Nuclear ground-state electrostatic properties

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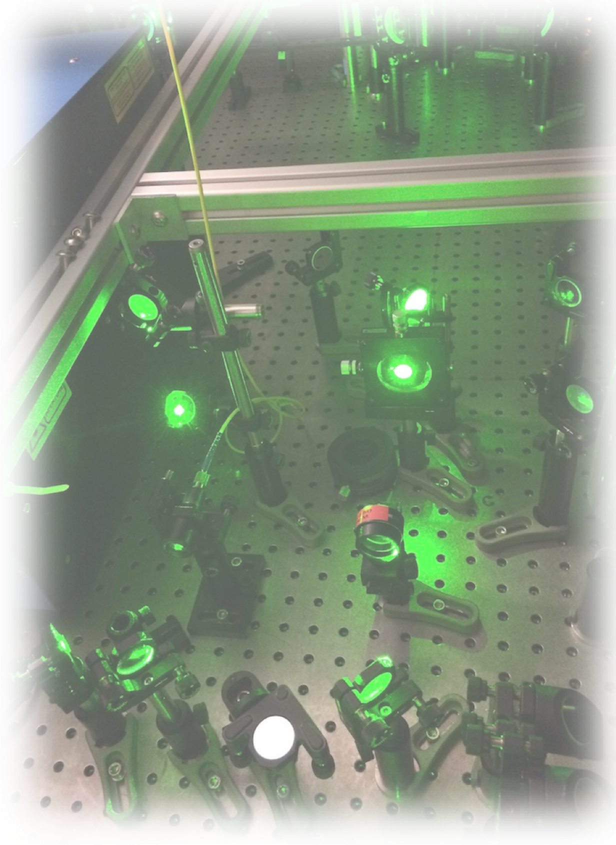


FNPMLS

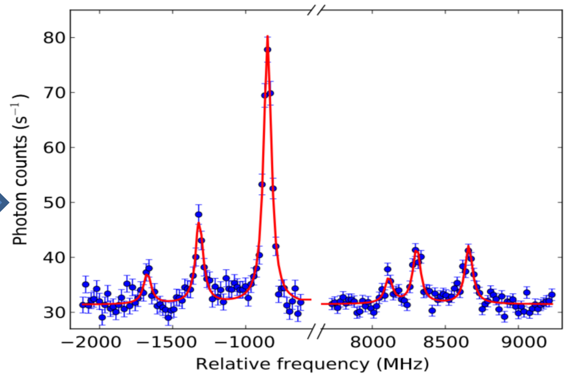
Overview

- Brief overview of laser spectroscopy
- Hyperfine structure and atomic physics consideratios
- Considerations for electromagnetic moments and connection with electro-weak currents
- Isotope shifts and charge radii as a test for inter-nucleon interactions and many-body methods
- Recent examples in the Ca, Ni and Sn regions
- Concluding remarks

Experimental Overview

Narrow bandwidth laser

Laser Spectroscopy

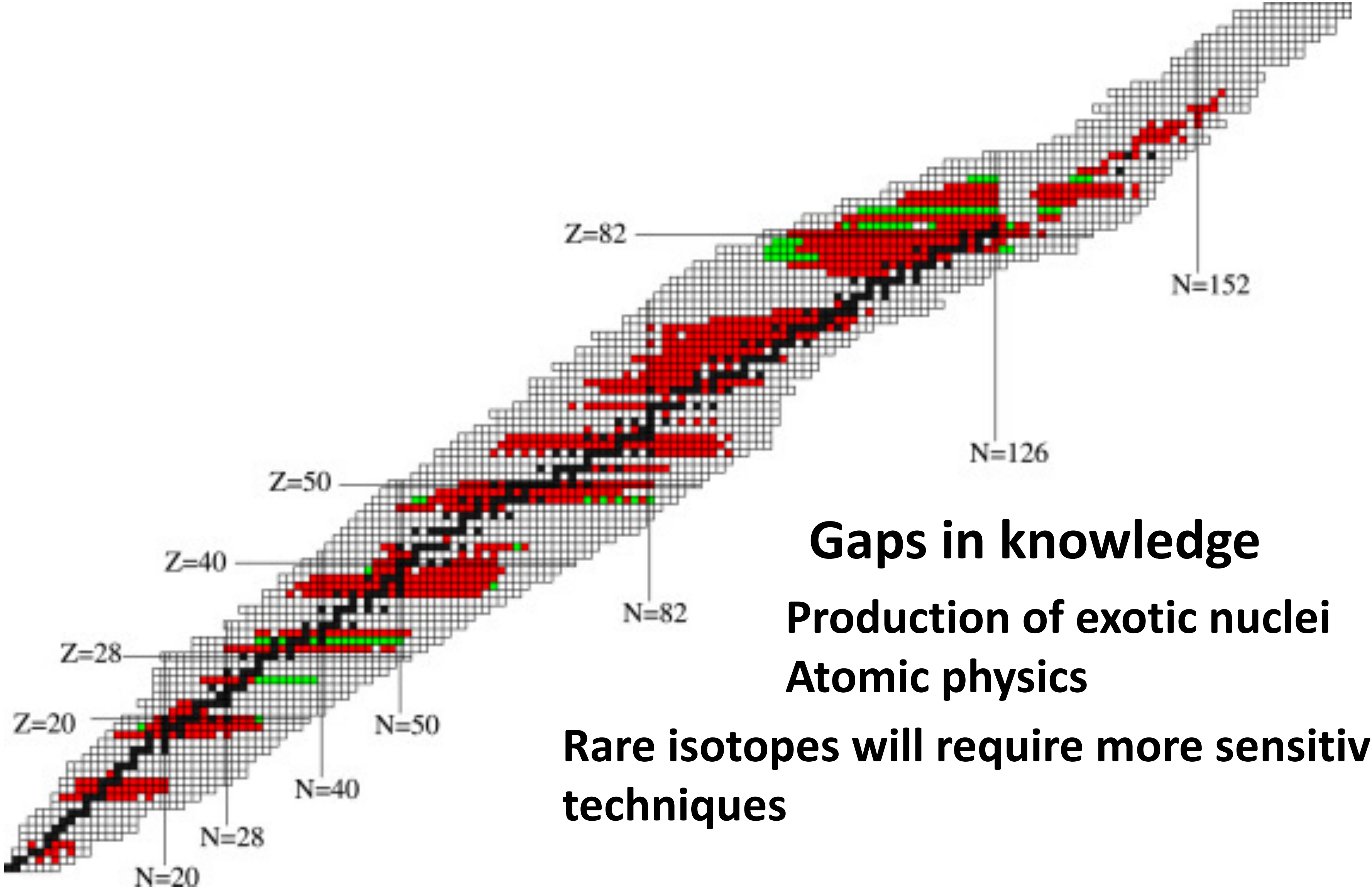


Atomic Physics

Radioactive ion beam

- Nuclear moments (magnetic dipole, electric quadrupole)
- Charge radii
- Spin
- Do not rely on assumptions of a particular nuclear model

Status of Laser spectroscopy: 2016



Gaps in knowledge

Production of exotic nuclei

Atomic physics

Rare isotopes will require more sensitive techniques

P. Campbell, I.D. Moore, M.R. Pearson, Progress in Particle and Nuclear Physics **86** (2016) p127

Laser Spectroscopy Requirements

Exotic nuclei at the limits of stability

Expected yields <<1 atom/second
Lifetimes <1s
Relatively large isobar contamination

Very little known low resolution ok

Technique :
Fast due to short half-lives
Highly selective due to isobars
Low yield requires a high sensitivity
Lower resolution is acceptable

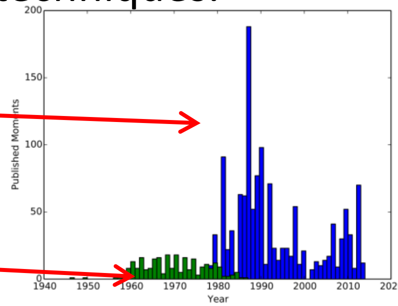
Near Stability Nuclei

Expected yields >10^8 atom/second
Lifetimes >>1s
High purity (large fraction of the beam)

Resolution/precision frontier

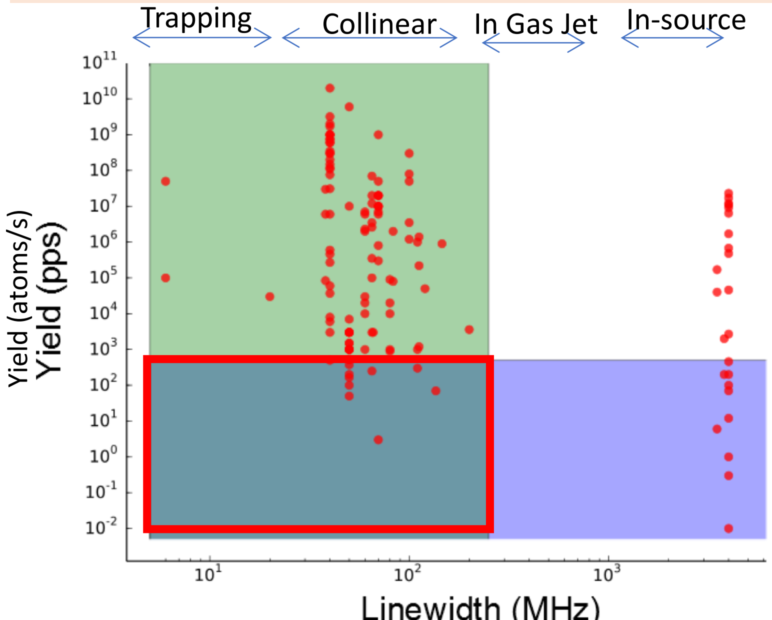
Technique :
New physics requires high resolution
Sensitivity is not critical
The method can be slow

Selection of published radioactive measurements (where yields are known)
Tempting to define experiments in a future laboratory with todays techniques.



Laser Spectroscopy

Atomic Beam Magnetic Resonance



Atomic Physics

- ○ Coupling of electrons to nuclear moments yields the hyperfine splitting

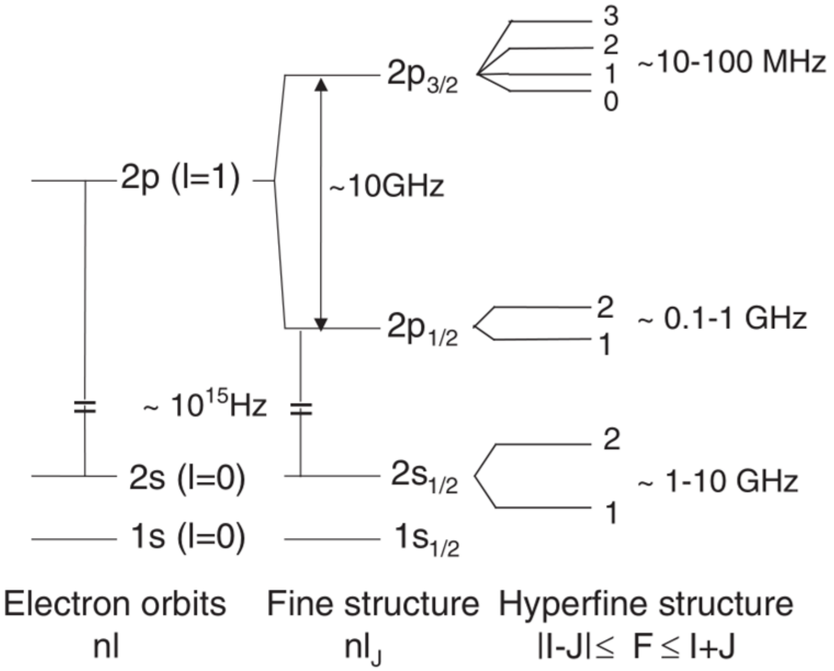
$$W^{(1)}_{F,J} \simeq W^{M1}_{F,J} + W^{E2}_{F,J},$$

$$W^{M1}_{F,J} = A_{hf}\mathbf{I}.\mathbf{J},$$

$$W^{E2}_{F,J} = B_{hf}\frac{3(\mathbf{I}.\mathbf{J})^2 + \frac{3}{2}(\mathbf{I}.\mathbf{J}) - I(I+1)J(J+1)}{2I(2I-1)J(2J-1)}$$

$$A_{hf} = g_I\mu_N\frac{\langle J||T_e^{(1)}||J\rangle}{\sqrt{J(J+1)(2J+1)}},$$

$$B_{hf} = 2Q\left[\frac{J(2J-1)}{(J+1)(2J+1)(2J+3)}\right]^{1/2}\langle J||T_e^{(2)}||J\rangle$$

