Nuclear structure studies by the measurement of nuclear spins, moments and charge radii via collinear laser spectroscopy: results and perspectives

Gerda Neyens
KU Leuven, Belgium

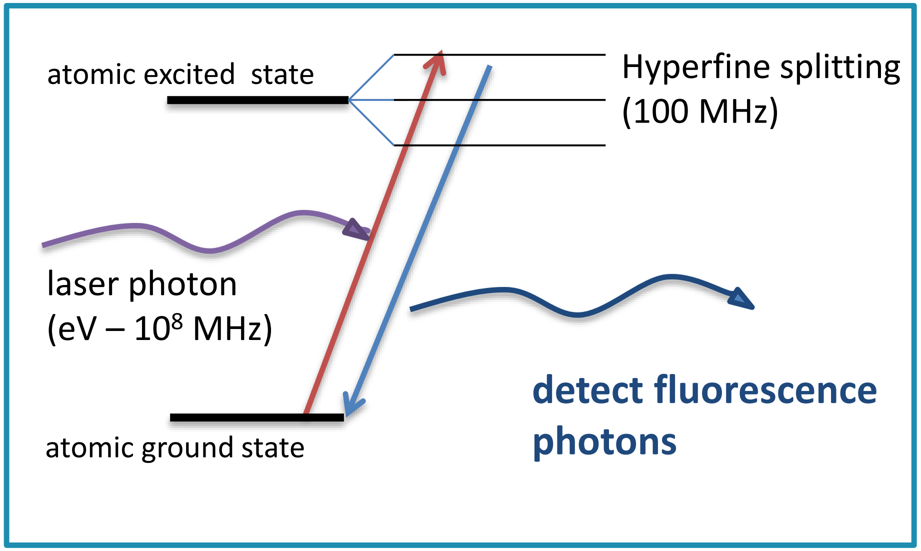
with thanks to the
COLLAPS and CRIS
collaborations at
ISOLDE-CERN

BriX
Belgian Research
Initiative
on Exotic nulcei

KU LEUVEN

Collinear laser spectroscopy at ISOLDE-CERN

COLLAPS



atomic excited state

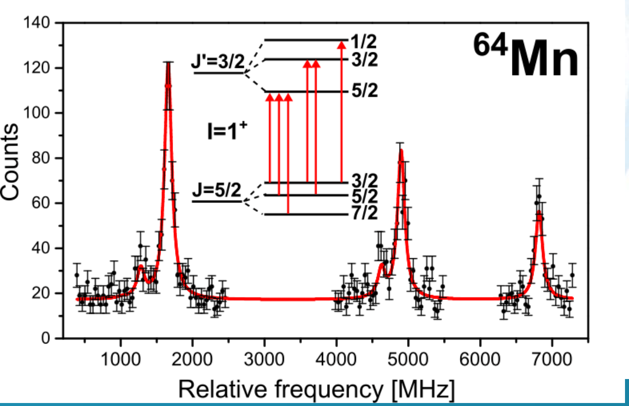
Hyperfine splitting (100 MHz)

laser photon (eV – 10^8 MHz)

