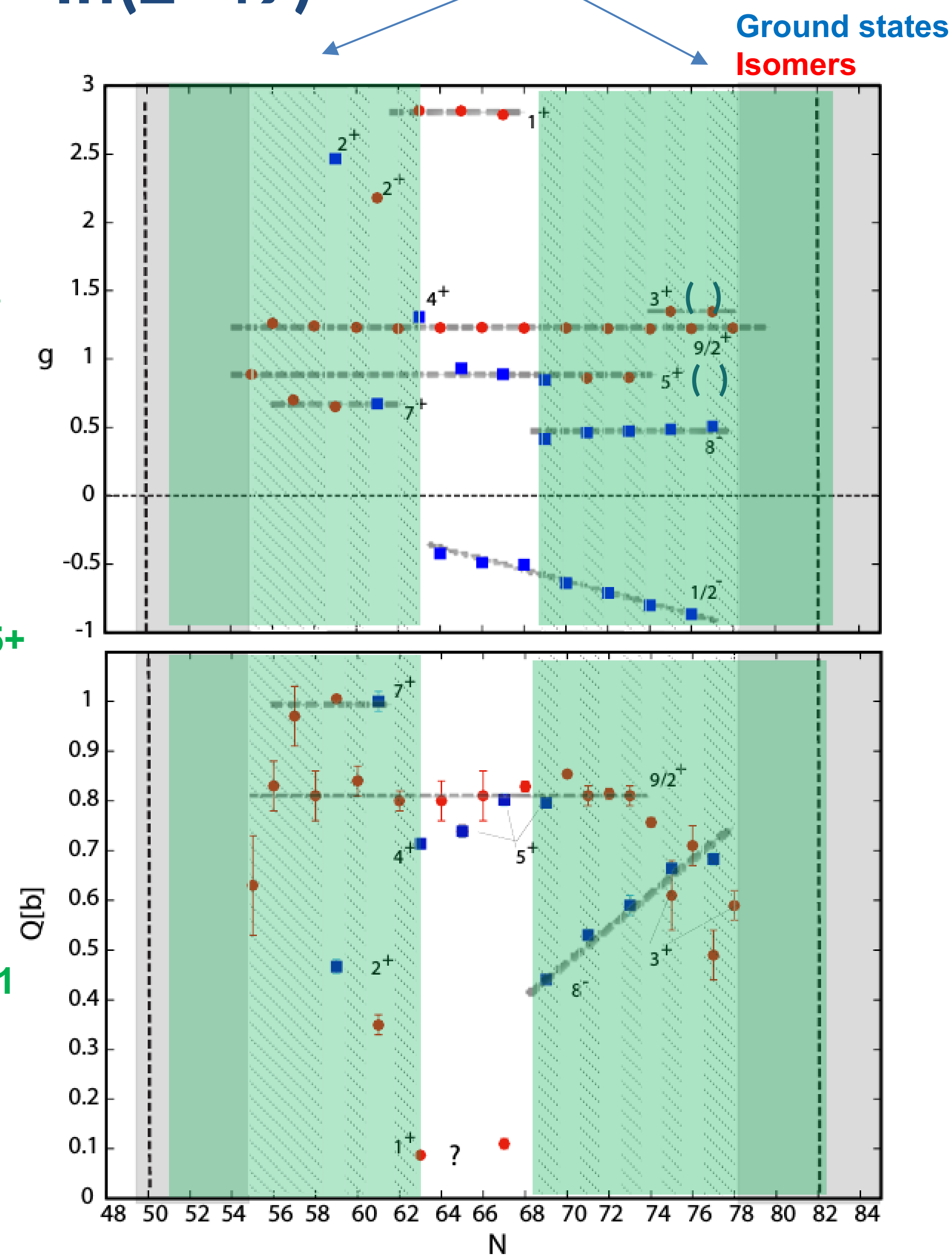
-
- Proton-neutron interaction?





Results 2017/2018 : $^{101-131}$In(Z=49)

(New results)



❑ **A successful experimental campaign!**

Several new results for electromagnetic moments and charge radii of:

- ✓ 1+ states in 114, 116, 118, 120, 122
- ✓ 9/2 states in 129, 131
- ✓ 1/2 states in 127, 129 and 131
- ✓ high spin isomers (>21/2) in 127, 129
- ✓ ground and isomeric states in 128 3+, 8-
- ✓ ground and isomeric states in 130: 1-, 10-, 5+

- ✓ 3+ state in 104
- ✓ 6+ state in 102
- ✓ 9/2+ states in 103, 101
- ✓ 1/2- states in 111, 109, 107, 105, 103, and 101
- ✓ high spin isomers (19/2-) in 109
- ✓ New isomeric states in 101

4 PhD Theses

Results 2017/2018 : $^{101-131}$In(Z=49)

CRIS

(New results)

❑ A successful experimental campaign!

Several new results for electromagnetic moments and charge radii of:

- ✓ 1+ states in 114, 116, 118, 120, 122
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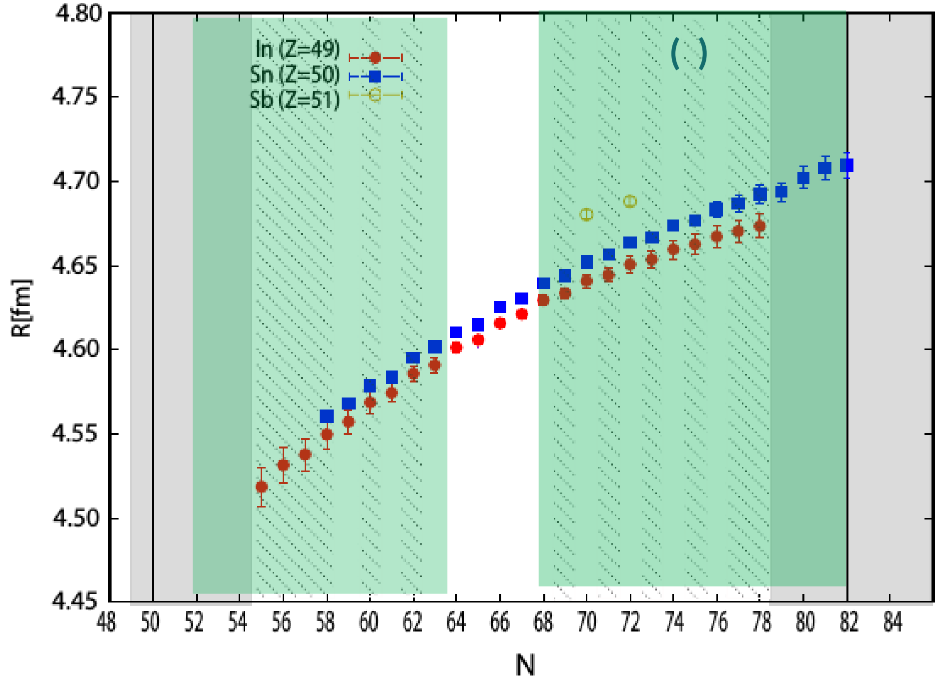
- ✓ ground and isomeric states in 130: 1-, 10-, 5+



- ✓ 3+ state in 104
- ✓ 6+ state in 102
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- ✓ 1/2- states in 111, 109, 107, 105, 103, and 101
- ✓ high spin isomers (19/2-) in 109
- ✓ New isomeric states in 101

4 PhD Theses

Outstanding issues

Isotope shift

Atomic parameters

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

Specially challenging for atomic theory

Nuclear charge radius

Field shift:

$$F_i = \frac{\pi\, a_o}{Z}\,\Delta\,|\psi_{ns}(0)|^2_{\mathrm{nr}}\; f_i(Z)$$

Mass shift:

$$H_{\mathrm{MS}} = \frac{1}{2M_a}\sum_{ij}^{N_e}\left[\mathbf{p}_i\cdot\mathbf{p}_j - \frac{\alpha Z}{r_i}\left(\boldsymbol{\alpha}_i + \frac{(\boldsymbol{\alpha}_i\cdot\mathbf{r}_i)\,\mathbf{r}_i}{r_i^2}\right)\cdot\mathbf{p}_j\right].$$