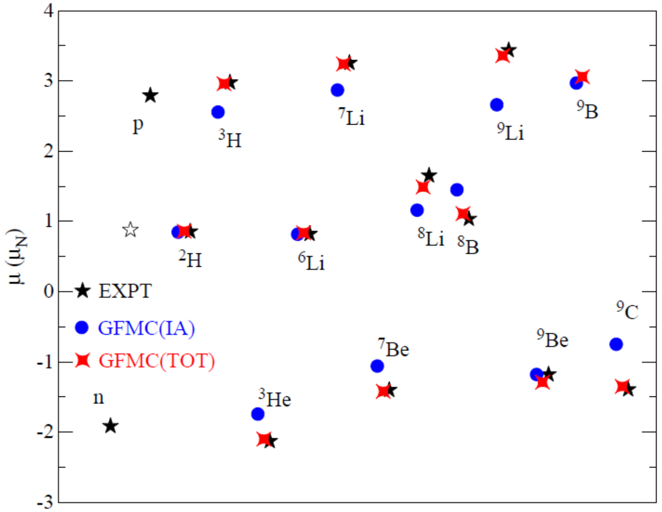


- The electronic operators are typically constant across an isotope chain.
- If a precise moment has been measured with another technique extraction is trivial.
- Reference measurement is often the limit on the absolute precision.
- More precise atomic physics calculations required in many regions of the nuclear chart

Electromagnetic moments

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

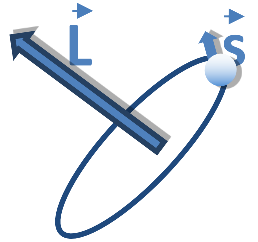
Ab-initio calculations (QMC)



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

Impulse approximation (IA):

$$\hat{\mu} = \frac{\mu_N}{\hbar}\left(\sum_i^A g_L^i \hat{L}^i + \sum_i^A g_S^i \hat{S}^i\right) \qquad Q_2 = e\sum_{i=1}^{A} g_L^{(i)} \mathbf{r}_i^2 P_2(\theta_i)$$



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

- ***Ground-state spins are essential for our understanding of nuclear structure***
- ***Charge radii provides a test to inter-nucleon interactions and many-body methods***
  [Hagen et al, Nature Physics 12, 186 (2016)] [Garcia Ruiz et al, Nature Physics 12, 594 (2016)]
- ***Electromagnetic moments are sensitive probes to the role of electro-weak currents***
  [Pastore et al. PRC 87, 035503 (2013)] [Carlson et al. Rev. Mod. Phys. 87, 1067 (2015)]
  [Ekstrom et al. PRL 113, 262504 (2014)]

Electromagnetic moments

$$\rho_c(r) = \sum_i \rho_{c,i}(r) + \xcancel{\sum_{i<j} \rho_{c,ij}(r) + \sum_{i<j<k} \rho_{c,ijk}(r) + \ldots,}$$

$$j(r) = \sum_i j_i(r) + \xcancel{\sum_{i<j} j_{ij}(r) + \sum_{i<j<k} j_{ijk}(r) + \ldots.}$$

Impulse approximation (IA):

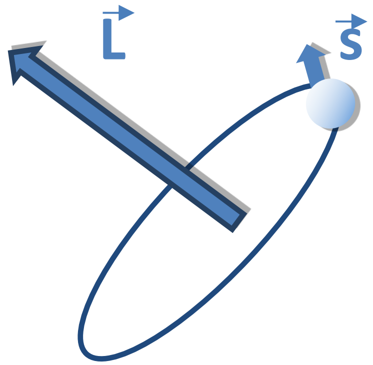
Magnetic moment

$$\mu \equiv \langle I, m = I \mid \mathbf{M}_1 \mid I, m = I \rangle$$

$$\mathbf{M}_1 = \sum_i (g_L^{(i)} \mathbf{L}_i + g_S^{(i)} \sigma_i)$$

$$\text{for an odd proton:} \begin{cases} \mu = j - \frac{1}{2} + \mu_p & \text{for } j = l + \frac{1}{2} \\ \mu = \dfrac{j}{j+1}\left(j + \dfrac{3}{2} - \mu_p\right) & \text{for } j = l - \frac{1}{2} \end{cases}$$

$$\text{for an odd neutron:} \begin{cases} \mu = \mu_n & \text{for } j = l + \frac{1}{2} \\ \mu = -\dfrac{j}{j+1}\mu_n & \text{for } j = l - \frac{1}{2} \end{cases}$$

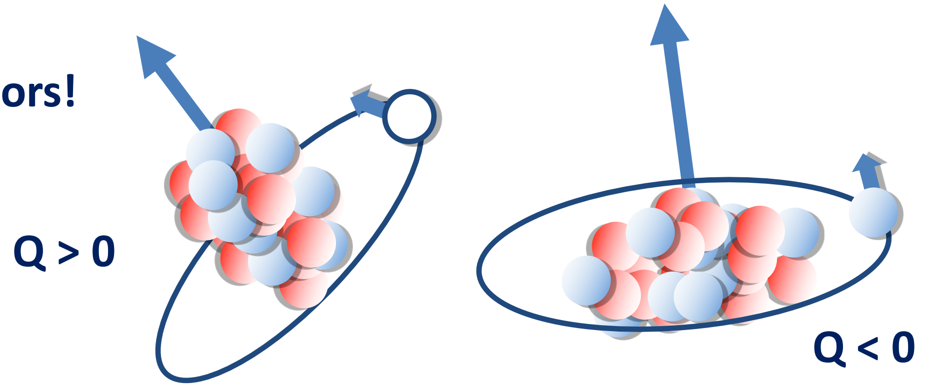


Quadrupole moment

Effective operators!

$$Q \equiv \langle I, m = I \mid \mathbf{Q}_2 \mid I, m = I \rangle$$

$$\mathbf{Q}_2 = e \sum_{i=1}^{A} g_L^{(i)} \mathbf{r}_i^2 P_2(\theta_i)$$



$$\langle Q \rangle(n_0) = \langle Q_{\mathrm{sp}} \rangle \left[\frac{-2(j - n_0) - 1}{2j - 1}\right] \qquad \langle Q \rangle(n) = \langle Q_{\mathrm{sp}} \rangle \left[\frac{2(j - n) + 1}{2j - 1}\right]$$

$$Q_{\mathrm{s.p.}} = -e_j \frac{2j - 1}{2j + 2} \langle r_j^2 \rangle$$

Effective moments:

H. Miyazawa, Prog. Theor. Phys. (1951) 6 (5): 801-814.

Magnetic moments near closed shells

Magnetic moment of ^{207}Tl

R Neugart Phys. Rev. Lett. 55 (15), 1559 (1984)

$$\boldsymbol{\mu}_{\mathrm{eff}} = (g_s + \delta g_s)\mathbf{s} + (g_l + \delta g_l)\mathbf{l} + g_p[\mathbf{s} \times \mathbf{Y}^2]^{(1)}$$

- For simple systems +/- nucleon outside of a closed shell the effective magnetic moment can be written as above.
- Spin and orbital g-factors are free nucleon values and δg_s and δg_l arise from both core polarization and meson exchange (final term arises due to dipole-dipole interaction)
- Special case of isotopes with a nucleon in a $s_{1/2}$ state outside a double magic nucleus (^{3}He, ^{3}H and ^{207}Tl) where tensor and orbital term vanish.

- Makes ^{23}O especially interesting!

General comments

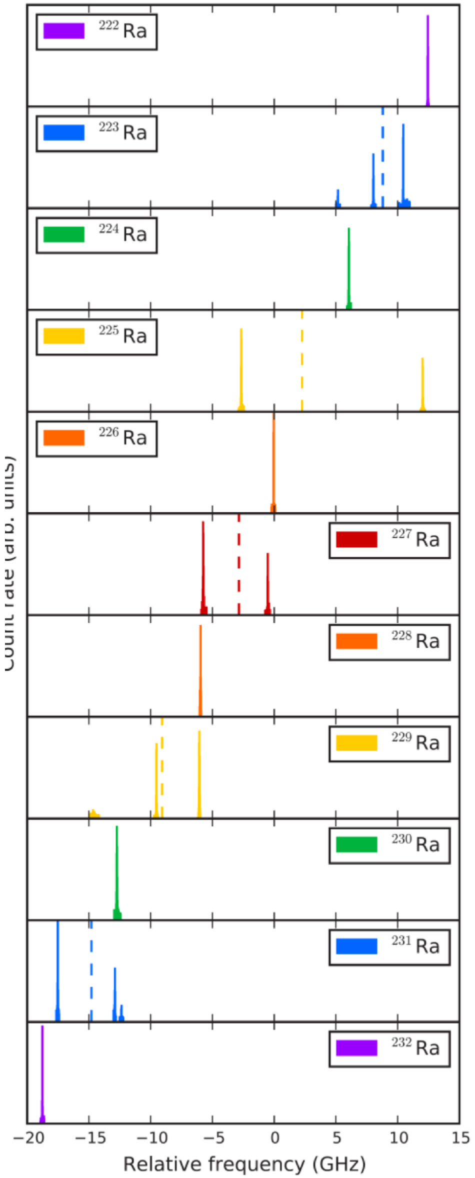
- There are inconsistent uses of effective g-factors and effective charges. For each region are different, calcium (gfree), others in the region g_eff=0,7 gfree. For the Ni region people seems to use 0.7, and for heavier nuclei lower values. Tin region ~0.6....

- Majority of theoretical results, come from shell model and single particle interpretations. They seem to give a good (surprisingly very good) descriptions of the trends, but the quenching is not understood.

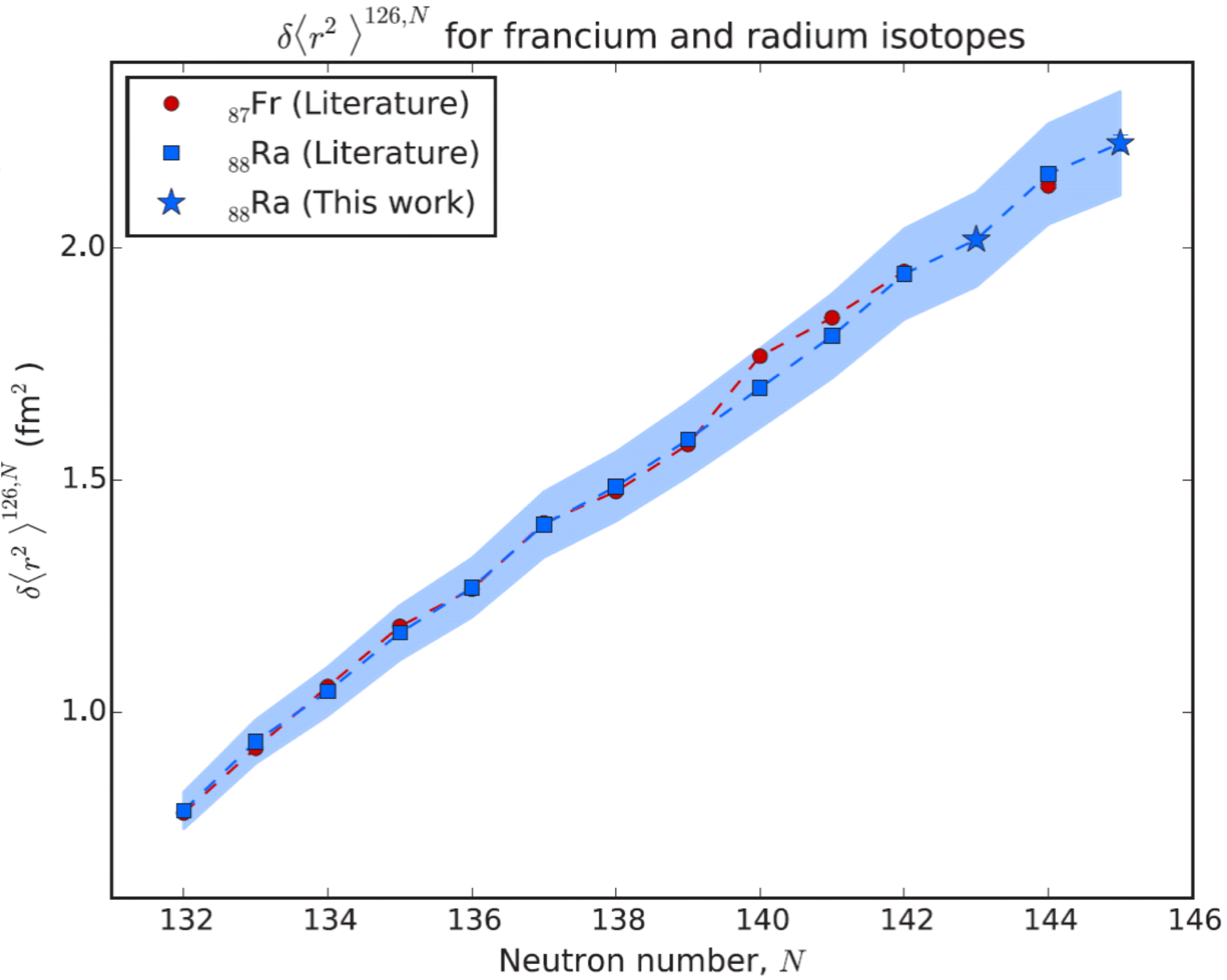
- That the contributions to the operators (two body currents ~ MEC) are unknown in medium and heavy mass nuclei.