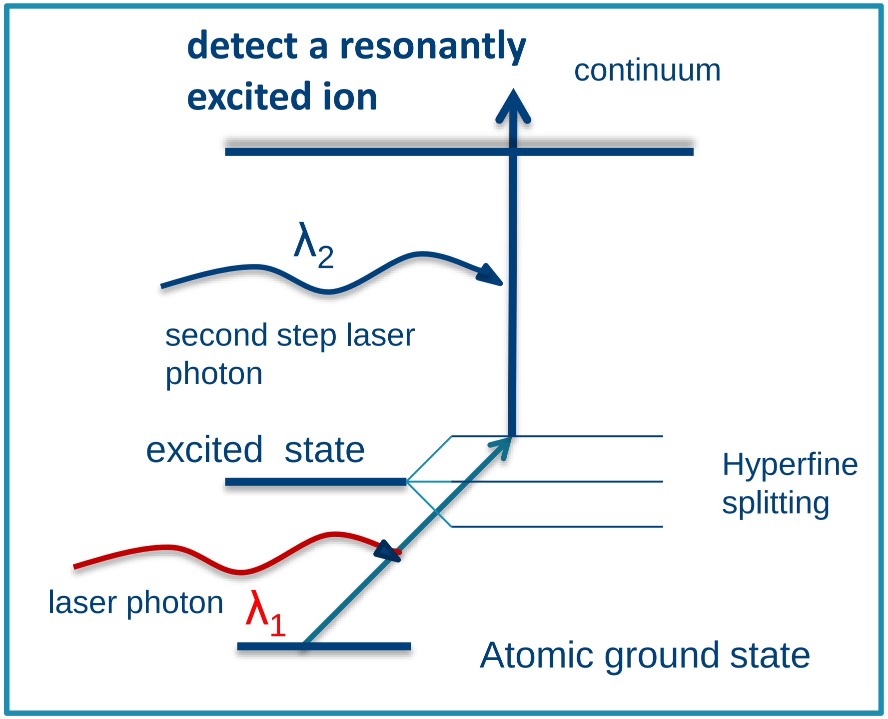
detect fluorescence photons

atomic ground state

- low background with bunched beams (few/s)
- **need few 1.000's ions/s** from ISOLDE
- 'simple'



CRIS (since 2012)



detect a resonantly excited ion

continuum

λ_2

second step laser photon

excited state

Hyperfine splitting

laser photon λ_1

Atomic ground state

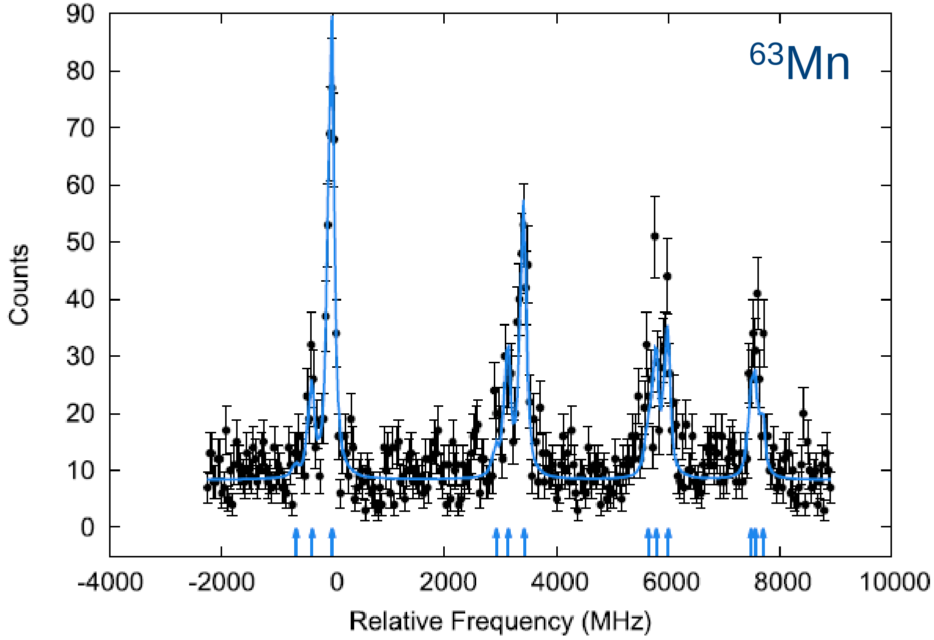
- ultra-low background (1 event /10 min)
- **need few 10's ions/s** from ISOLDE
- 'more demanding'

Collinear = high resolution: 20-60 MHz
→ can resolve all hyperfine peaks to extract I, μ, Q, $\delta\langle r^2\rangle$