Outstanding issues

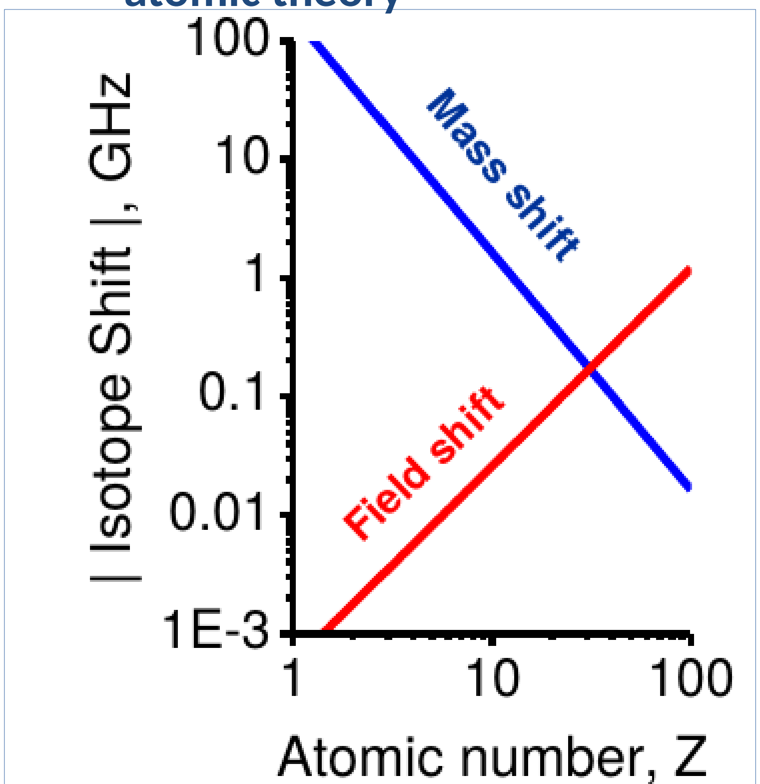
Isotope shift

Atomic parameters

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

Specially challenging for atomic theory

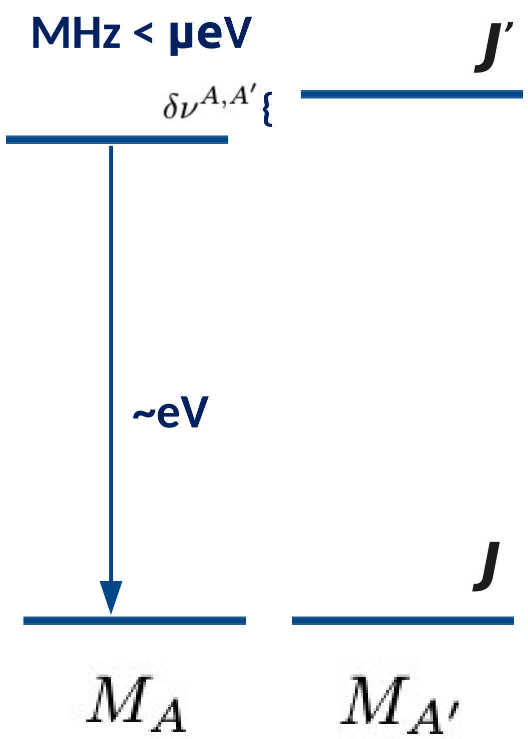
Nuclear charge radius



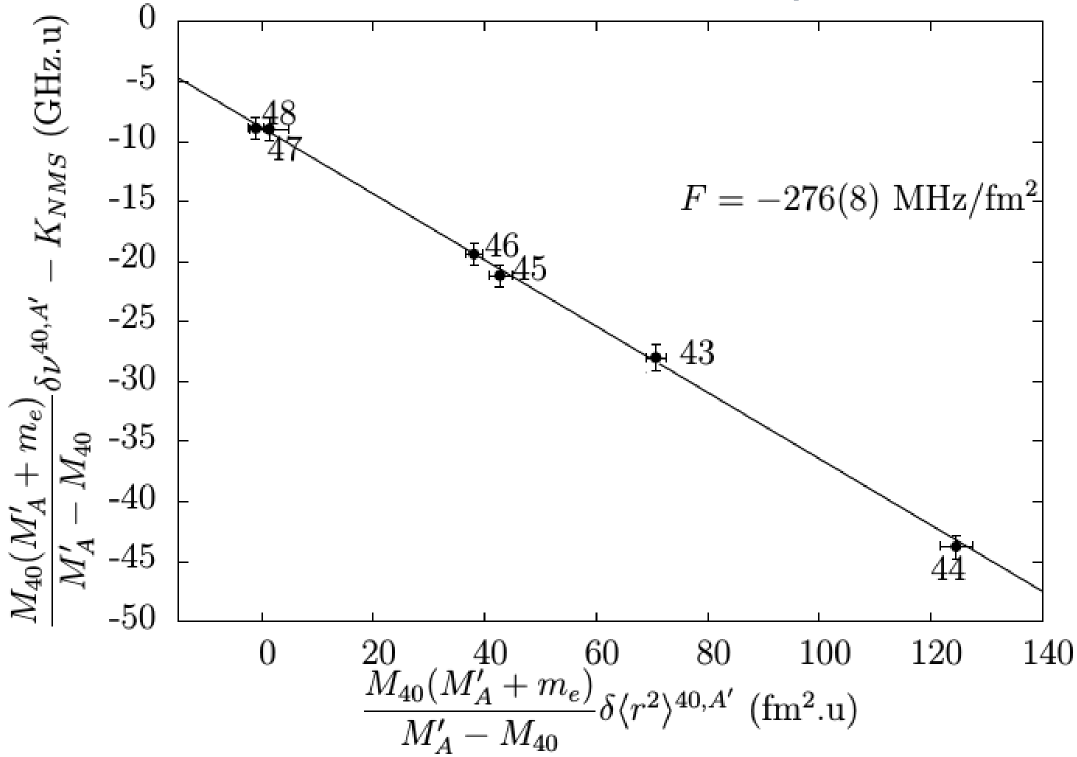
- Uncertainties dominated by M and F values
- Do not allow firm conclusions of nuclear structure
- Impossible to compare isotones

⟹ **Need of electron scattering data**

King plot



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

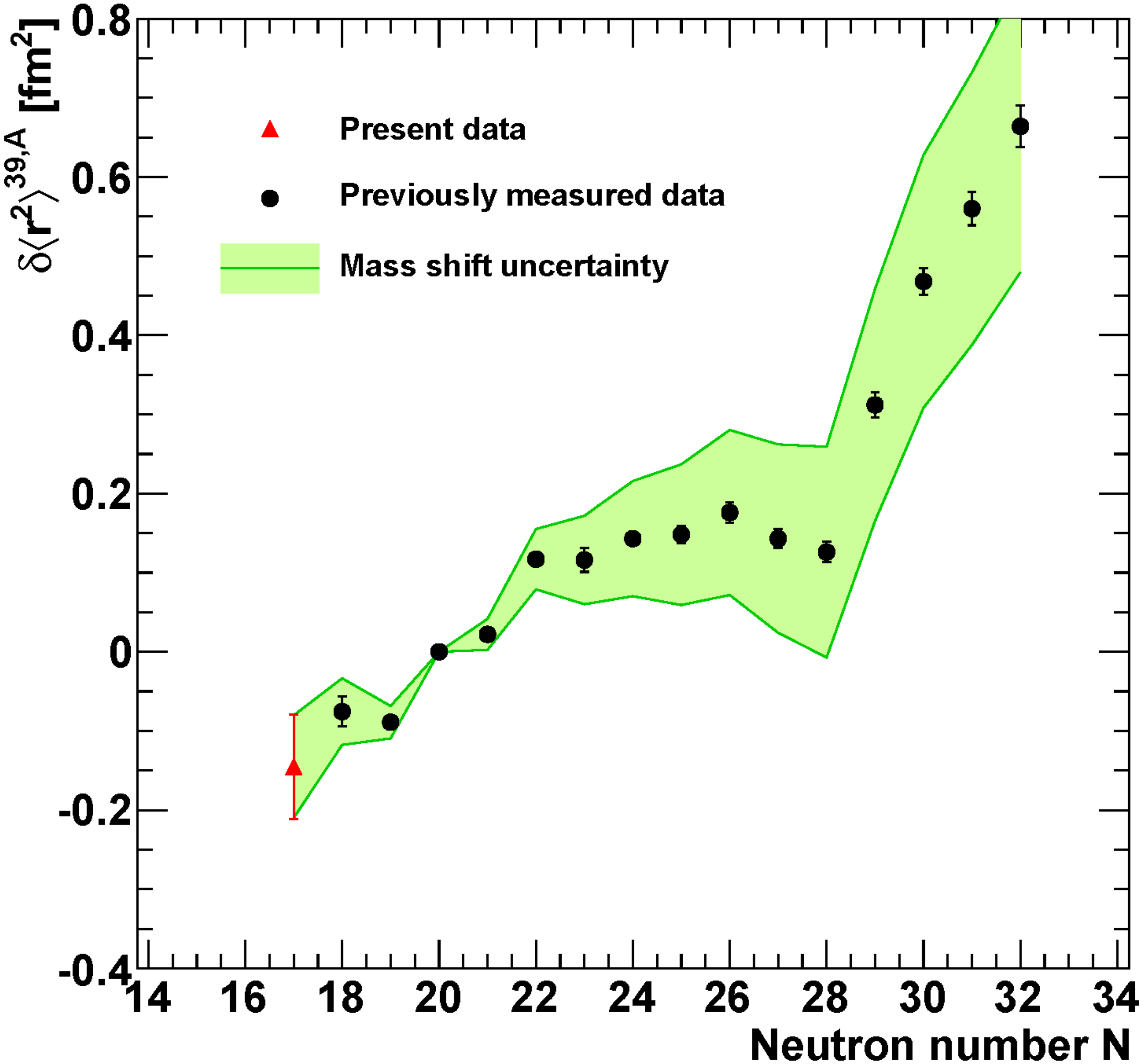


Atomic parameters

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

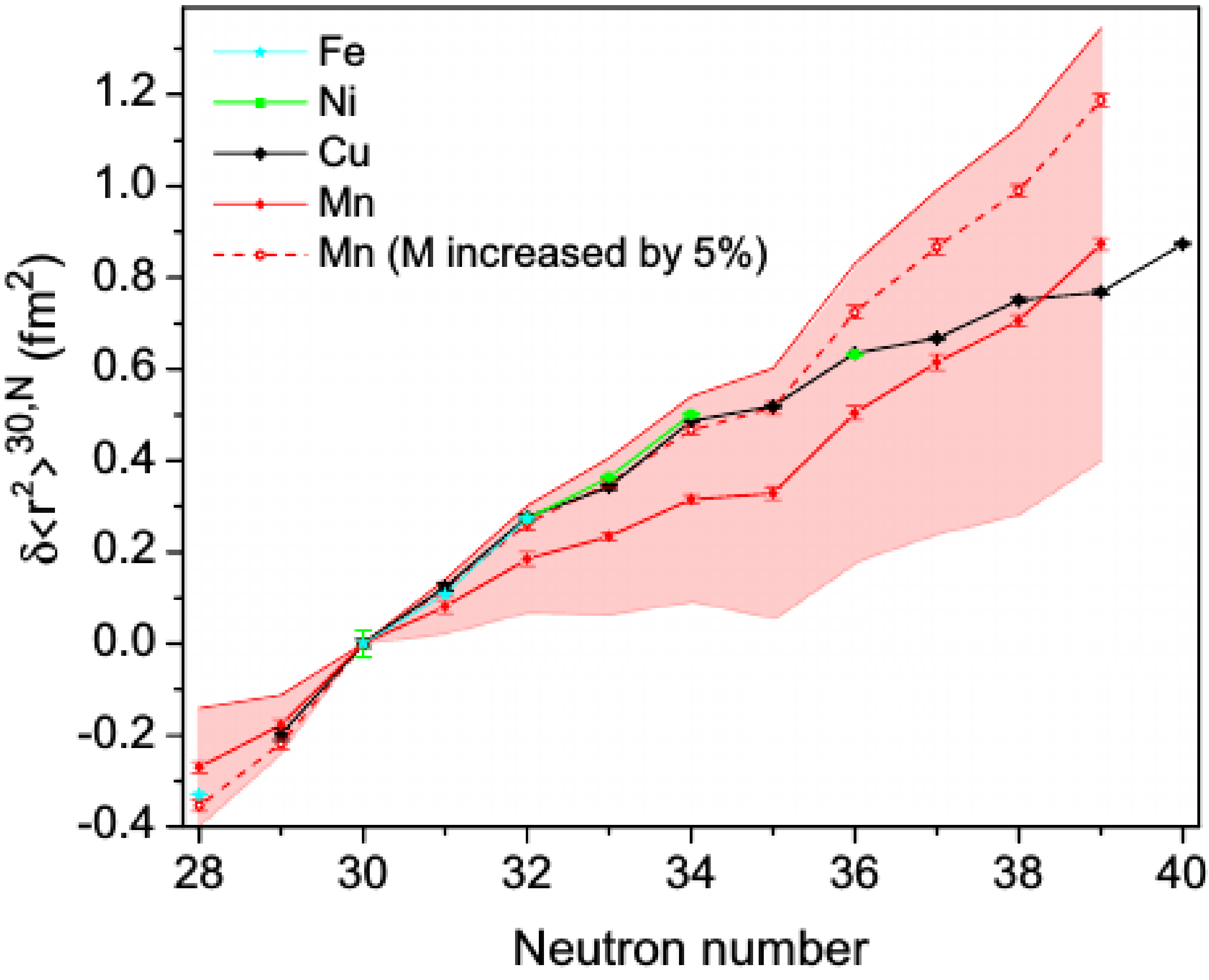
Nuclear charge radius

Charge Radii of Potassium isotopes (Z=19) isotopes



[Minamisono et al. Phys. Rev. C , 92, 014305 (2015)]