- Some phenomenological work has been done by Stone, Towner on extending the one-body operator.

Charge radii from isotope shift measurements



$$\delta\nu^{A,A'} = \delta\nu_{\mathrm{FS}}^{A,A'} + \delta\nu_{\mathrm{MS}}^{A,A'}$$



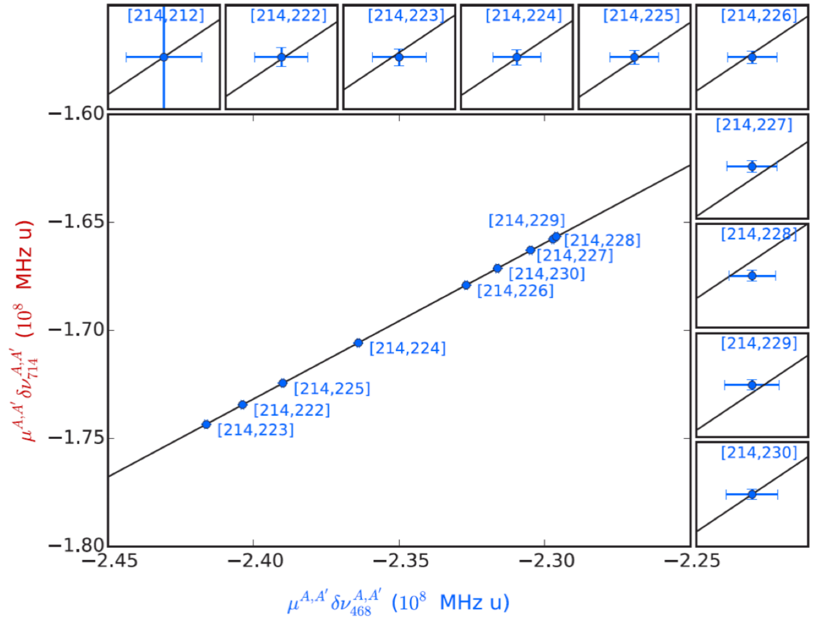
Charge radii from isotope shift measurements

$$\delta\nu^{A,A'} = \delta\nu_{\mathrm{FS}}^{A,A'} + \delta\nu_{\mathrm{MS}}^{A,A'} \qquad \delta\nu_{\mathrm{FS}}^{A,A'} = F\lambda^{A,A'}$$

$$\lambda^{A,A'} = \delta\langle r^2\rangle^{A,A'} + \frac{C_2}{C_1}\delta\langle r^4\rangle^{A,A'} + \frac{C_3}{C_1}\delta\langle r^6\rangle^{A,A'} + \dots$$

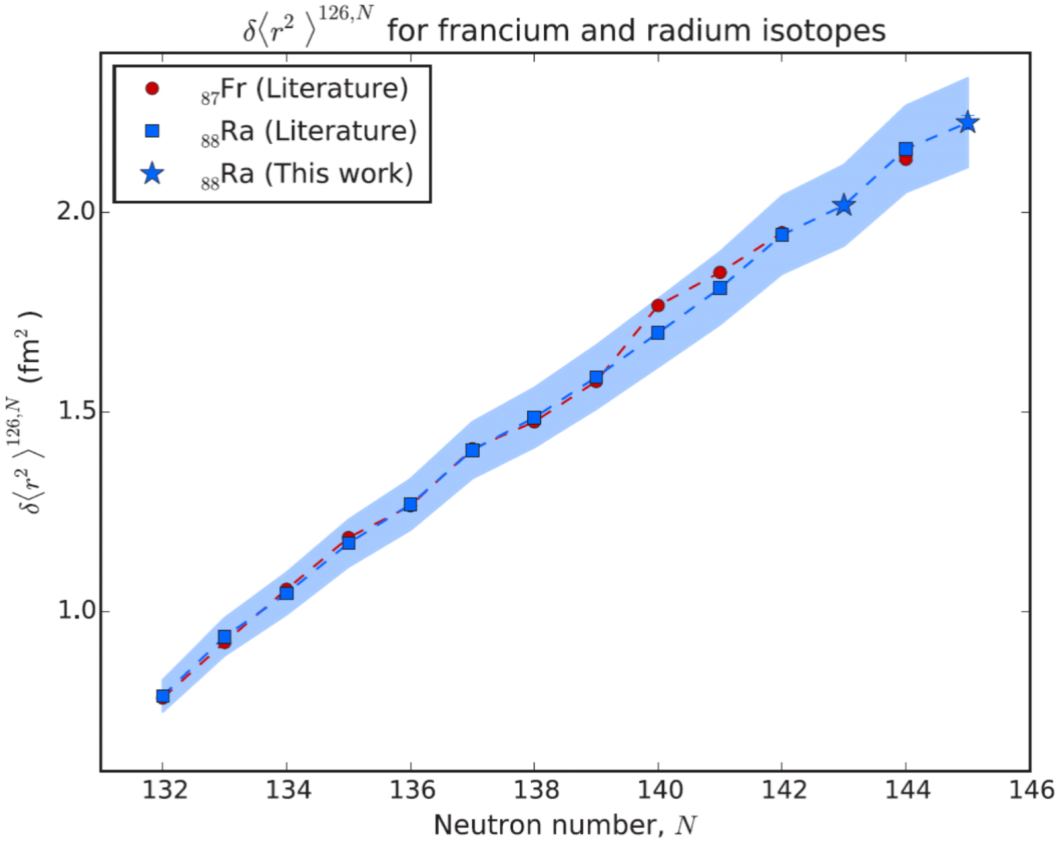
Mass shift includes term associated with electron correlations within the atomic system and nontrivial to calculate.

King plot method



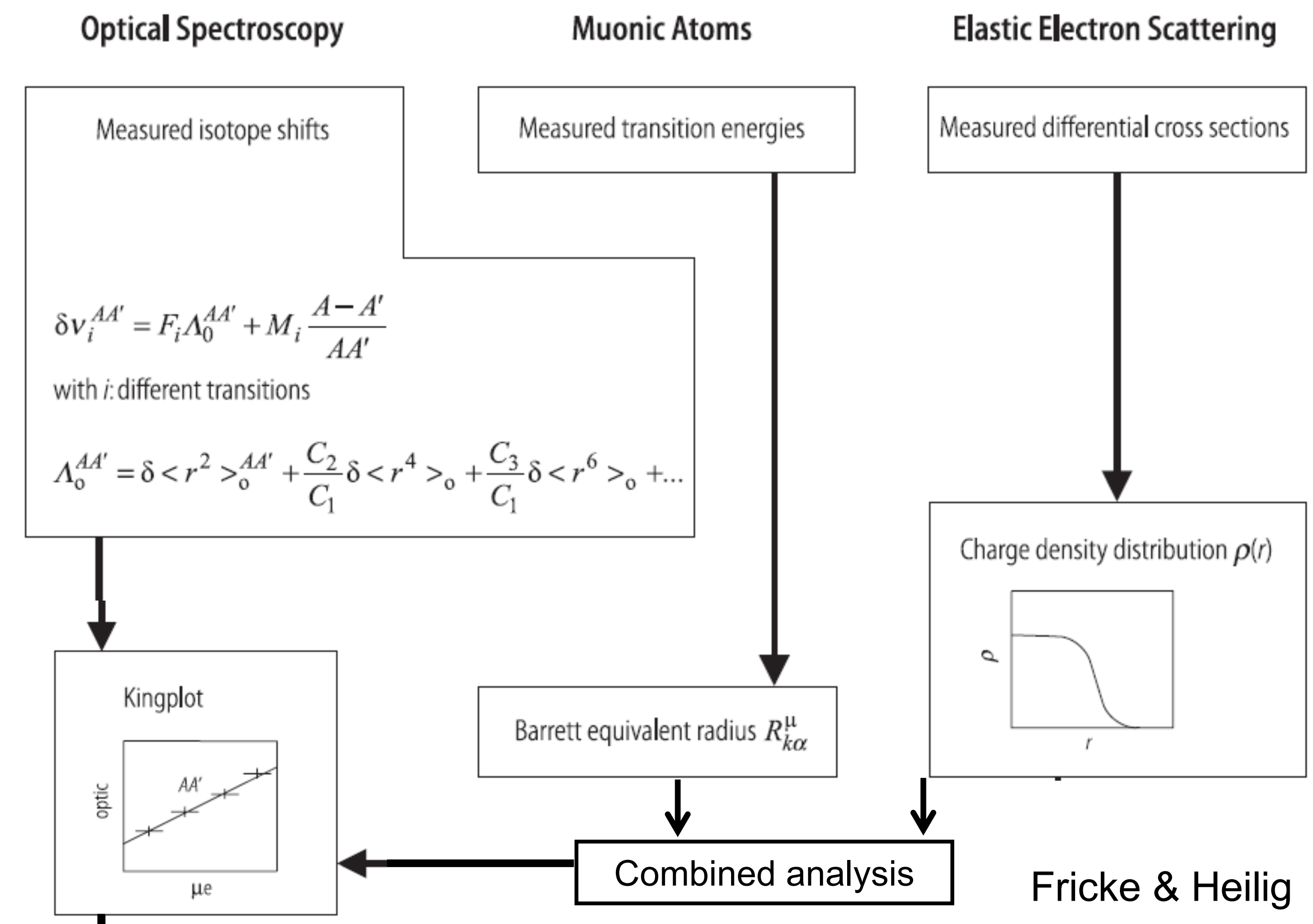
$$\delta\nu_{714}^{A,A'} = F_{714}\delta\langle r^2\rangle^{A,A'} + M_{714}\frac{A'-A}{AA'}$$

$$\mu^{A,A'}\delta\nu_{714}^{A,A'} = \frac{F_{714}}{F_{468}}\mu^{A,A'}\delta\nu_{468}^{A,A'} + M_{714} - \frac{F_{714}}{F_{468}}M_{468}$$



KM Lynch et al. Physical Review C 97 (2), 024309

General Approach



Optical Spectroscopy

Muonic Atoms

Elastic Electron Scattering

Measured isotope shifts

$$\delta\nu_i^{AA'} = F_i \Lambda_0^{AA'} + M_i \frac{A-A'}{AA'}$$

with *i*: different transitions

$$\Lambda_0^{AA'} = \delta < r^2 >_0^{AA'} + \frac{C_2}{C_1}\delta < r^4 >_0 + \frac{C_3}{C_1}\delta < r^6 >_0 + \dots$$

Measured transition energies

Measured differential cross sections

Charge density distribution $\rho(r)$

Barrett equivalent radius $R_{k\alpha}^{\mu}$

Kingplot

Combined analysis

Requires long chains where measurements exist across many isotopes.
Typically challenging for for odd-Z cases and everything beyond Pb.