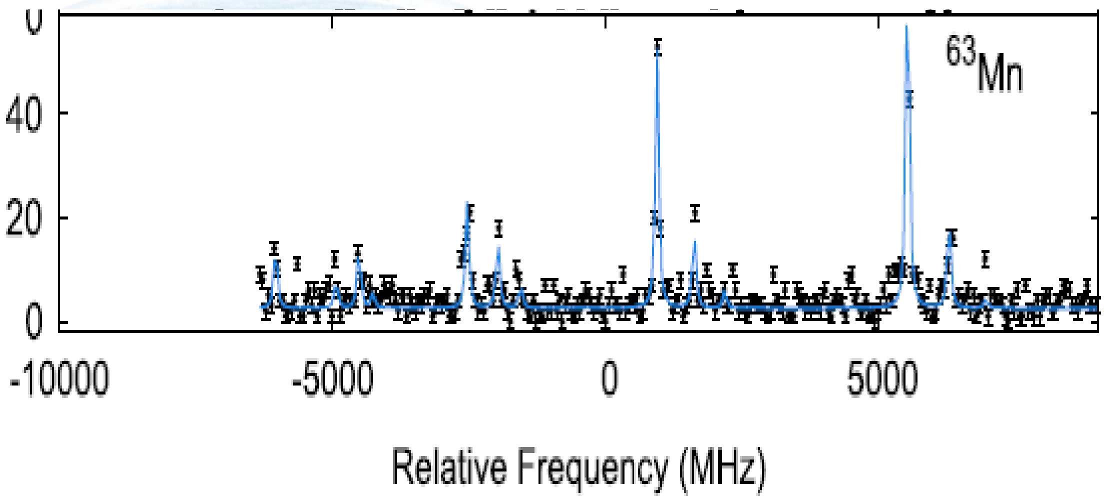
P. Vingerhoets et al., PRC82, 064311 (2010)

R.P. de Groote et al., PRL115, 132501 (2015)

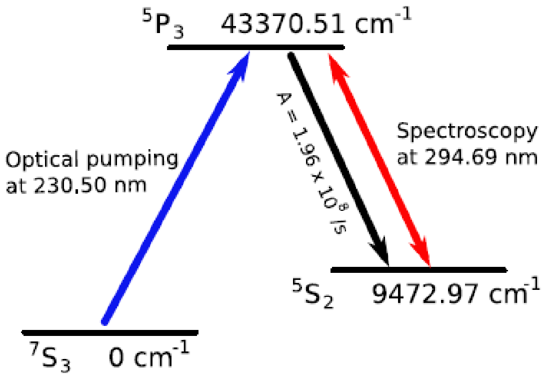
Even with high resolution
→ not always suitable transition from ground state (atom or ion)



➔ Peaks not enough resolved to get Q with good precision (5-10 %)



➔ SOLUTION: optical pumping to metastable state in ISCOOL

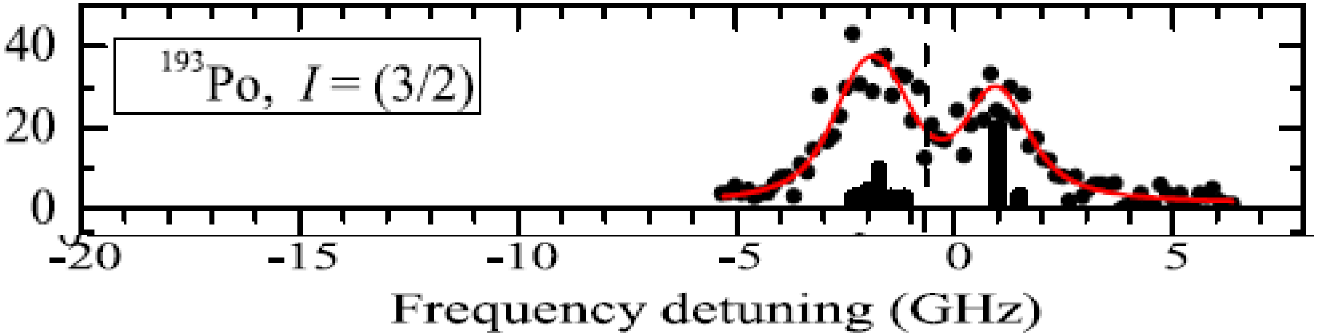


C.Babcock, H. Heylen et al., PLB 760 (2016) 387

Collinear RIS versus in-source / in-gas-cell / in-jet

In-source and in-gas-cell: resolution ~ 5 -10 GHz / only heavy elements (large HFS), only μ,$<r^2>$

M.D. Seliverstov et al. PLB 719 (2013) 362 (RILIS@ISOLDE)