Charge Radii of Manganese isotopes (Z=25) isotopes



[Heylen et al. Phys. Rev. C 94, 054321 (2016)]

Future Perspectives

→ Towards few-body physics

$^{28-34}$Si(Z=14) @ NSCL

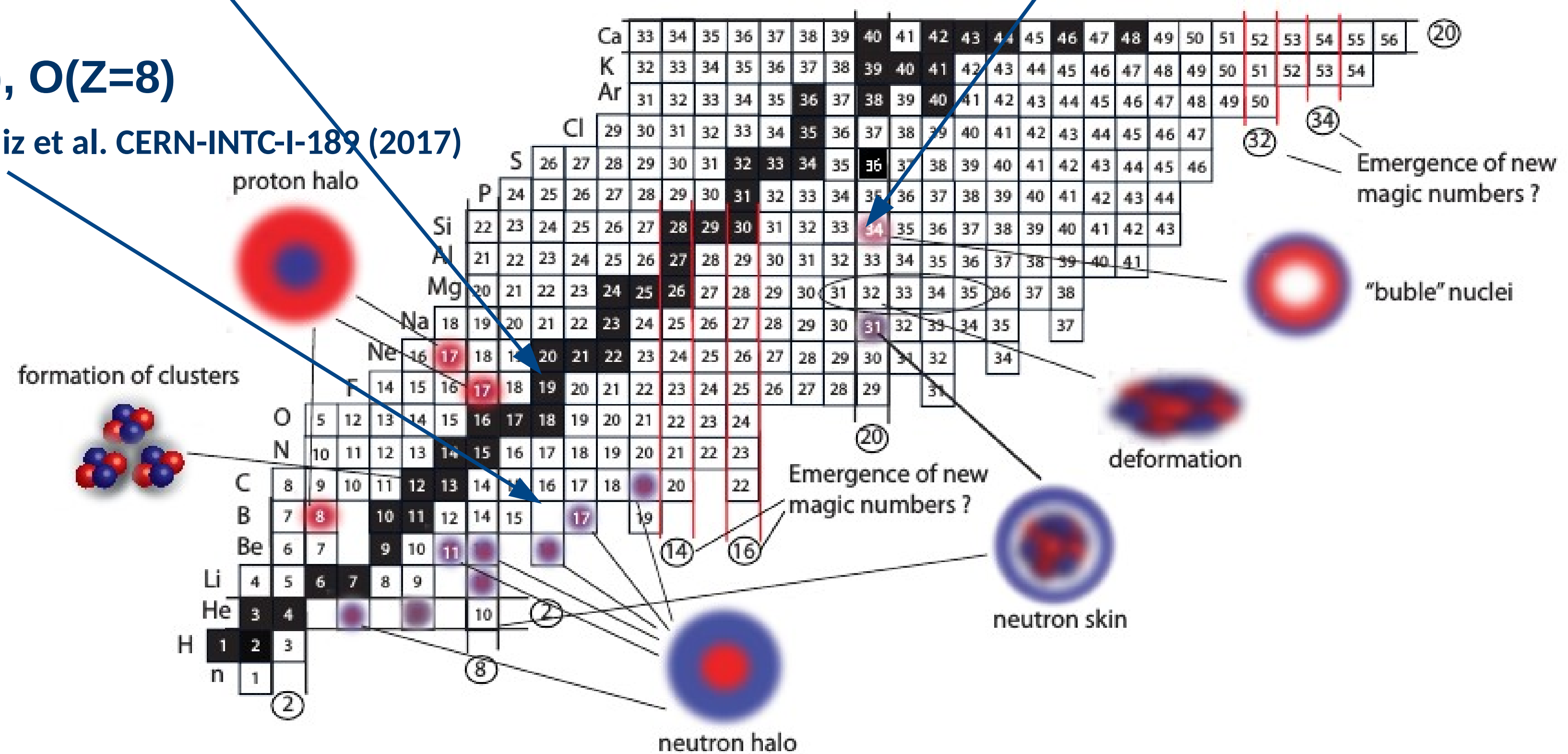
Garcia Ruiz and Minamisono et al. No. 17034, PAC 41 (2017)

$^{17-23}$F(Z=9)

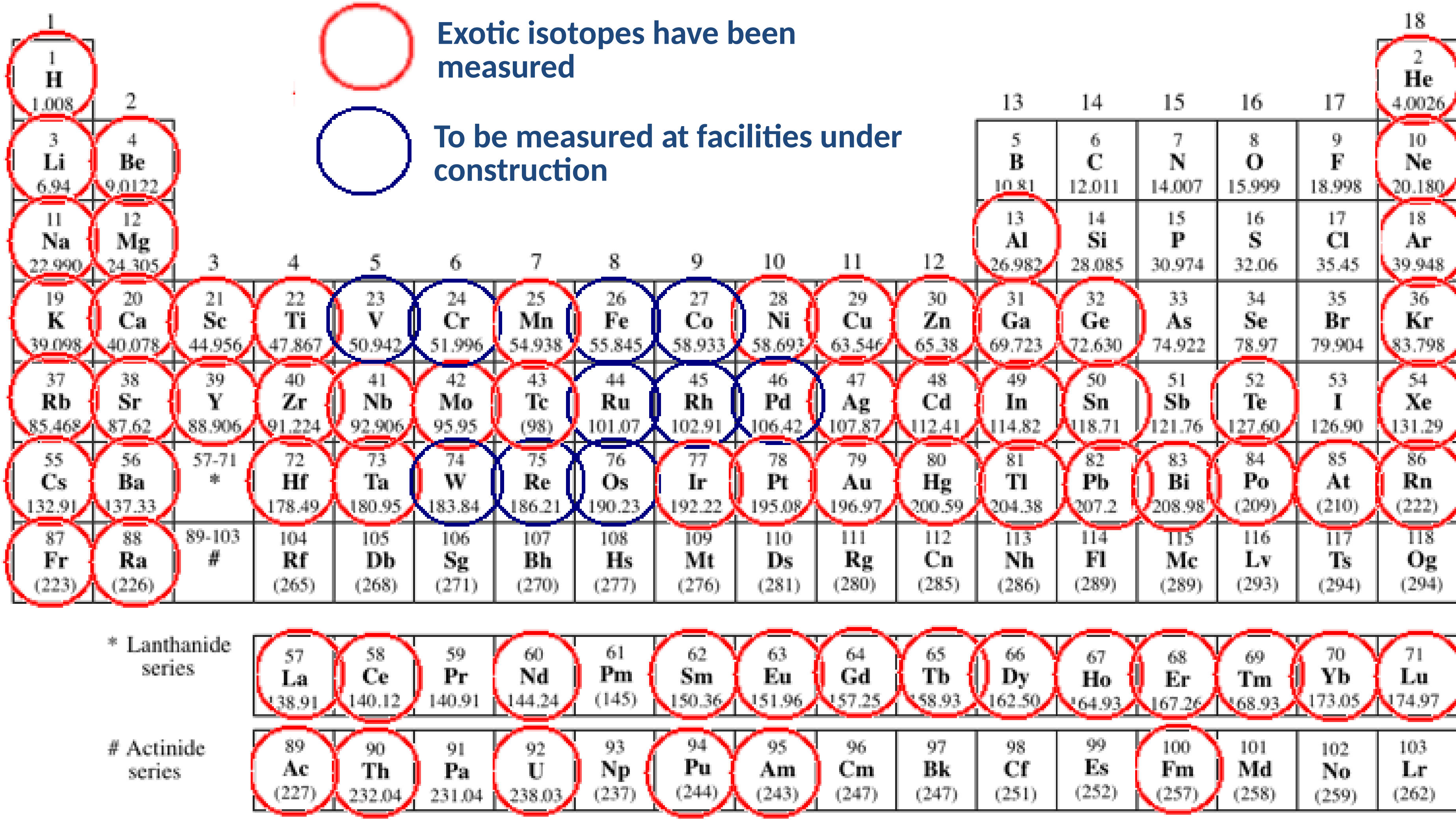
Garcia Ruiz et al. CERN-INTC-2016-037 (2015)

C(Z=6), O(Z=8)

Garcia Ruiz et al. CERN-INTC-I-189 (2017)