Fricke & Heilig *Nuclear Charge Radii* (Springer 2004)

Analysis of stable isotopes

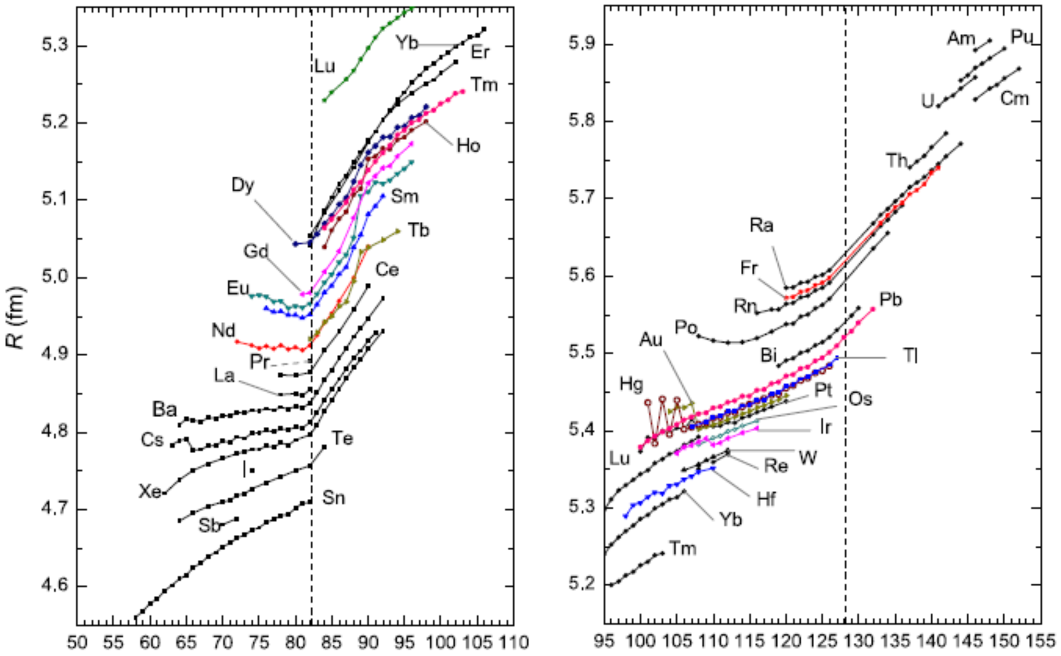
Result: F_i and M_i providing $\delta<r^2>$ for all isotopes (including radioactive)

MANCHESTER 1824

The University of Manchester

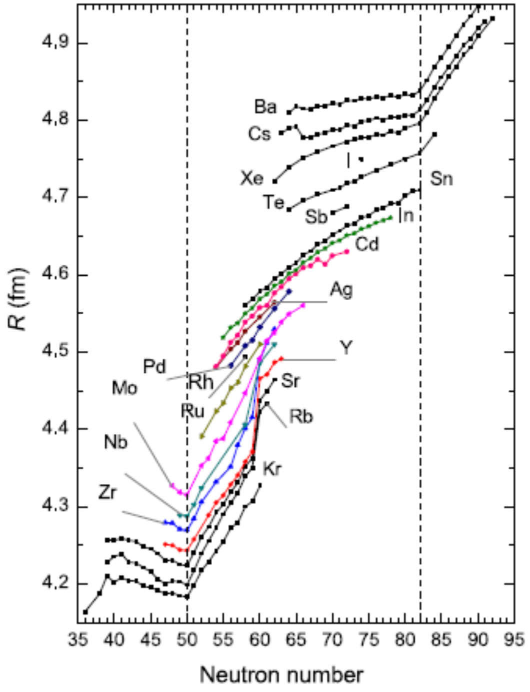
rms nuclear charge radii, *including radioisotopes*, for medium mass and heavy elements

Angeli & Marinova
Atomic Data and Nuclear Data Tables 99 (2013) 69



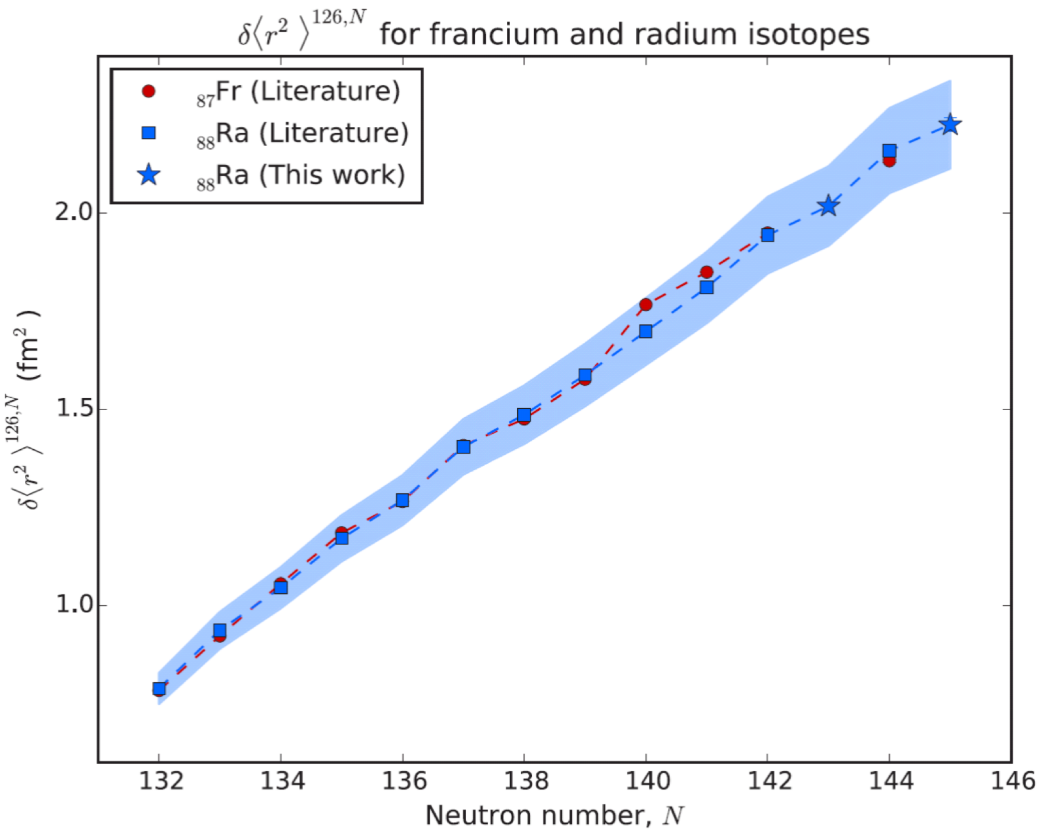
Features:

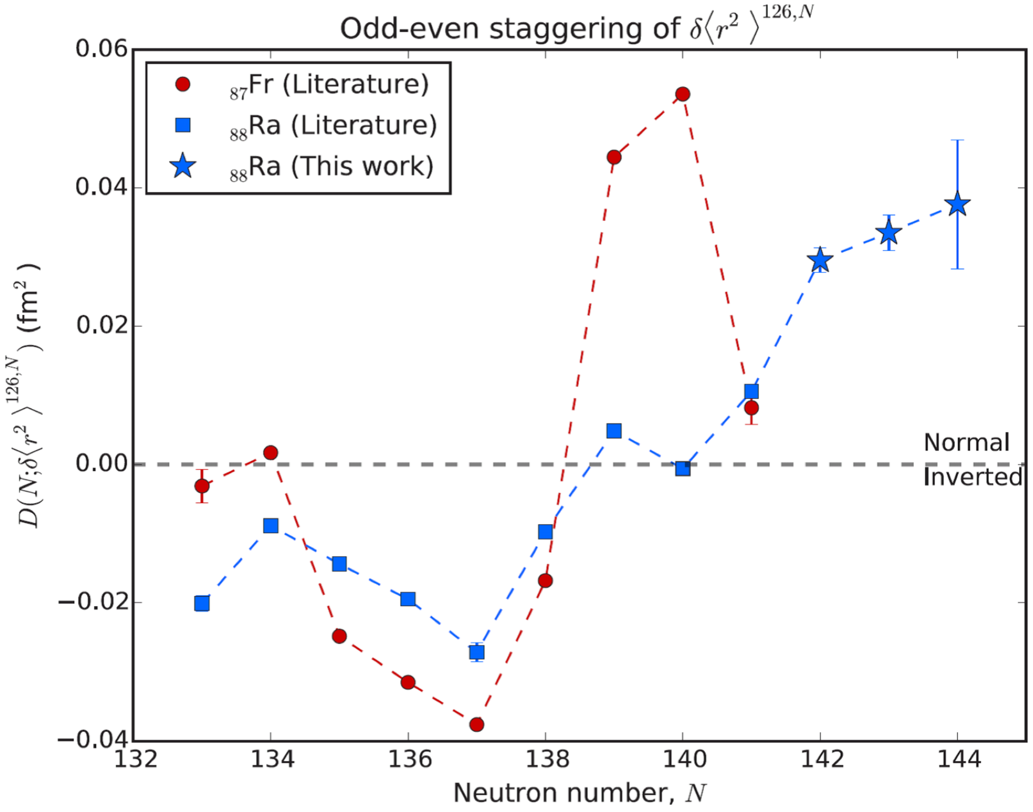
- Kinks at closed neutron shells
- Regular odd-even staggering (sometimes reversed due to nuclear structure effects)
- Obvious shape effects (Light Hg, N=60…)
- Radii of isotopes increase at ~half rate of $1.2A^{1/3}$ fermi (neutron rich nuclei develop neutron skin)



Odd even staggering within region of reflection asymmetry

$$D(N;\delta\langle r^2\rangle^{126,N}) = (-1)^N(\delta\langle r^2\rangle^{126,N} - \tfrac{1}{2}(\delta\langle r^2\rangle^{126,N-1} + \delta\langle r^2\rangle^{126,N+1}))$$

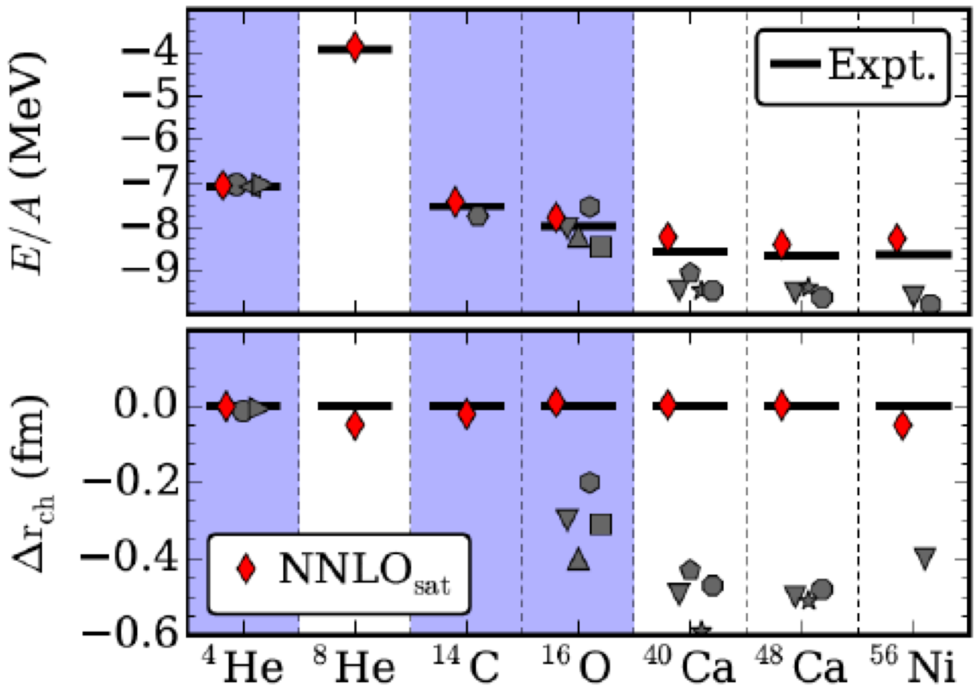

$\delta\langle r^2\rangle^{126,N}$ for francium and radium isotopes


Odd-even staggering of $\delta\langle r^2\rangle^{126,N}$

KM Lynch et al. Physical Review C 97 (2), 024309

Charge radii: A challenge for nuclear theory

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

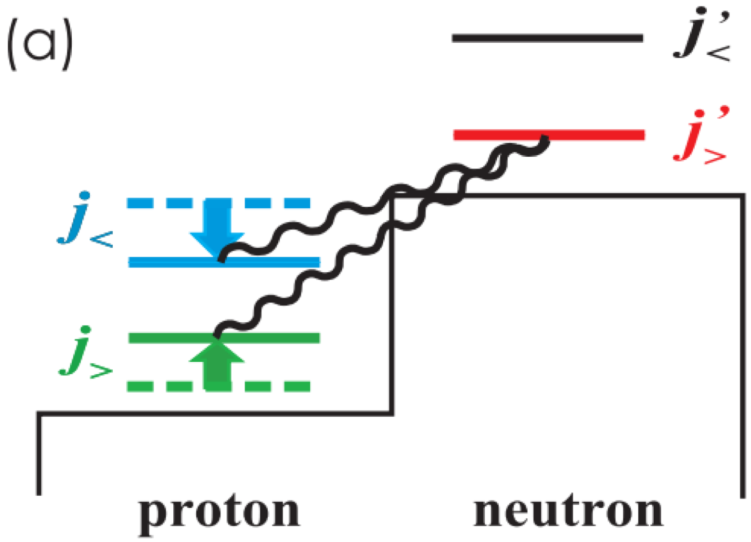


- ● **Phys. Rev. Lett. 99 042501 (2007)**
- ▼ **Phys. Lett. B 736 119 (2014)**
- ▲ **Phys. Rev. Lett. 112 102501 (2014)**
- ◀ **Phys. Rev. Lett. 109 252501 (2012)**
- ▶ **Phys. Rev. C 90 014314 (2014)**
- ⬢ **Phys. Rev. Lett. 94 212501 (2005)**
- ■ **Phys. Rev. Lett. 108 242501 (2012)**
- ⬟ **Phys. Rev. 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)**