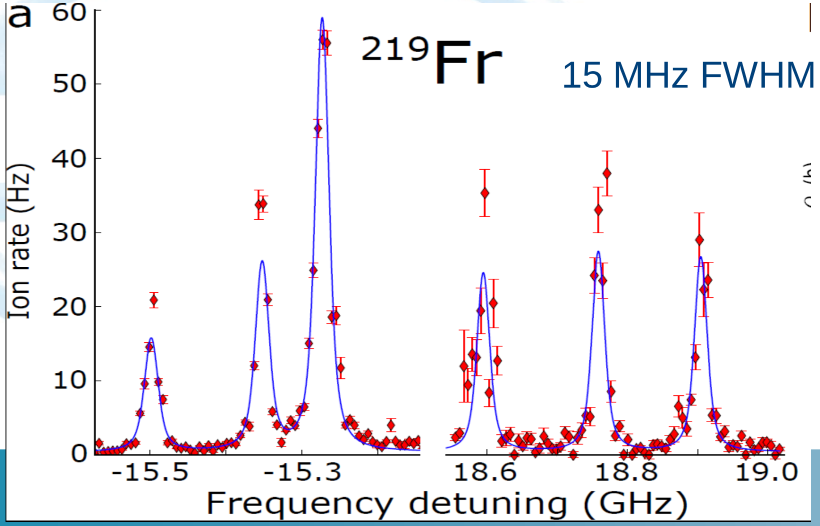
< 0.1/s

Collinear: resolution ~ 50 MHz and < 20/s

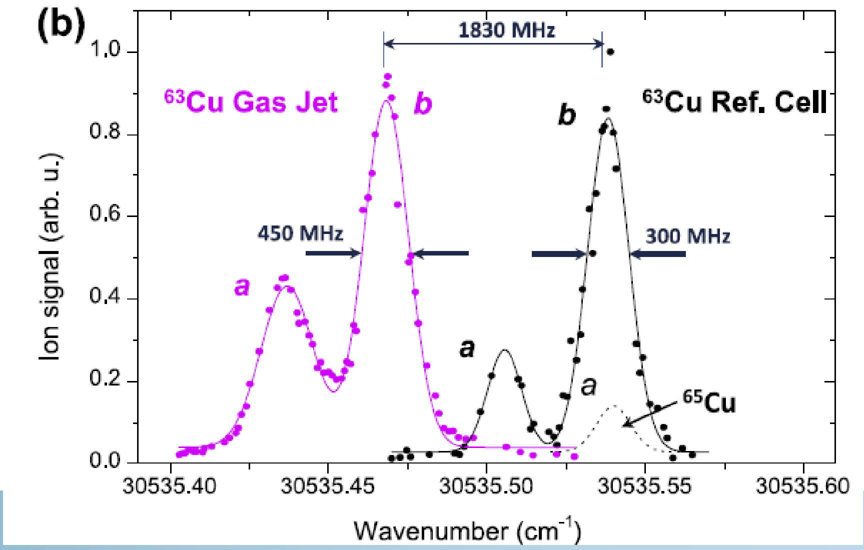
In-jet: 300-400 MHz (ongoing)

R.P. de Groote et al. PRL115 132501 (2015) (CRIS@ISOLDE)

Yu. Kudryavtsev et al. / NIMB 297 (2013) 7 (LEUVEN)