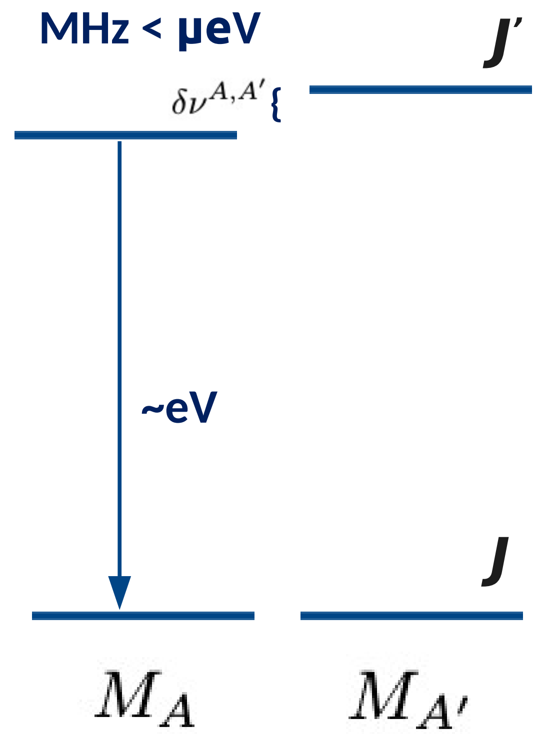


Radioactive Elements measured by Laser Spectroscopy



New opportunities:
Probing new Forces from isotope shifts

Isotope Shifts



Atomic parameters

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

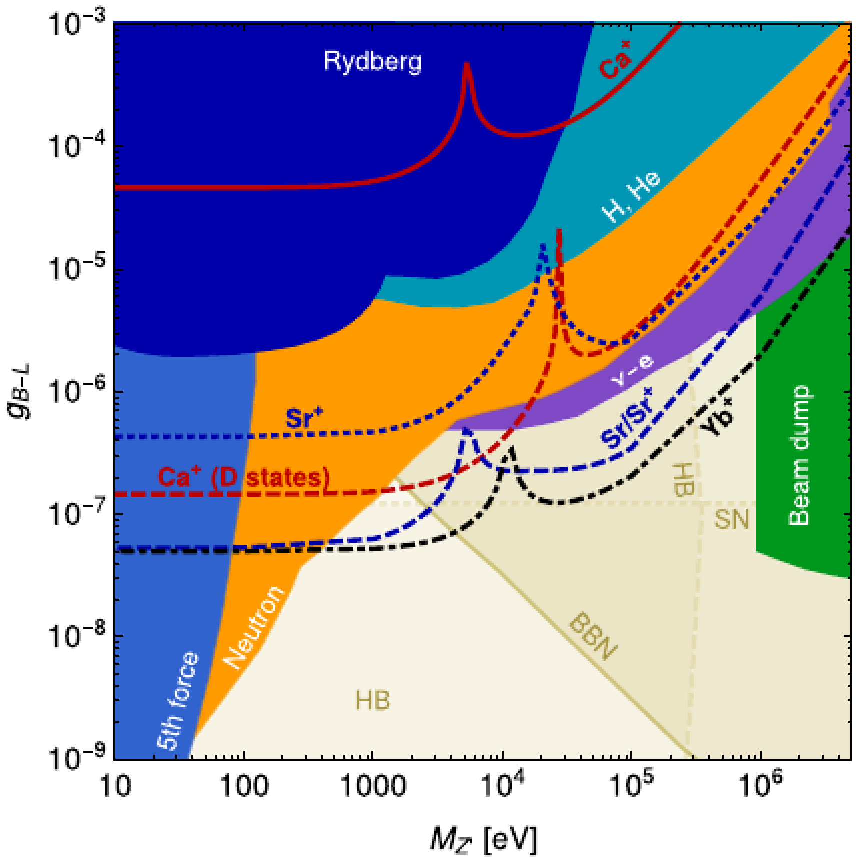
Electromagnetic corrections
+
New nucleon-electron interactions

Nuclear charge radius

PHYSICAL REVIEW D **96,** 015011 (2017)

Constraining new physics models with isotope shift spectroscopy

Claudia Frugiuele, Elina Fuchs, Gilad Perez, and Matthias Schlaffer
Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot 7610001, Israel
(Received 14 May 2017; published 12 July 2017)



Constraints on a Z' gauge boson from $U(1)_{B-L}$

Element	Transition	λ(nm)	σ (MHz)	n	Ref.
Ca^+	$4S_{1/2} \to 4P_{1/2}$ (D1)	397	0.1	3	[32]
	$3D_{3/2} \to 4P_{1/2}$	866	0.1	3	[32]
	$4S_{1/2} \to 4P_{3/2}$ (D2)	393	0.1	3	[33]
Yb	$6^1S_0 \to 6^1P_1$	399	0.5	4	[30]
	$6^1S_0 \to 6^3P_1$	555.65	0.5	4	[31]
	$6^3D_2 \to 6^1S_0$	404	10	3	[34]
	$6^3D_1 \to 6^1S_0$	408	2	3	[34]

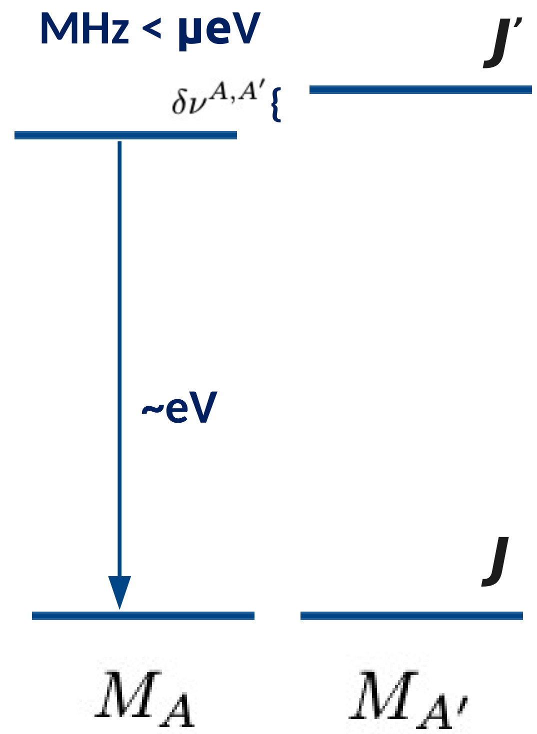
New physics interaction

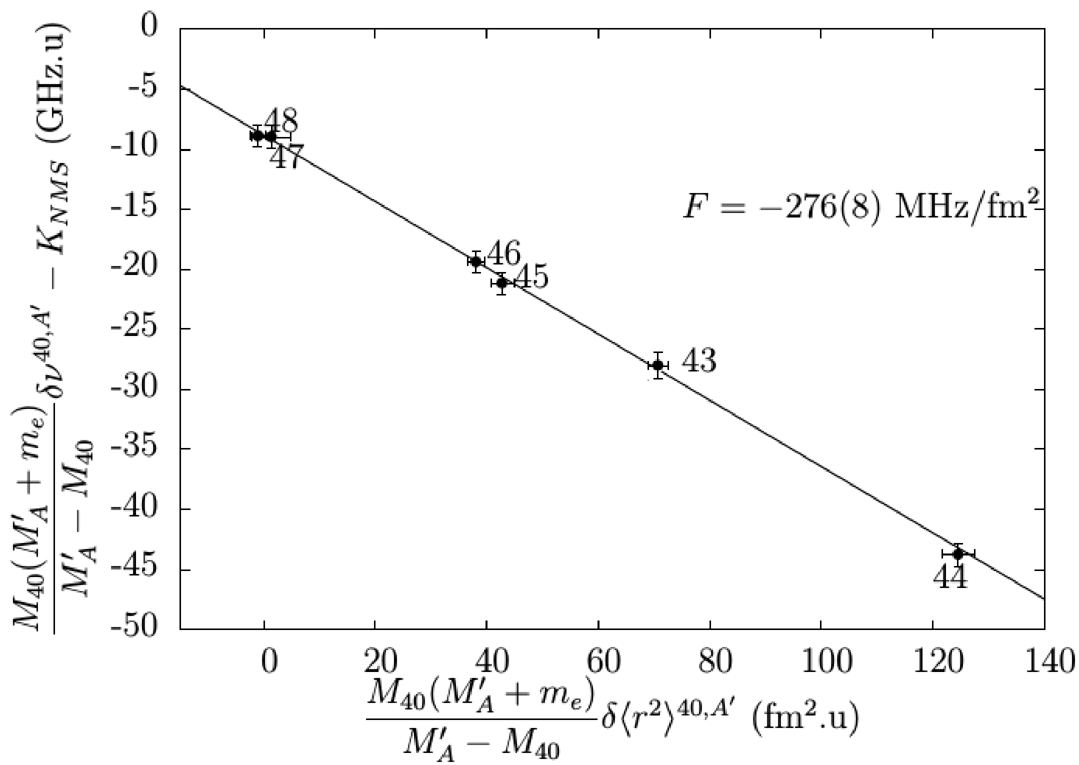
$$V_{\rm NP}(m_\phi, r) = \frac{y_e y_n}{4\pi}(A-Z)\frac{e^{m_\phi r}}{r}$$

$$\overrightarrow{m\nu}_i = K_i \overrightarrow{m\mu} + F_i \overrightarrow{m\delta\langle r^2\rangle} + y_e y_n X_i \vec{h},$$

King plot

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



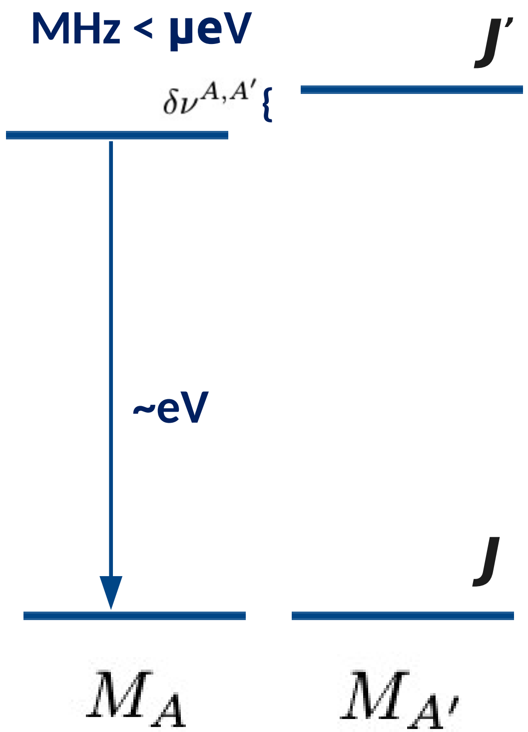


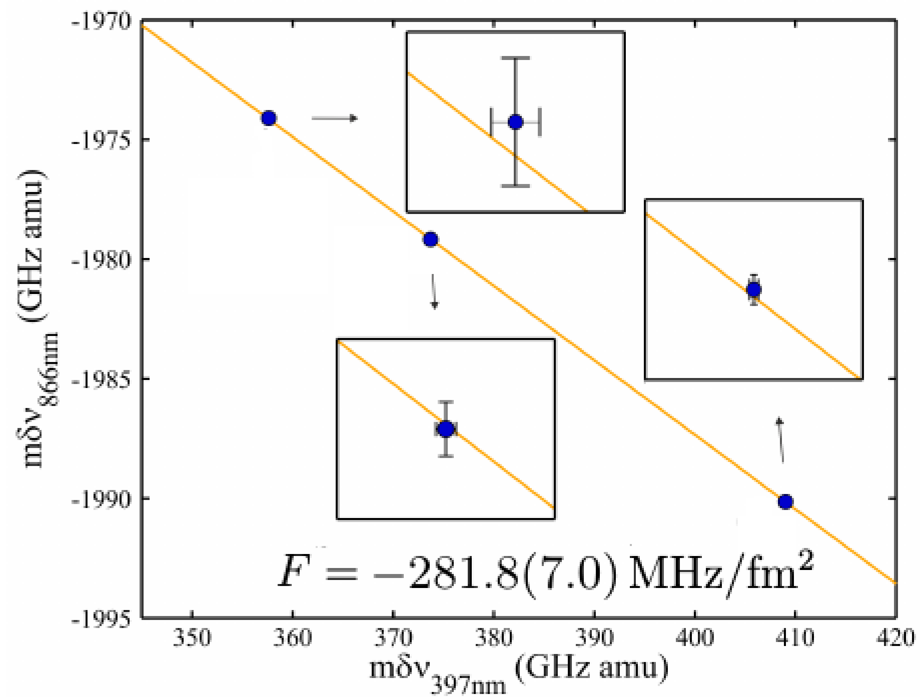
Atomic parameters

$$\delta\nu^{A,A'} = K_{MS}\frac{M_{A'} - M_A}{M_{A'}M_A} + F\delta\langle r^2\rangle^{A,A'} + \left\{ \begin{array}{l}\text{Electromagnetic corrections} \\ + \\ \text{New nucleon-electron interactions}\end{array}\right.$$