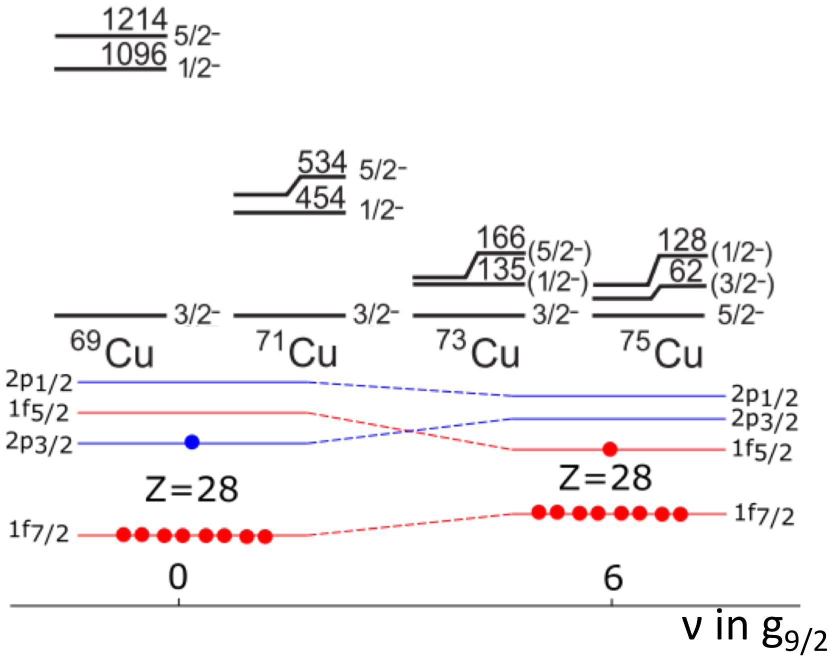
[Hagen et al. 2016]

Shell evolution of fission fragments: Ni region

- Nucleon-nucleon interaction: single-particle energies evolve as function of nucleons in an orbit
- Away from stability, this can lead to (dis)appearance of shell closures
- Cu chain: *Z*=29: probe for the magicity of *Z*=28 and *N*=28,40,50

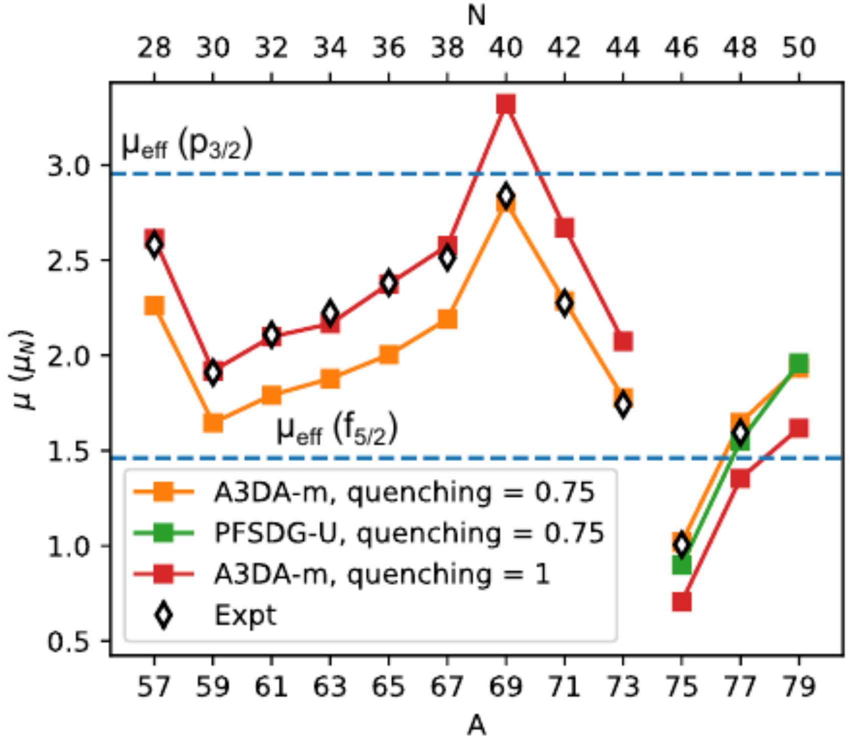


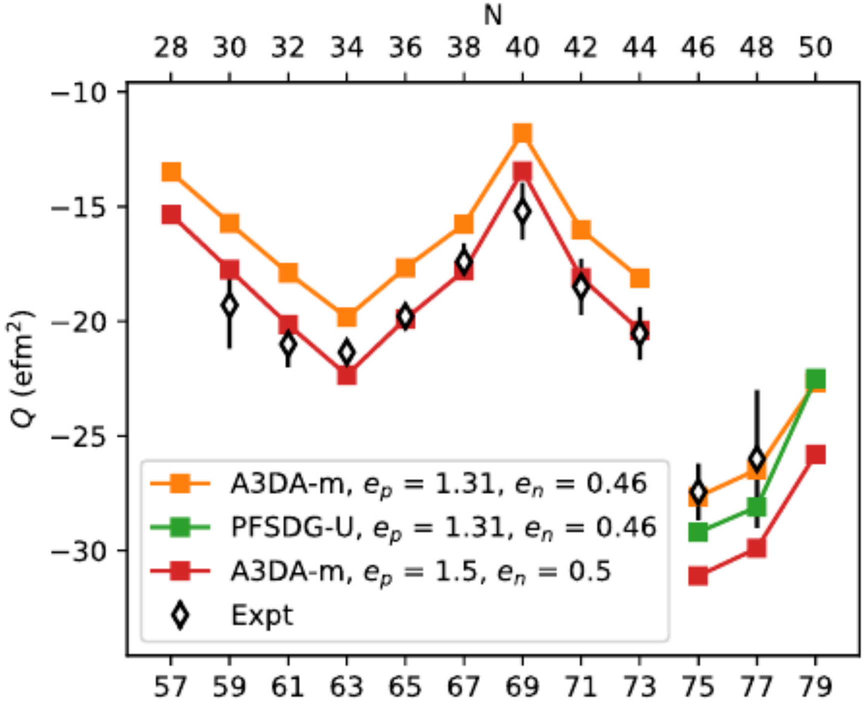
T. Otsuka et al, PRL **104**, 012501 (2010)

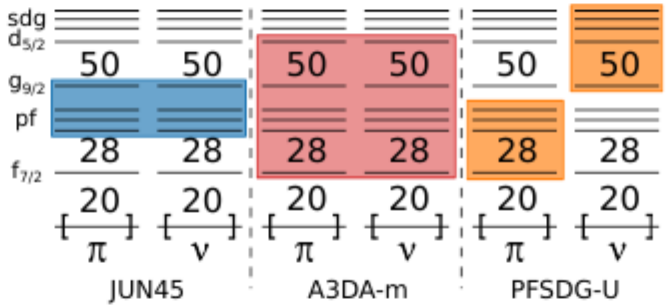


K.T. Flanagan et al, PRL **103**, 142501, 2009

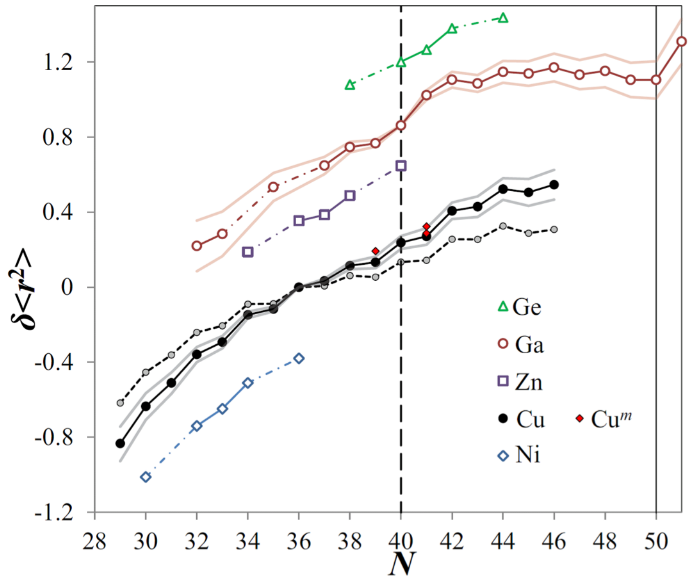
Results: Copper isotopes around ^{78}Ni







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

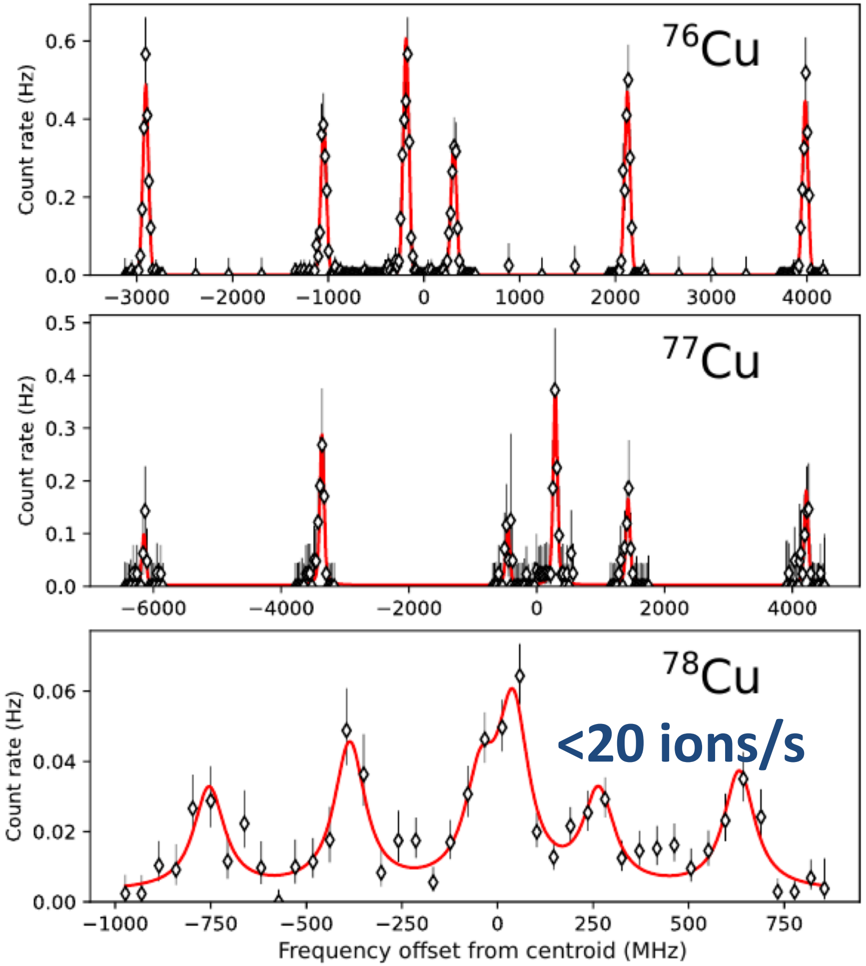


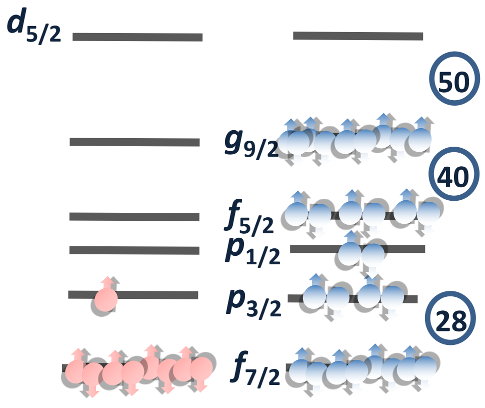
ML Bissell et al, Phys Rev C 93 064318 (2016)

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

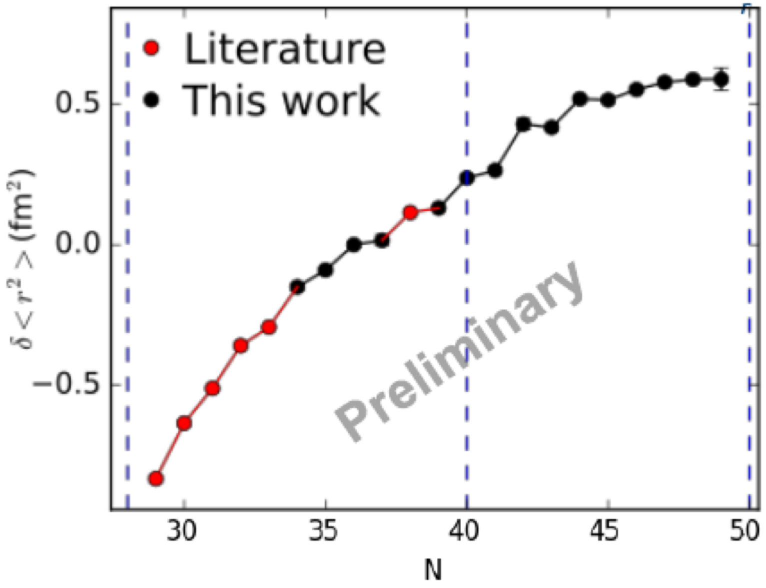
Dipole and quadrupole moments of $^{73\text{-}78}$Cu as a test of the robustness of the Z = 28 shell closure near ^{78}Ni