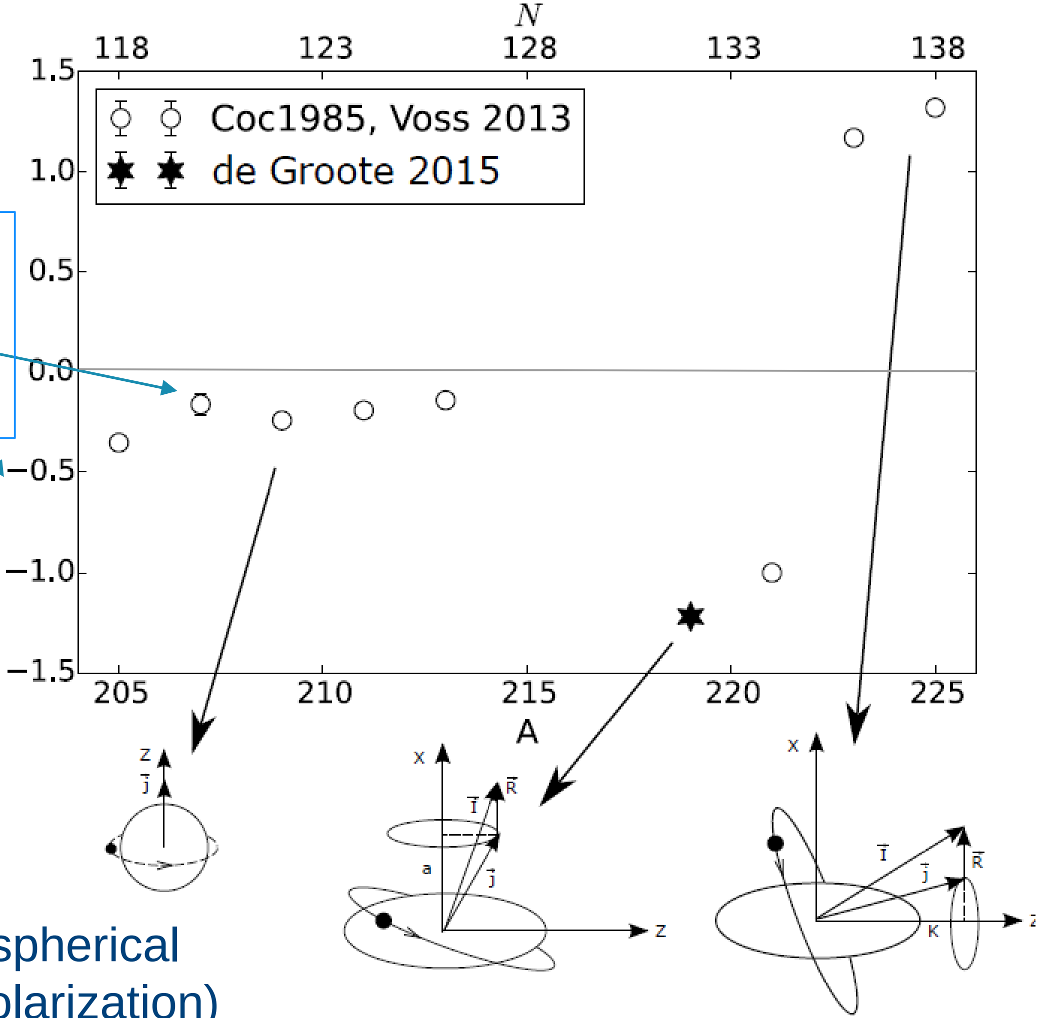


15 MHz FWHM



Shape changes in Fr isotopes:

Other new CRIS-data (deviates)
K. Lynch et al. in preparation



Nearly spherical
(core polarization)