Nuclear charge radius

King plot





Gebert et al. Phys. Rev. Lett. 115, 053003 (2015)

Atomic parameters

$$\delta\nu^{A,A'} = K_{MS}\frac{M_{A'} - M_A}{M_{A'}M_A} + F\delta\langle r^2\rangle^{A,A'} + \begin{cases}\text{Electromagnetic corrections} \\ + \\ \text{New nucleon-electron interactions}\end{cases}$$

Nuclear charge radius

PHYSICAL REVIEW A **97**, 032510 (2018)

Isotope shift, nonlinearity of King plots, and the search for new particles

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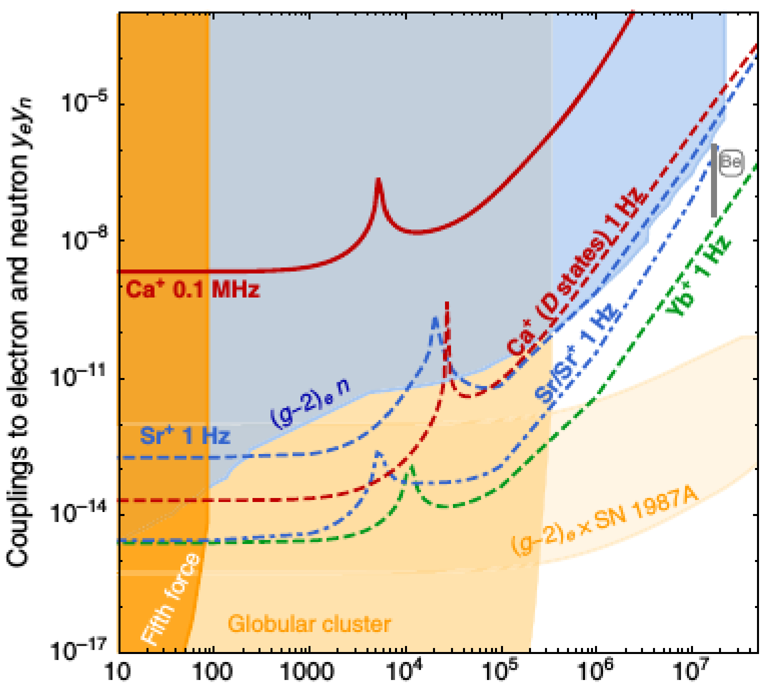
[1]*School of Physics, University of New South Wales, Sydney 2052, Australia*

PHYSICAL REVIEW LETTERS **120,** 091801 (2018)

Probing New Long-Range Interactions by Isotope Shift Spectroscopy

Julian C. Berengut,[1,*] Dmitry Budker,[2,3,4,†] Cédric Delaunay,[5,‡] Victor V. Flambaum,[1,§] Claudia Frugiuele,[6,‖]



Limits on the electron and neutron couplings ($y_e y_n$) of a new boson of mass m_ϕ

$$\nu_i^{AA'} = K_i \mu_{AA'} + F_i \delta\langle r^2\rangle_{AA'} + \alpha_{\rm NP} X_i \gamma_{AA'};$$

$$\alpha_{\rm NP} = (-1)^s y_e y_n / 4\pi.$$

Probing Long-Range Neutrino-Mediated Forces with Atomic and Nuclear Spectroscopy

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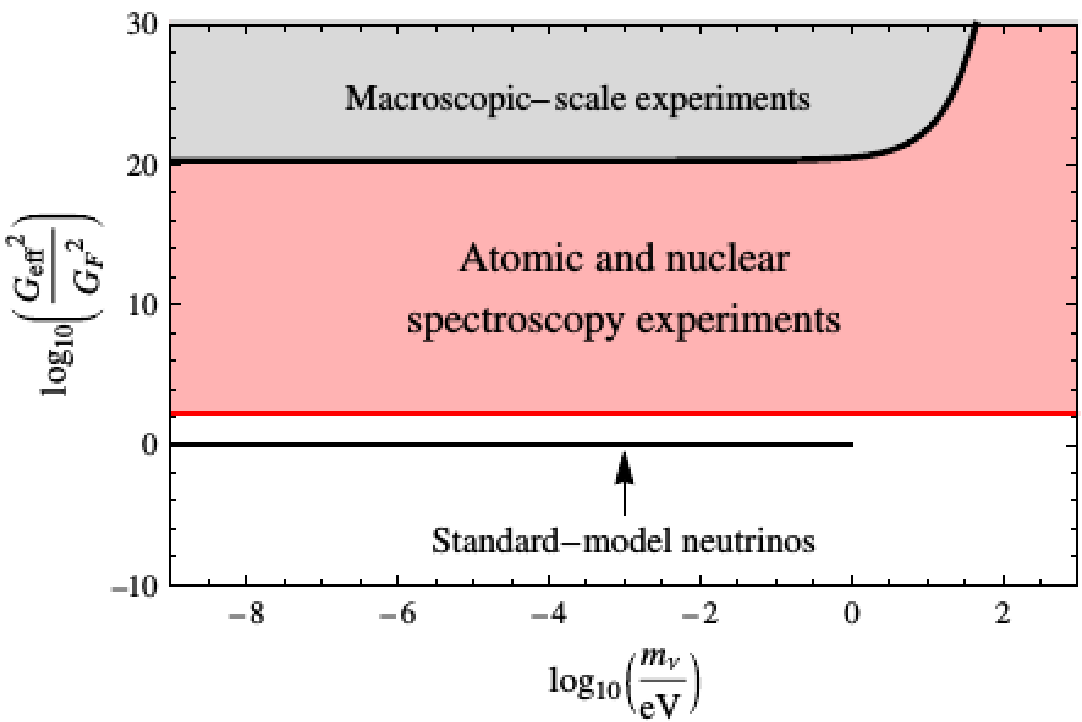
Helmholtz Institute Mainz, Johannes Gutenberg University of Mainz, 55128 Mainz, Germany

(Received 18 November 2017; published 1 June 2018)

Limits on the neutrino-mediated potential

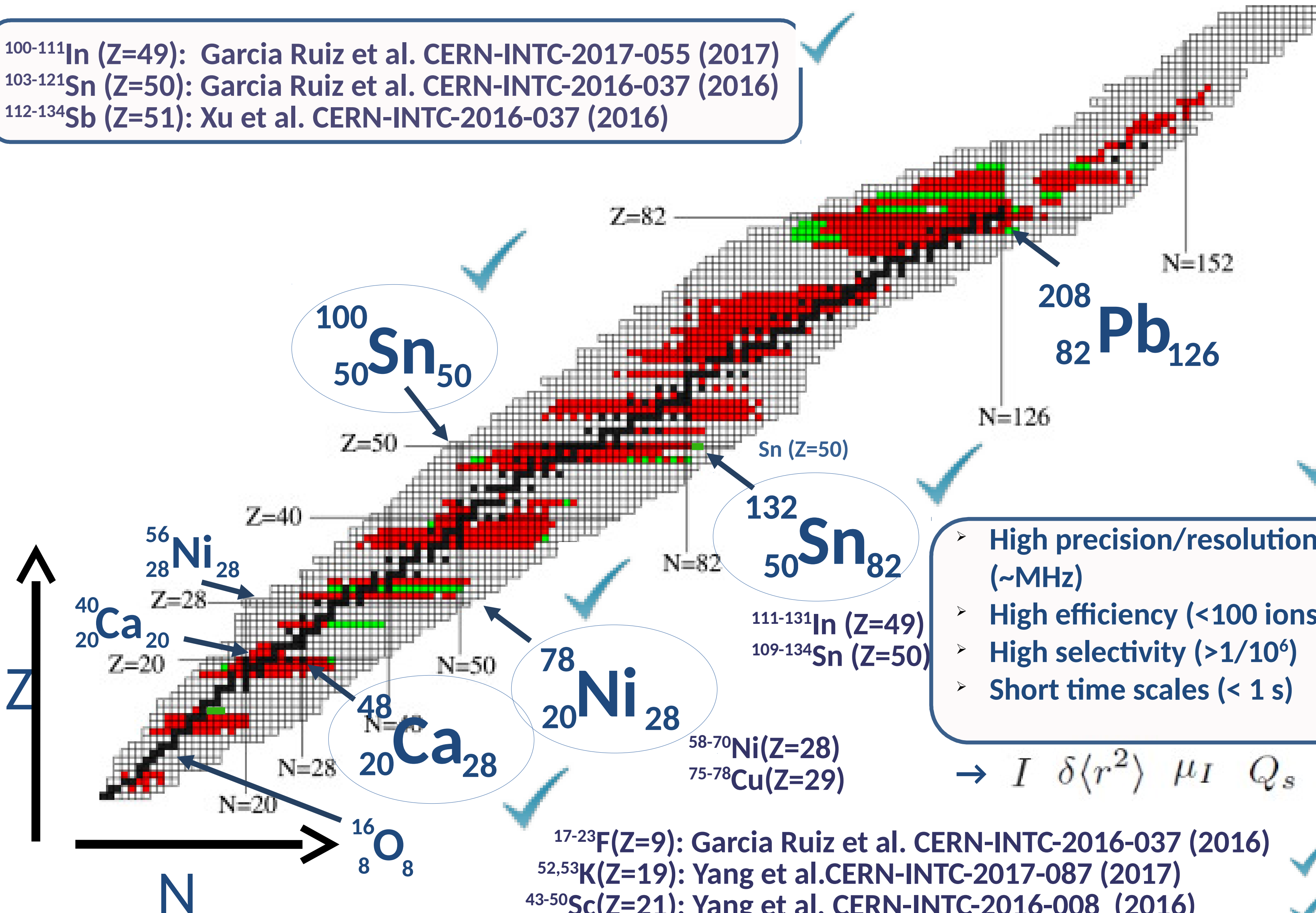


$$\nu_1^{AA'} \approx K_1 \mu_{AA'} + F_1 \delta \langle r^2 \rangle_{AA'} - \delta E_{\kappa=-1}^{AA'}$$

$$\delta E_\kappa \approx \frac{G_F^2}{4\pi^3} \frac{[(\kappa-\gamma)^2 + (Z\alpha)^2] Z (Z_i+1)^2}{(2-\gamma)\nu^3 R_{\rm nucl}^2 a_B^3} \times \frac{a_l Q_W}{[\Gamma(2\gamma+1)]^2} \left(\frac{a_B}{2ZR_{\rm nucl}}\right)^{2-2\gamma},$$

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)

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

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

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

$^{17-23}$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)

Summary and outlook

Laser spectroscopy + electron scattering

Nuclear Physics

→ To extract nuclear charge radii

→ Needed to provide firm conclusions of nuclear structure (Al, K, In...)