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





$^{78}_{29}\text{Cu}_{49}$



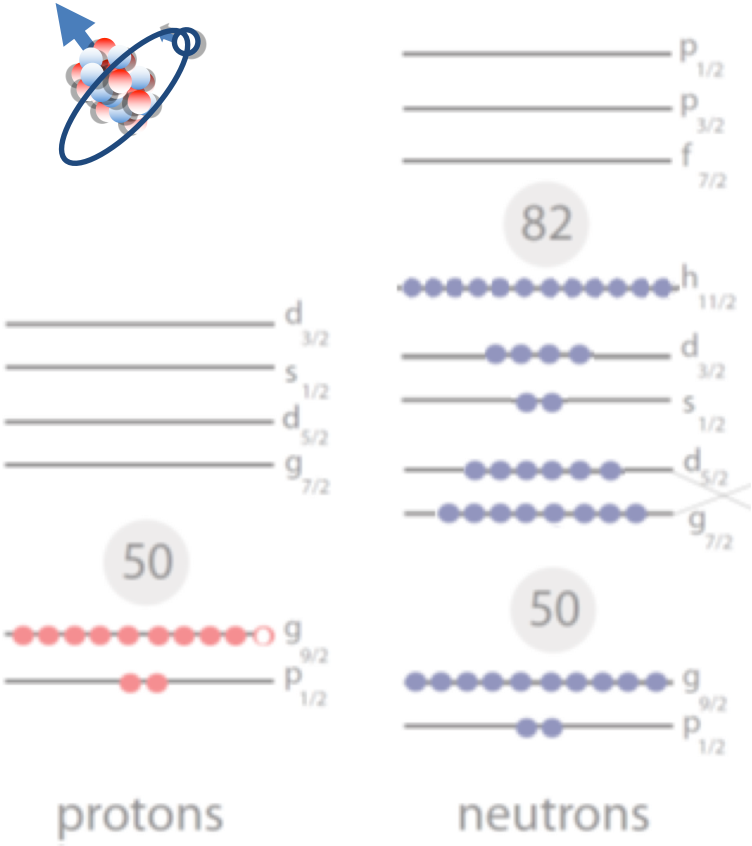
[In preparation (2018)]

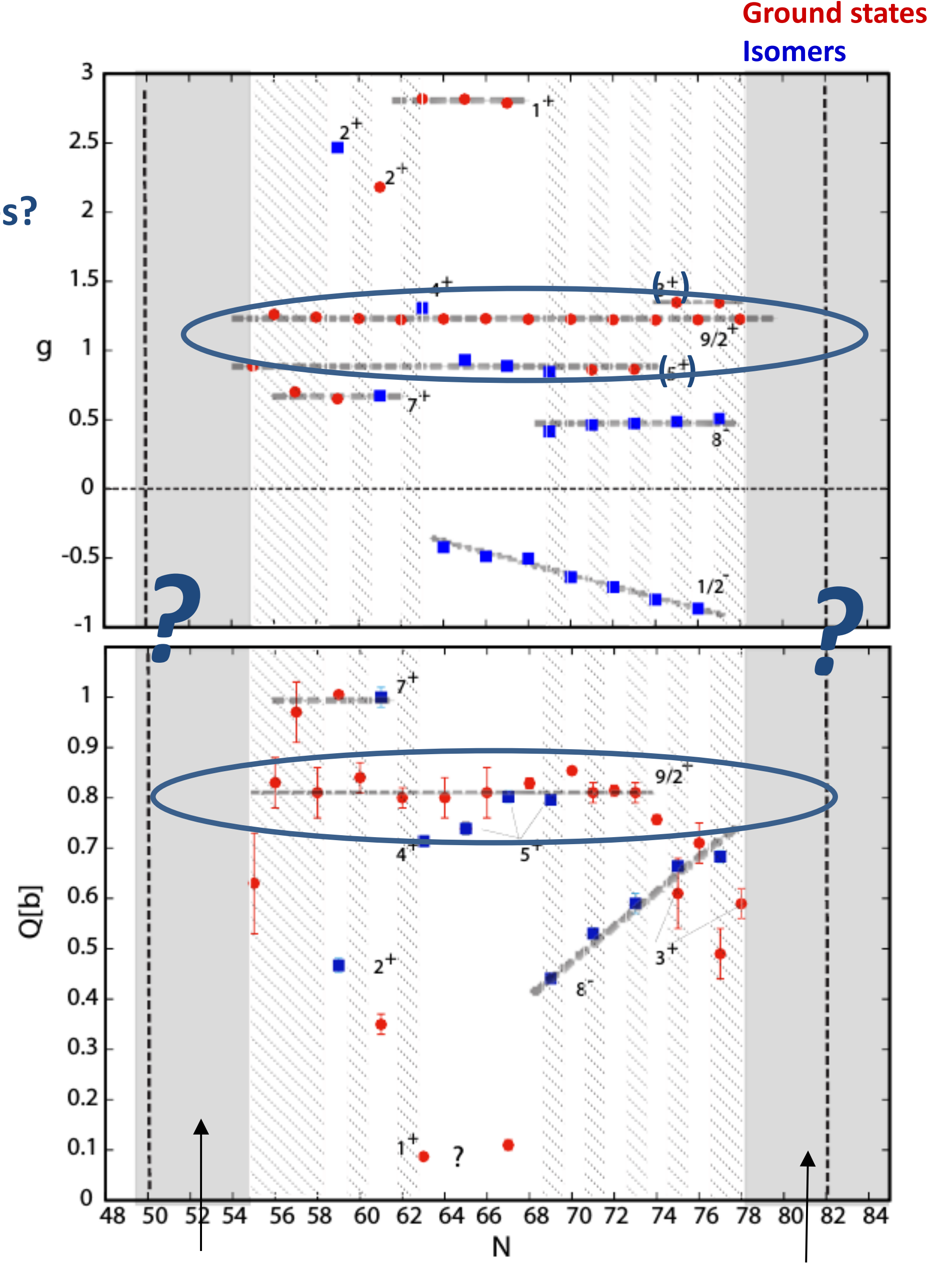
Charge radii and electromagnetic moments

Evolution of collectivity / single particle

- ○ Single particle behavior of g9/2 hole
- ○ p1/2 state particularly sensitive to MEC
- ○ approaching the N=Z=50 and N=82 shell closures?

- ○ Role of correlations across N=Z=50 and N=82?



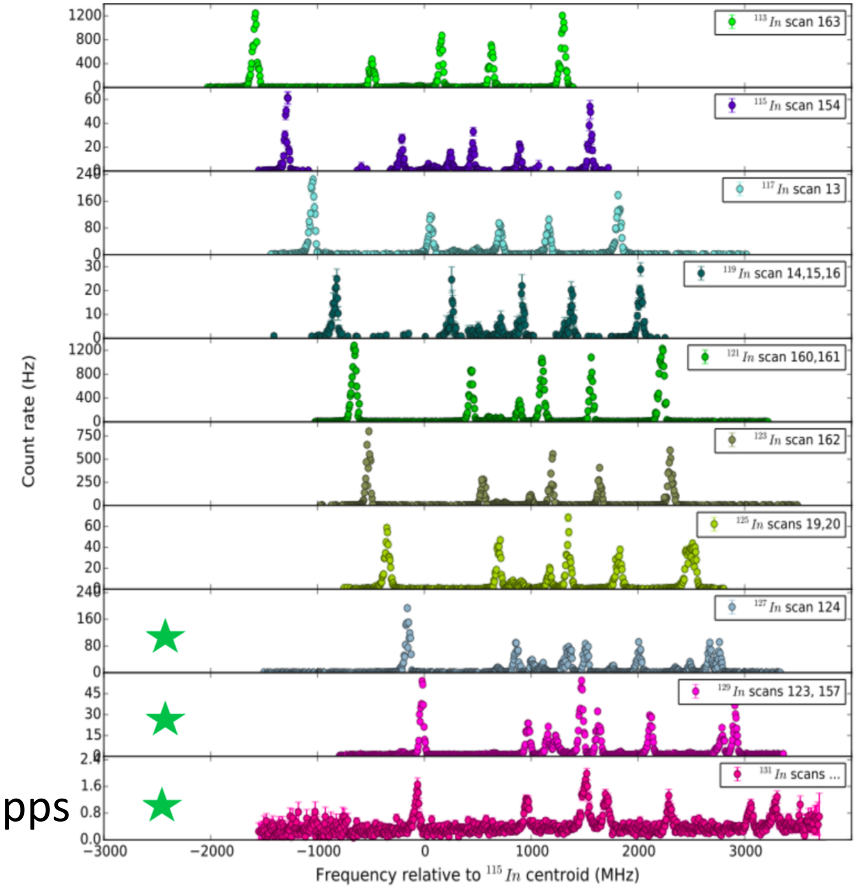


Unknown around N=50 and N=82!

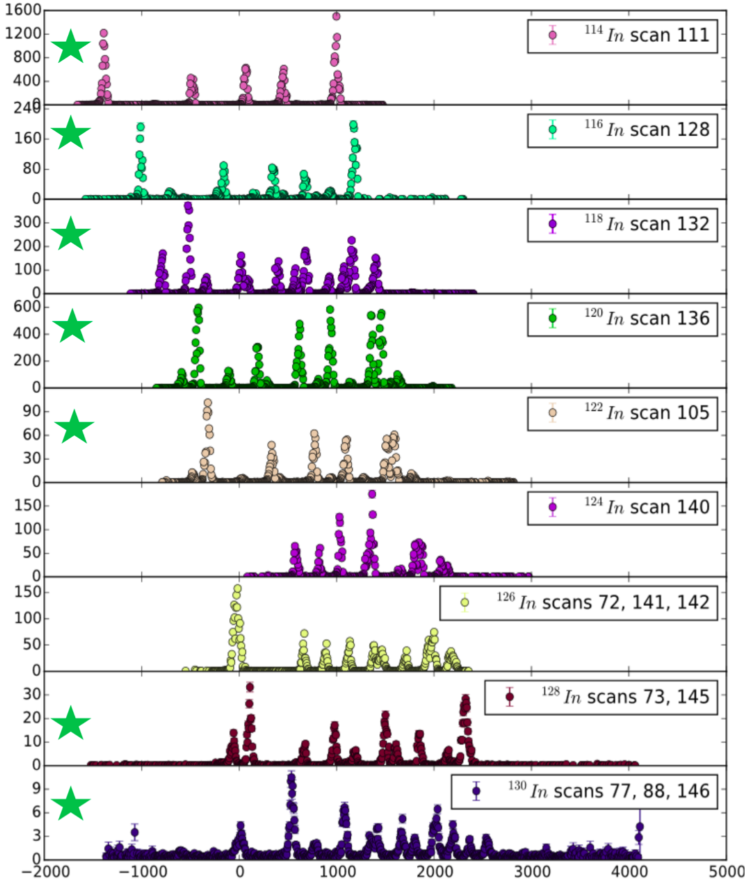
May 2017

(**New results** ★)

From ^{113}In up to ^{131}In

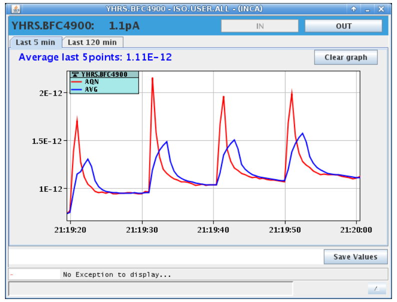


~500 pps



~5000 pps

Isobaric contamination at A=130,131 significantly larger than previous experiments in this region. A=131 3 pA (10^7 pps)


YHRS.BFC4900 - ISO.USER.ALL - (INCA)