spin decoupled
from deformation axis

spin strongly coupled
to deformation axis

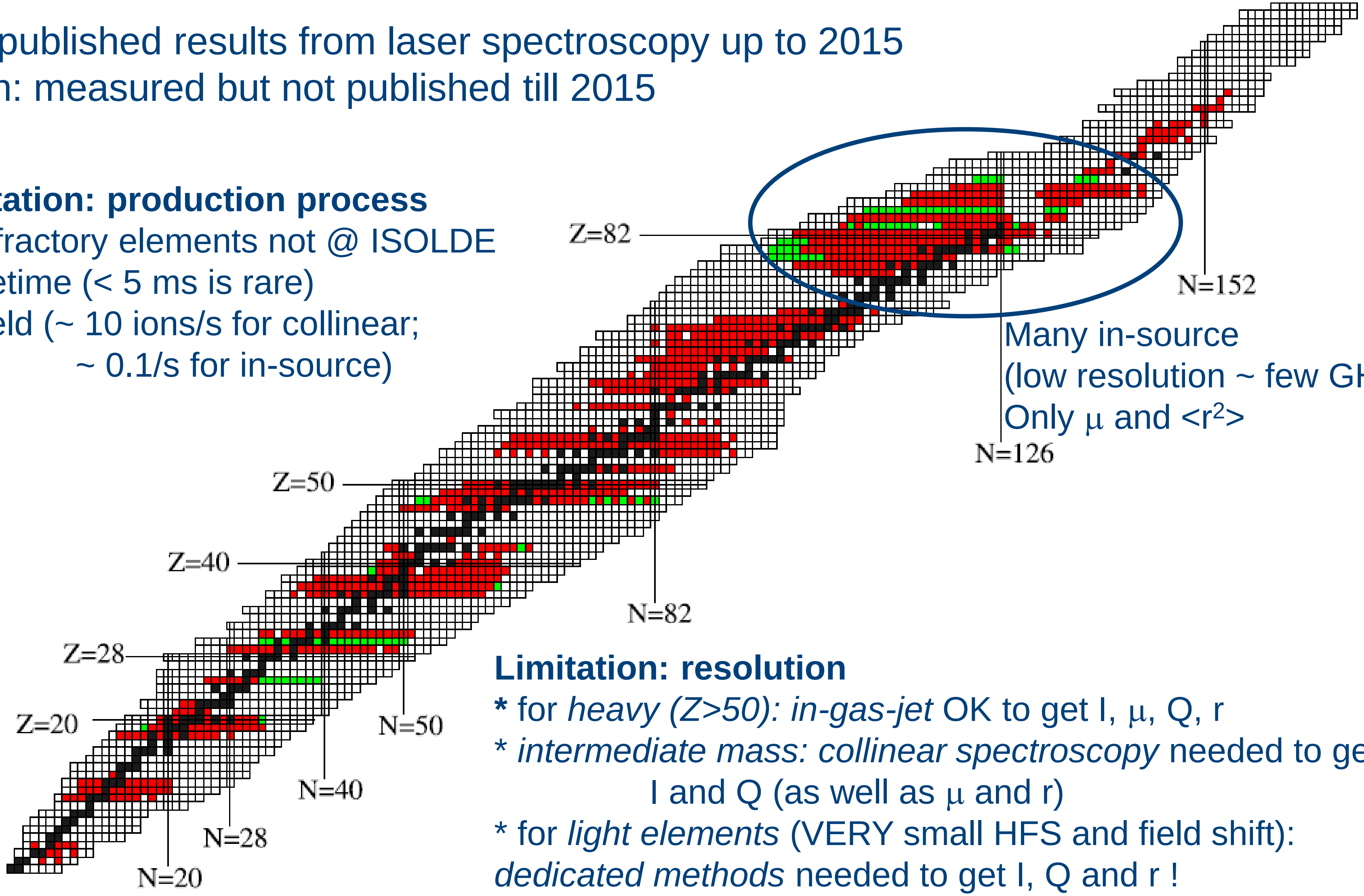
R.P. de Groote et al. PRL115 132501 (2015)

P. Campbell et al. / Progress in Particle and Nuclear Physics 86 (2016) 127–180

Red: published results from laser spectroscopy up to 2015
Green: measured but not published till 2015

Limitation: production process

- refractory elements not @ ISOLDE
- lifetime (< 5 ms is rare)
- yield (~ 10 ions/s for collinear;
  ~ 0.1/s for in-source)