→ To obtain absolute radii to compare with nuclear theory (Ca, Ni, Sn,...)

Atomic Physics

→ Provide model independent F and M values

→ Test of electron correlations in atoms.

Fundamental Physics

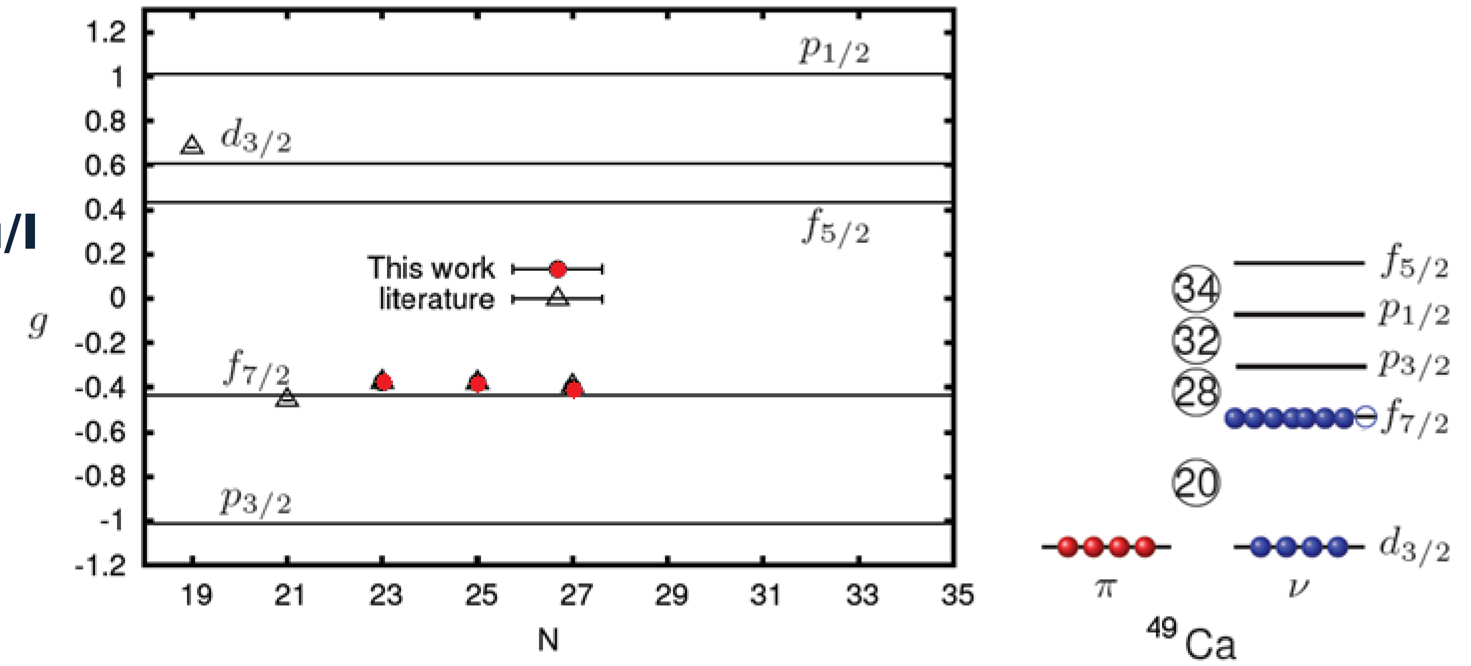
→ Constraint to new electron-nucleon interactions

$$\delta\nu^{A,A'} = K_{MS}\frac{M_{A'} - M_A}{M_{A'}M_A} + F\delta\langle r^2\rangle^{A,A'} + \left\{ \begin{array}{c} \text{Electromagnetic corrections} \\ + \\ \text{New nucleon-electron interactions} \end{array} \right.$$

Thanks for your attention!

EM: Ca(Z=20) isotopes

g=μ/I

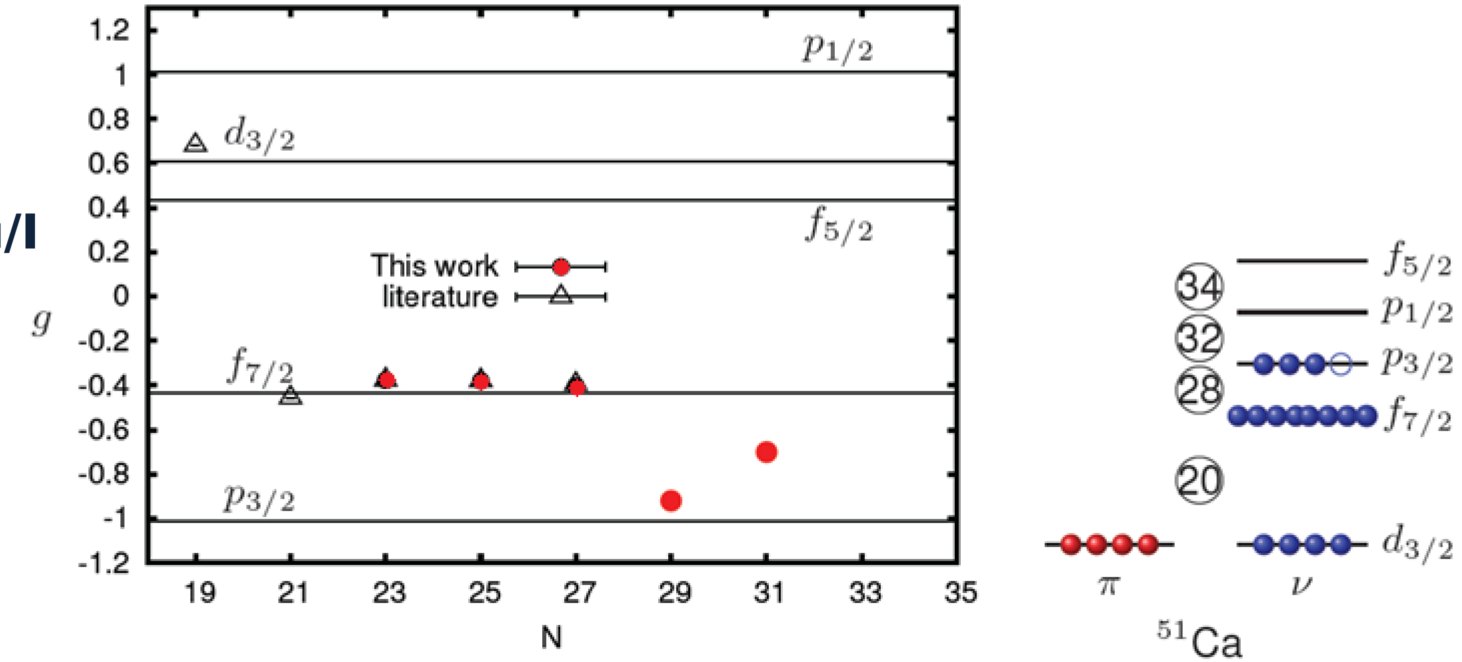


[R.F. Garcia Ruiz *et al.* PRC 91, 041304(R) (2015)]

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

EM: Ca(Z=20) isotopes

g=μ/I



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

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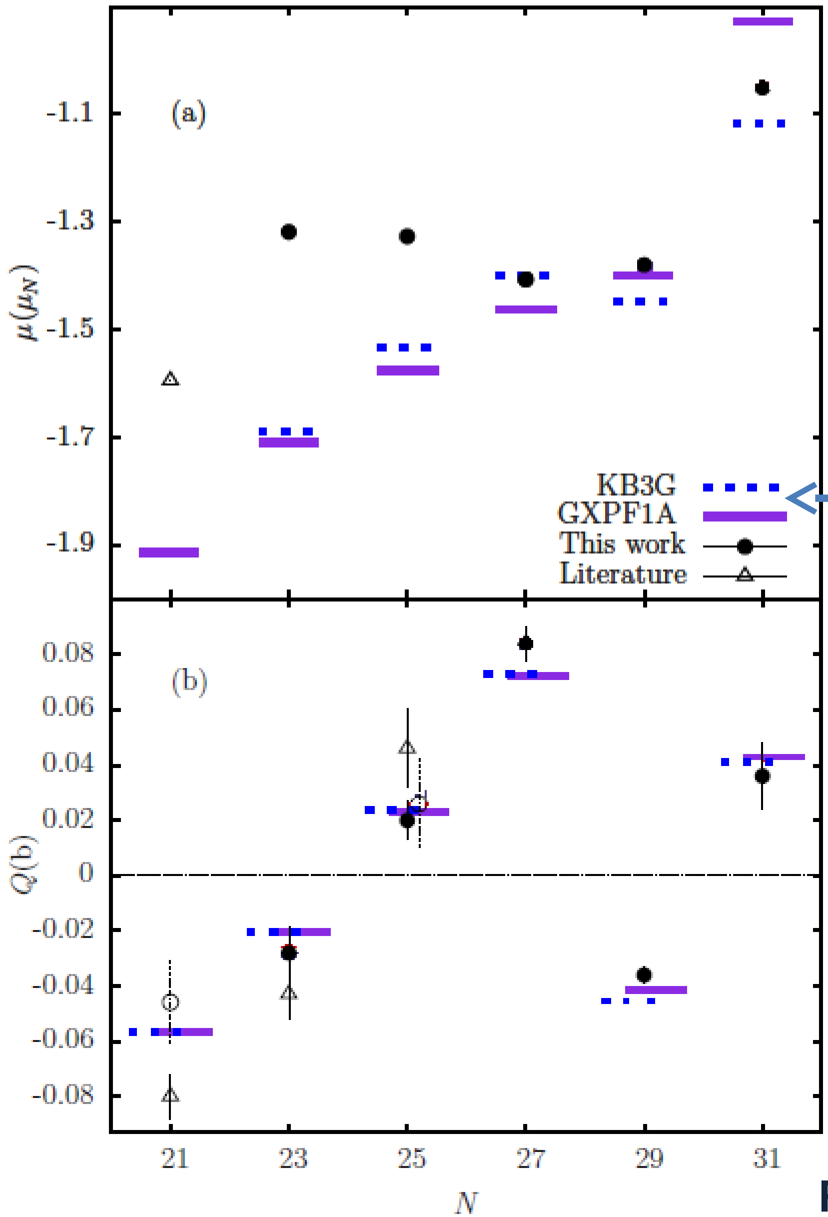