YHRS.BFC4900: 1.1pA

Average last 5points: 1.11E-12

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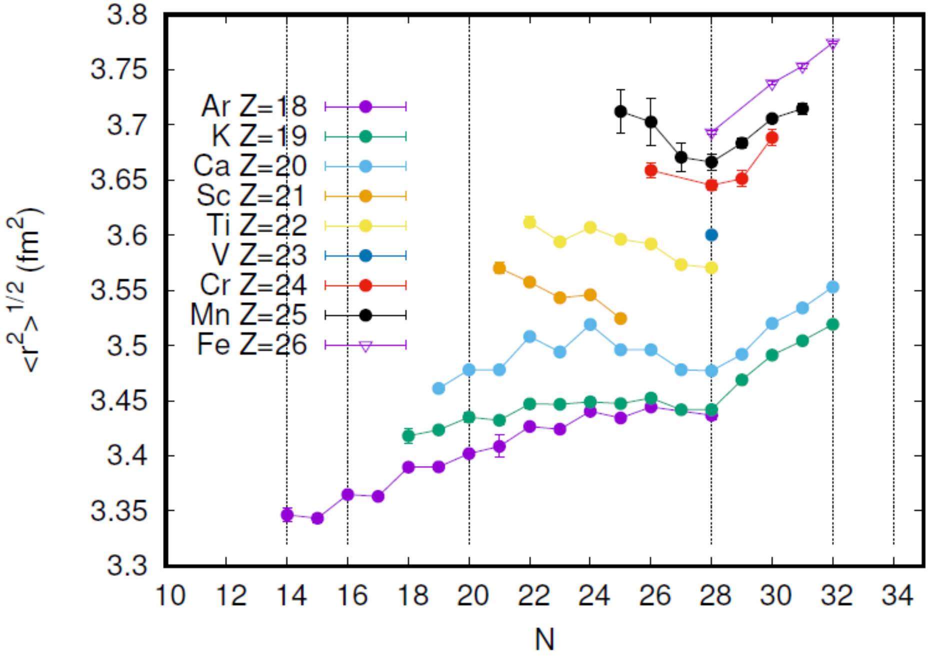
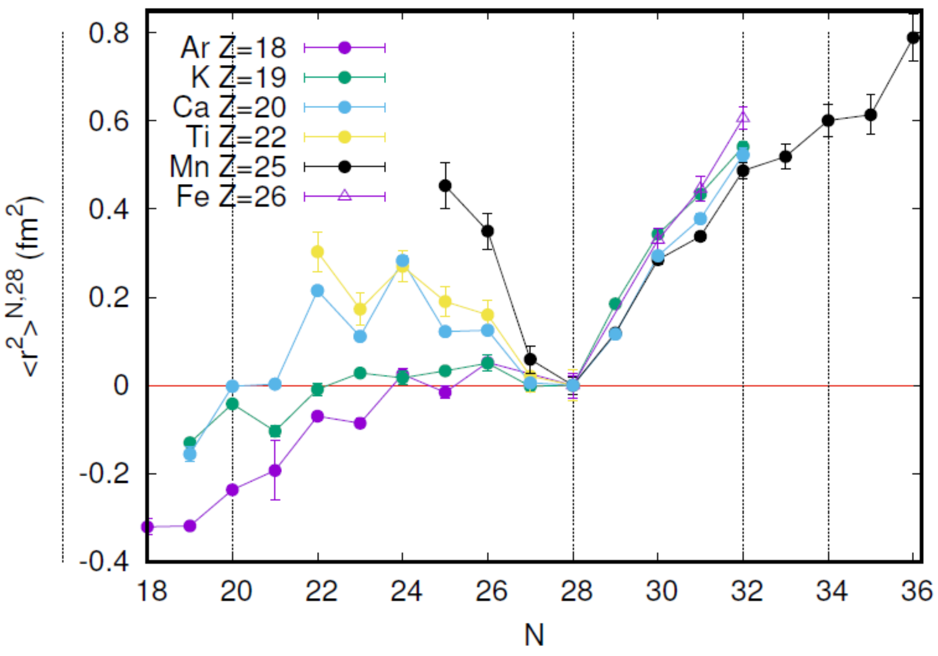
Charge radii systematic around the Ca region





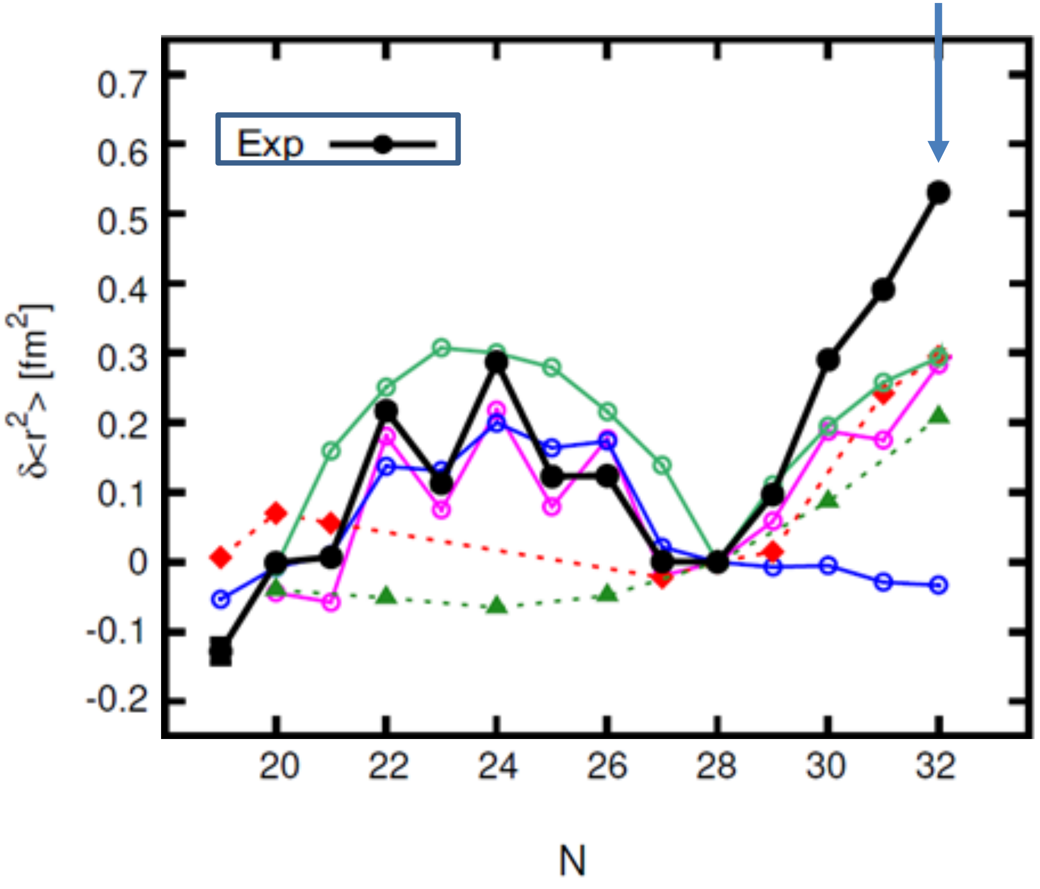
Mn (Z=25) -> [H. Heylen et al, Phys. Rev. C 94, 054321(2016)]

Ca (Z=20) -> [R.F. Garcia Ruiz et al., Nature Physics 12, 594 (2016)]

K (Z=19) -> [K. Kreim et al, Phys. Lett. B 731, 97 (2014)]

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)

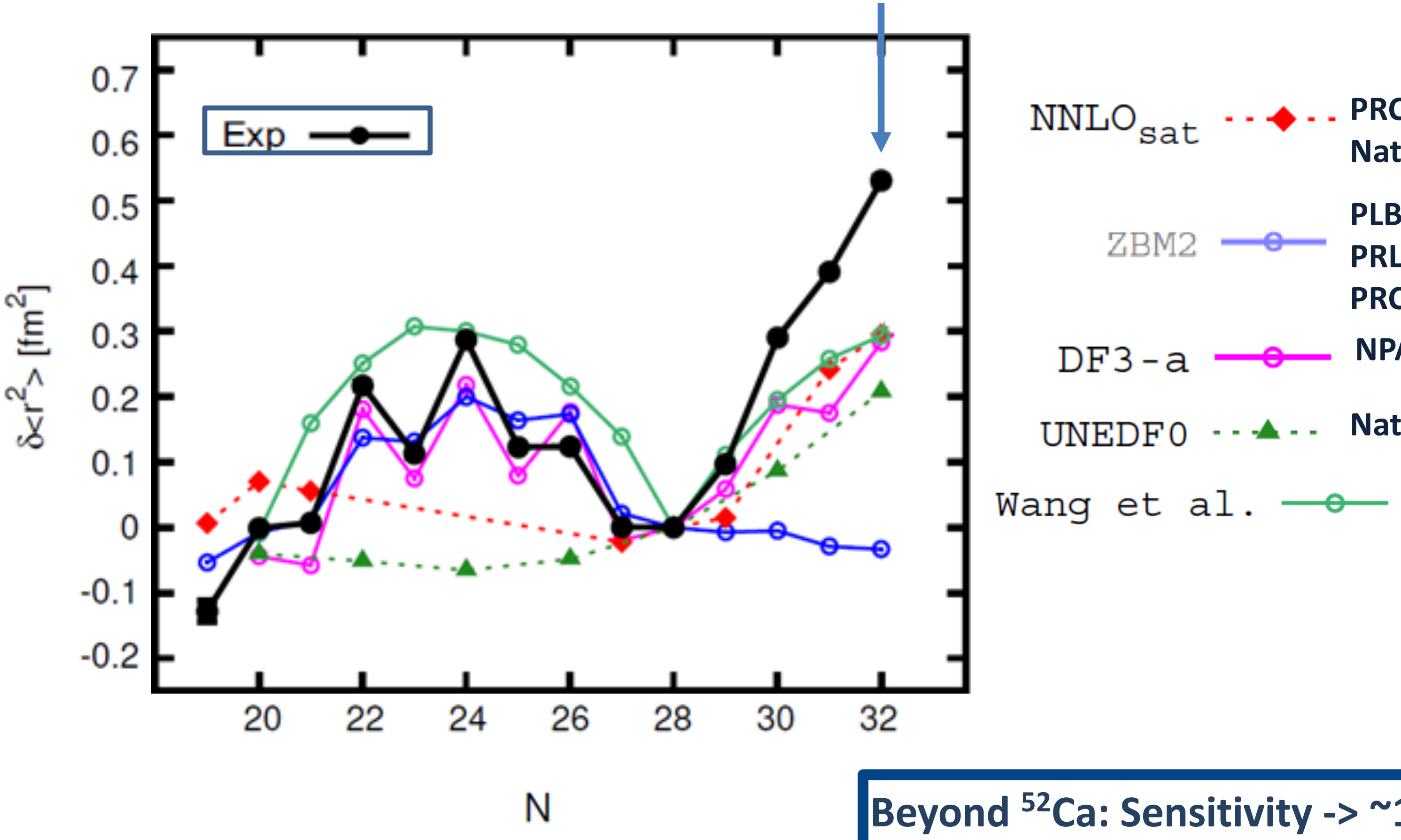
Wang et al. PRC 88, 011301(R) (2013)

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)

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

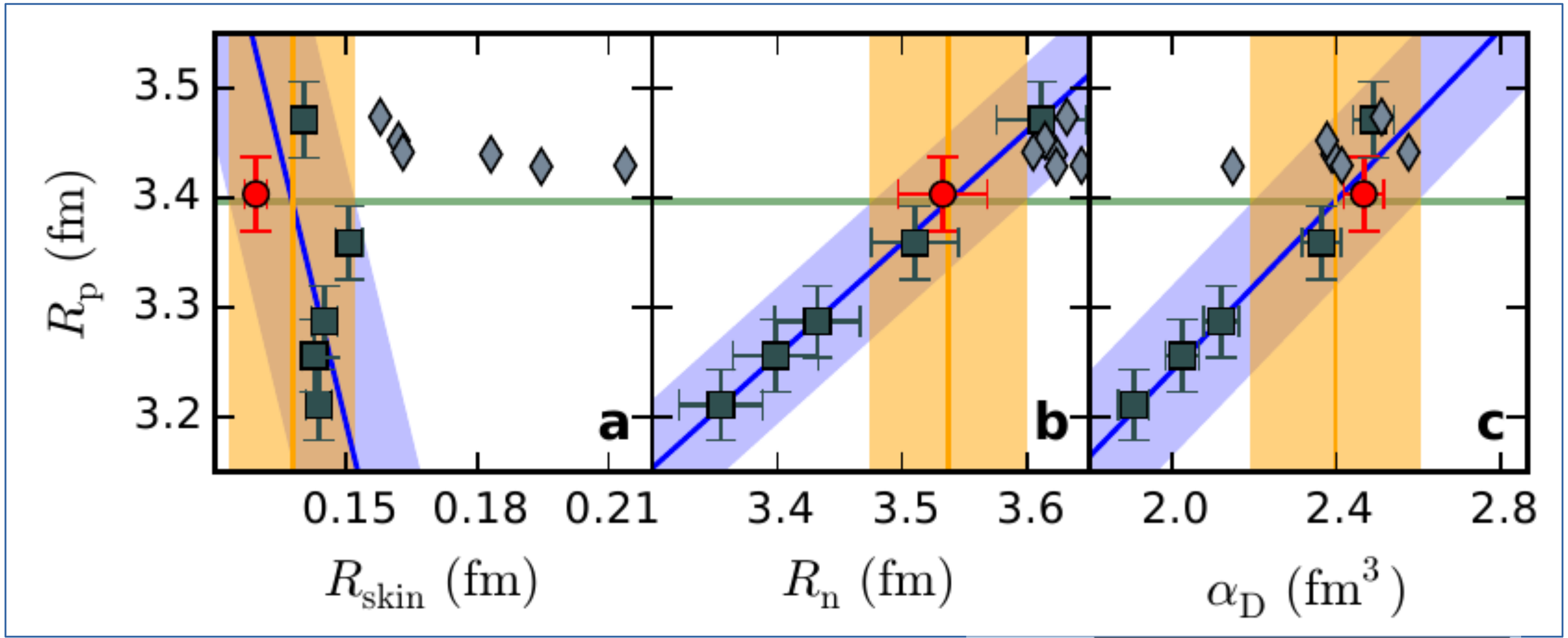
Radioactive detection of Collinear-laser optical pumping after Charge exchange