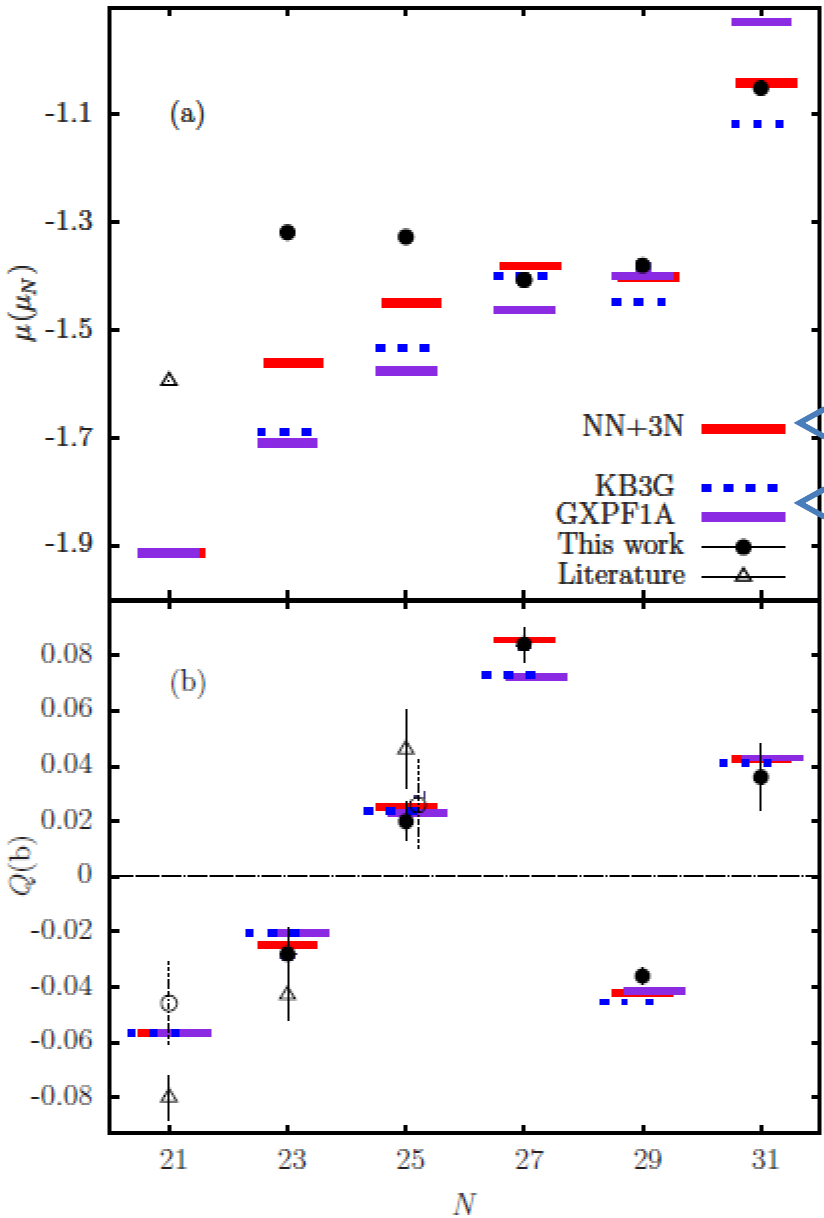
[R.F. Garcia Ruiz *et al.* PRC 91, 041304(R) (2015)]

Phenomenological interactions (^{40}Ca core)

NN interactions fitted to Ca region

Free g factors and effective charges (en=0.5, ep=1.5)

EM: Ca(Z=20) isotopes



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

NN+3N interactions fitted to A=3 systems

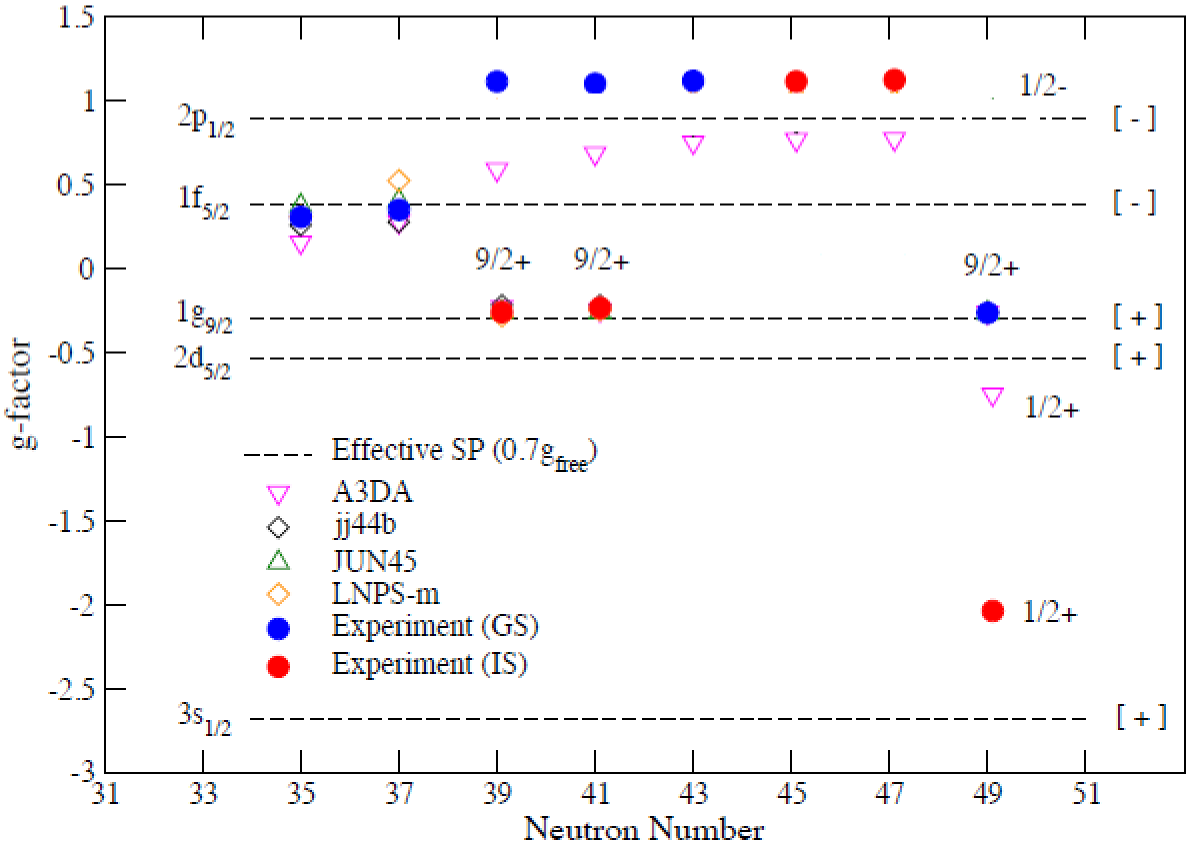
Microscopic interaction (ch-EFT) (^{40}Ca core)

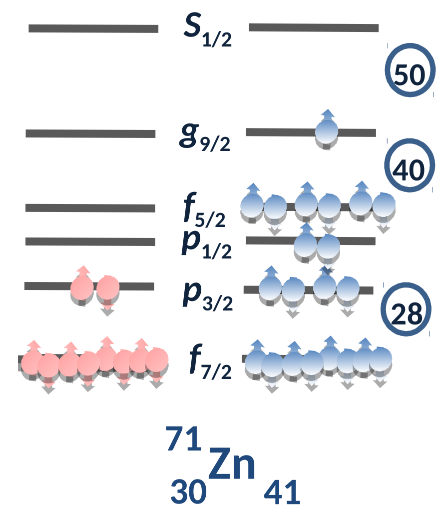
Phenomenological interactions (^{40}Ca core)

NN interactions fitted to Ca region

Free g factors and effective charges (en=0.5, ep=1.5)

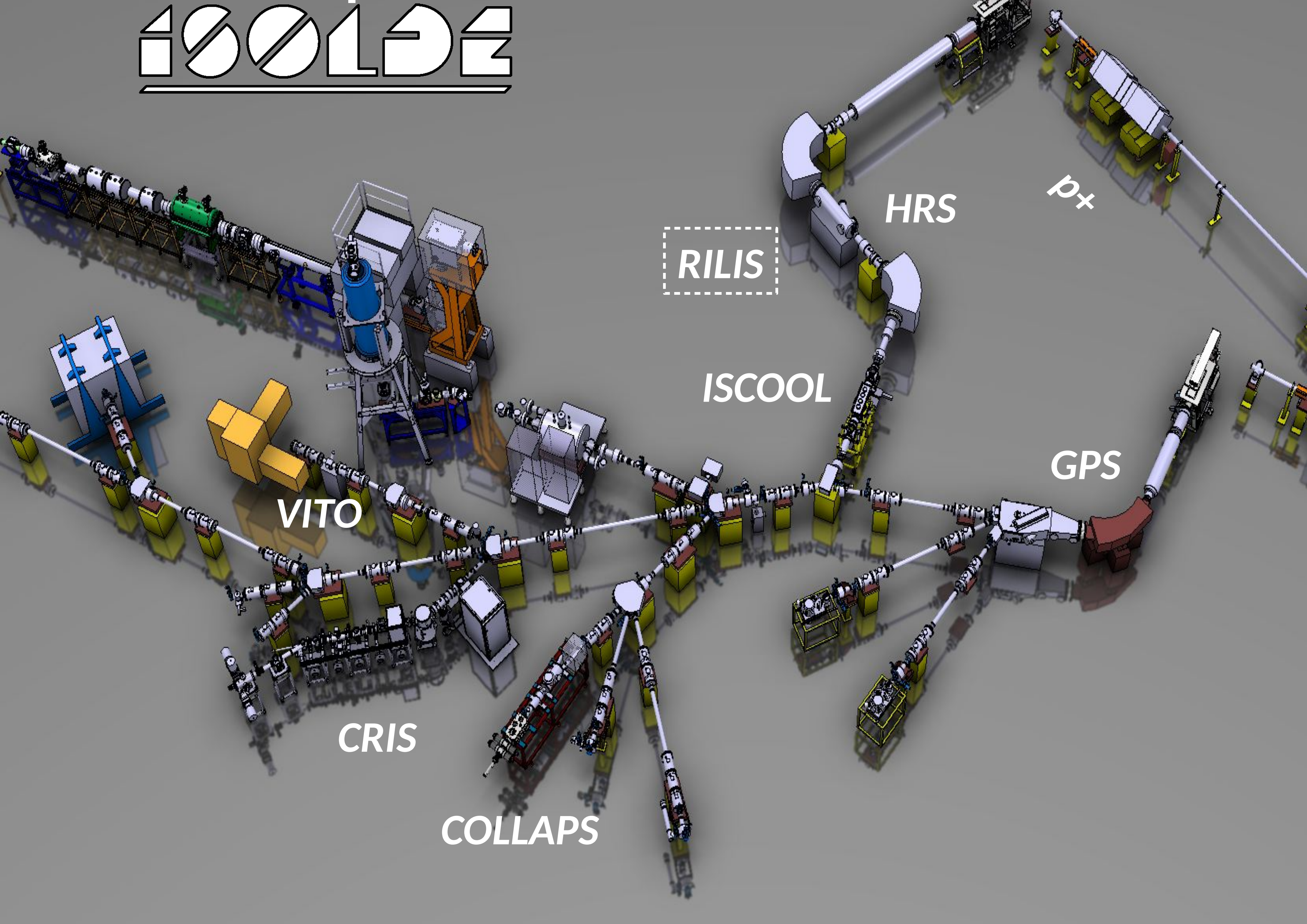
EM: Zinc (Z=30) isotopes



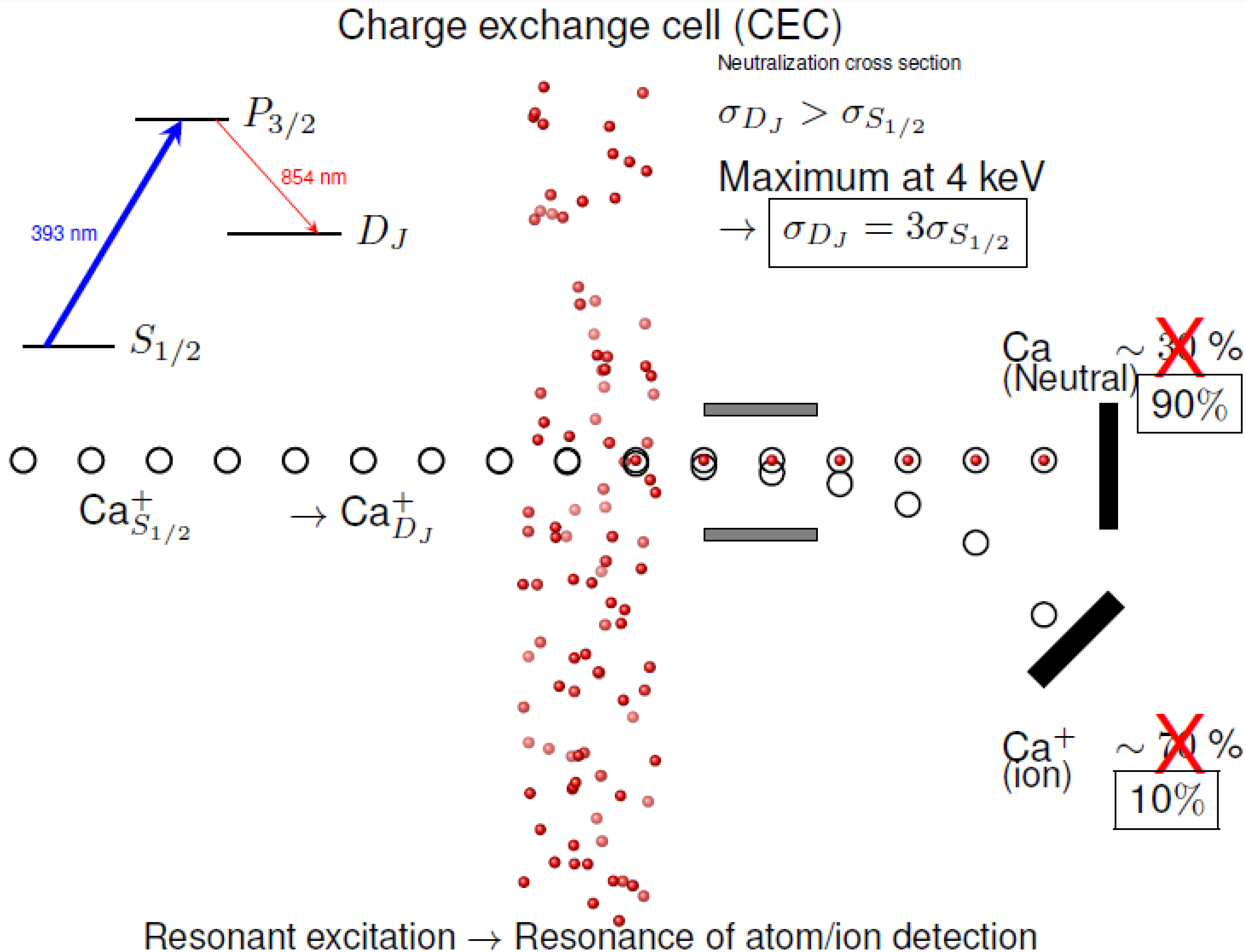


^{65,79}Zn(Z=30): Wraith et al. Phys. Lett. B 771, 385 (2017)

Development of CRIS at ISOLDE

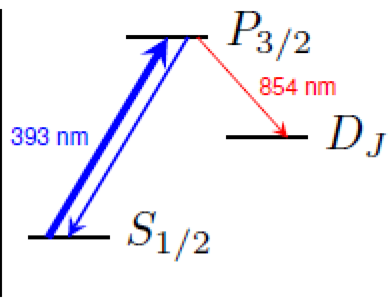


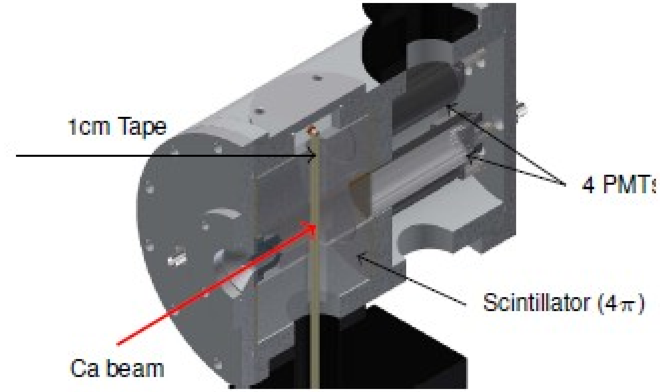
Optical pumping and state-selective neutralization

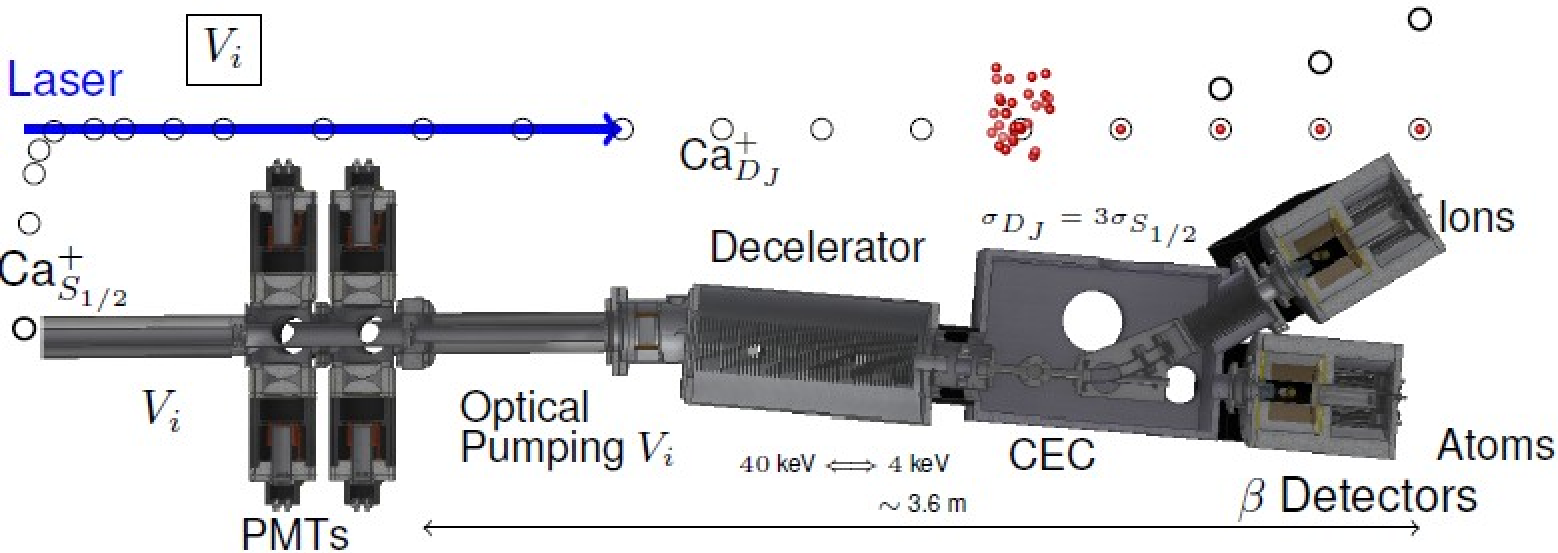


[R.F. Garcia Ruiz *et al*. J. Phys. G. 44, 044003 (2017)]

New experimental apparatus







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