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

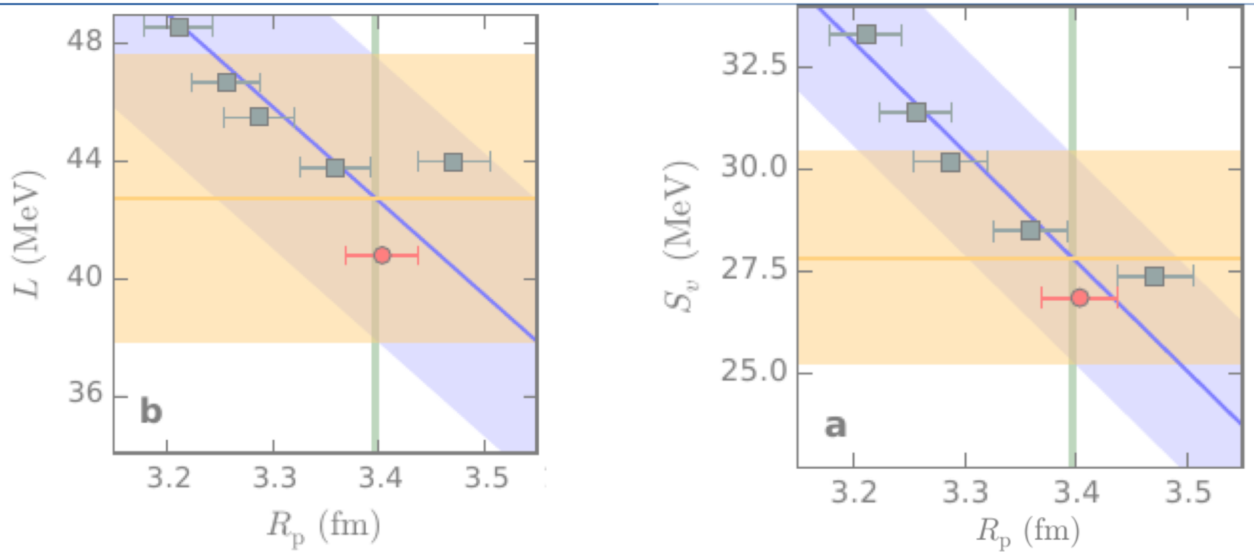
[L. Vermeeren et al Phys. Rev. Lett. 68 1679 (1992)]

^{48}Ca: Charge radii vs Dipole polarizability

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



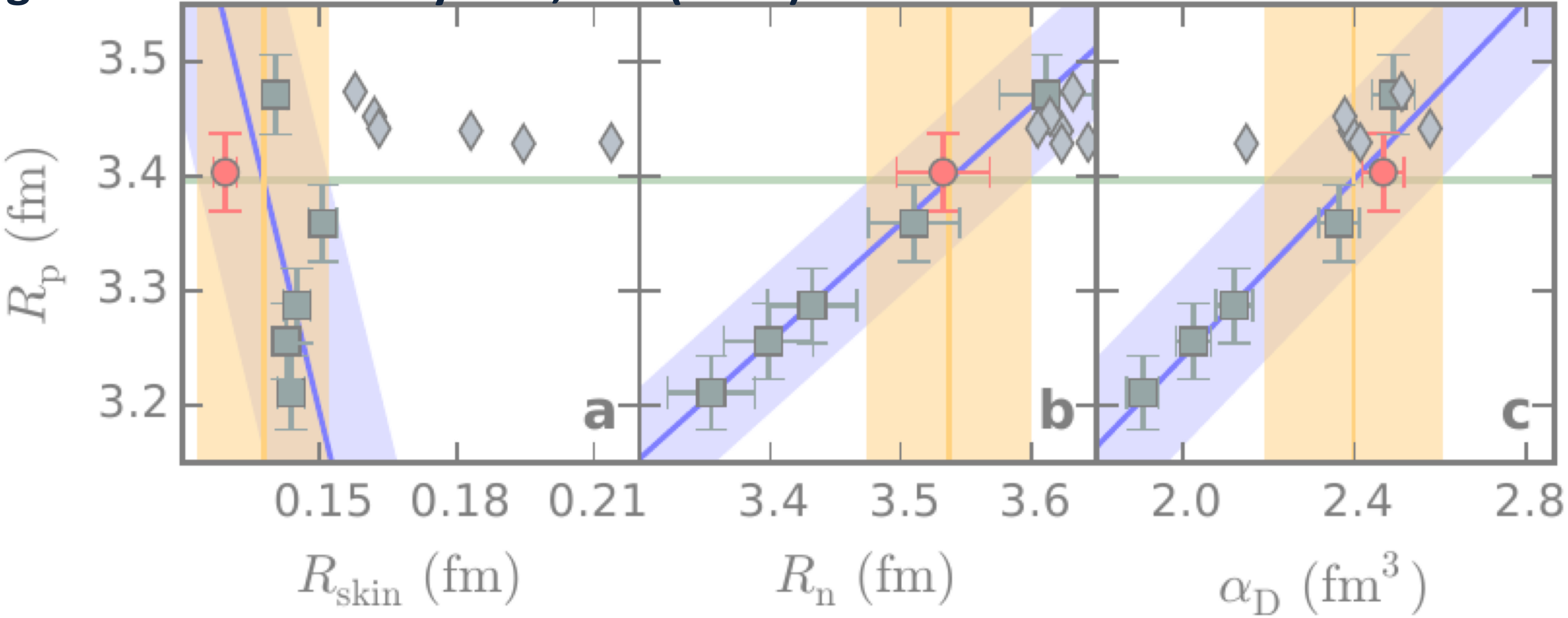
Constrain to properties of nuclear matter

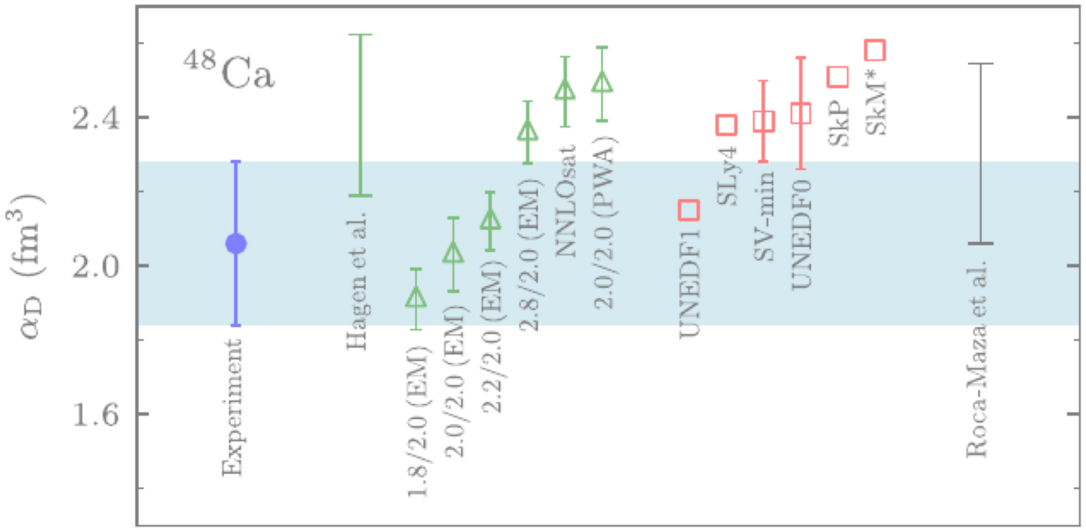


^{48}Ca: Charge radii vs Dipole polarizability

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

^{48}Ca

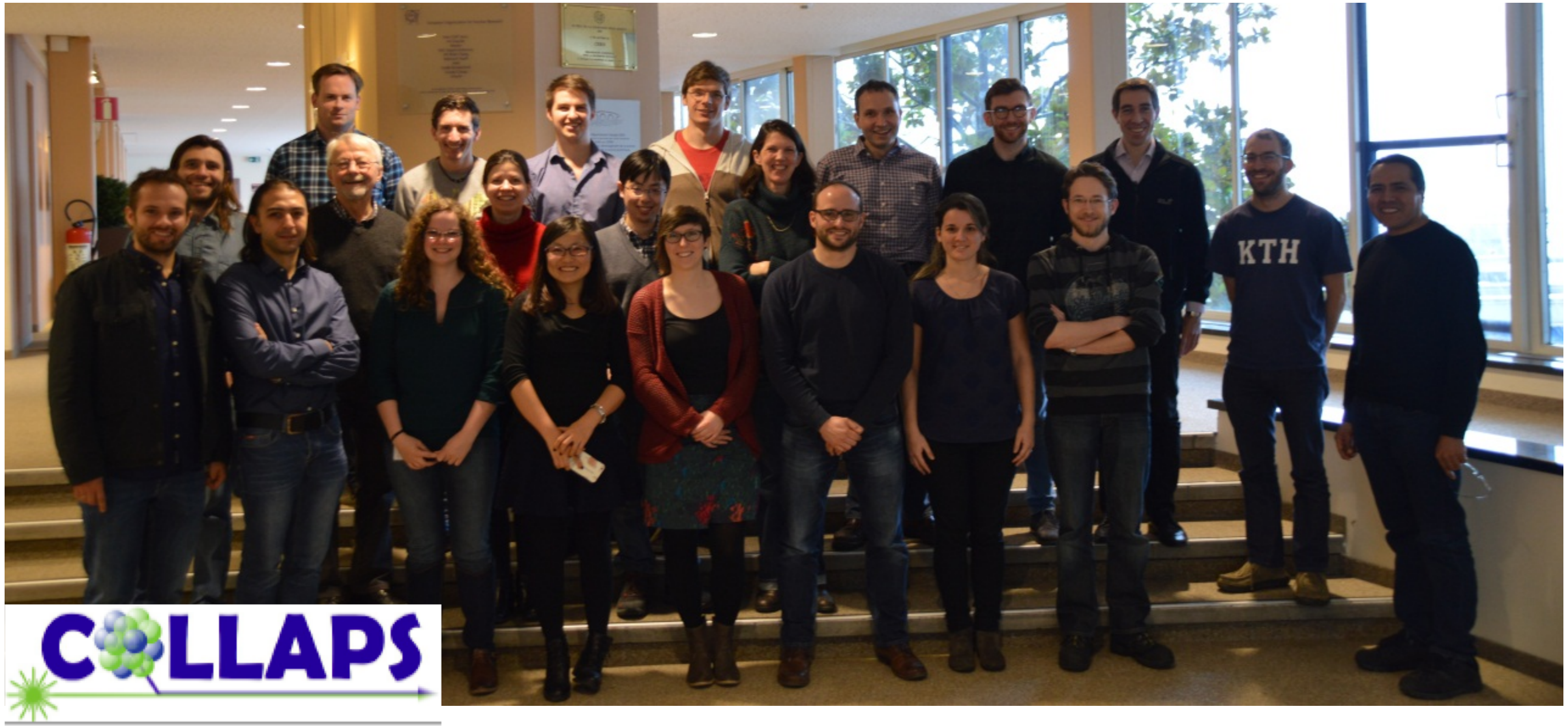




J. Birkhan et al.
Phys. Rev. Lett. 118, 252501 (2017)

Remarks

- Laser spectroscopy is currently a very active field with many groups around the world working towards the limits of nuclear existence.
- Atomic physics calculations often limit the precision of extracted nuclear observables
- Electromagnetic moments are sensitive probes of the role of electro-weak currents. In the case of medium and heavy mass nuclei the contributions to the operators (two body currents ~ MEC) are unknown.
- Charge radii provides a test to inter-nucleon interactions and many-body methods.



M.L. Bissell, K. Blaum, B. Cheal, S. Malbrunot-Ettenauer,, W. Gins, H. Heylen, A. Kanellakopoulos, Á. Koszorús, J. Krämer, S. Kaufmann, M. Kowalska, G. Neyens, R. Neugart, W. Nörtershäuser, R.F. Garcia Ruiz L. Vazquez, R. Sánchez, L. Xie, Z.Y. Xu, D.T. Yordanov. X.F. Yang,

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ISOLDE

Thank you