Many in-source
(low resolution ~ few GHz)
Only μ and $<r^2>$

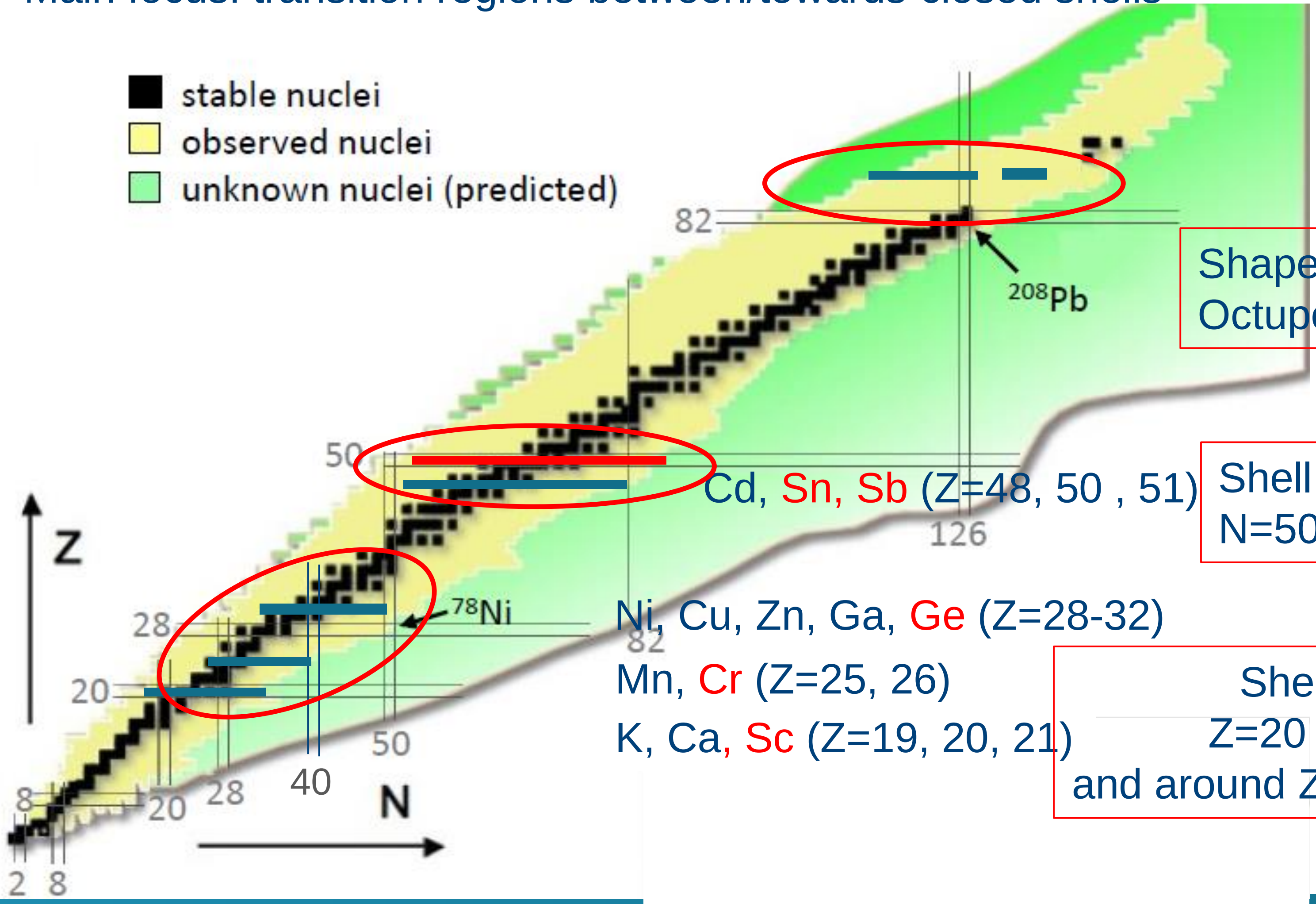
Limitation: resolution

- for *heavy (Z>50): in-gas-jet* OK to get I, μ, Q, r
- *intermediate mass: collinear spectroscopy* needed to get
  I and Q (as well as μ and r)
- for *light elements* (VERY small HFS and field shift):
  dedicated methods needed to get I, Q and r !

Collinear laser spectroscopy at ISOLDE

measure fundamental properties of exotic nuclei in order to investigate changes in nuclear structure far from stability

Main focus: transition regions between/towards closed shells



Fr, Ra, Po

Shape coexistence
Octupole deformation

Cd, Sn, Sb (Z=48, 50 , 51)

Shell evolution from
N=50 to beyond N=82

Ni, Cu, Zn, Ga, Ge (Z=28-32)

Mn, Cr (Z=25, 26)

K, Ca, Sc (Z=19, 20, 21)

Shell structure around
Z=20 and beyond N=32
and around Z=28 reaching ^{78}Ni

Some selected physics results around Z=20,28

- Magic numbers and shell evolution ?
- How magic is ^{78}Ni ?
- Shape coexistence along N=50 ?
- Is there a shell gap at N=40 ?
- How magic is N=32 ?
- Onset of collectivity between Z=20 and Z=28 ?

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R. Neugart, J. Billowes, M. L. Bissell, K. Blaum, B. Cheal, K. T. Flanagan, G. Neyens, W. Nörtershäuser, D. T. Yordanov

Collinear laser spectroscopy at ISOLDE: New methods and highlights.

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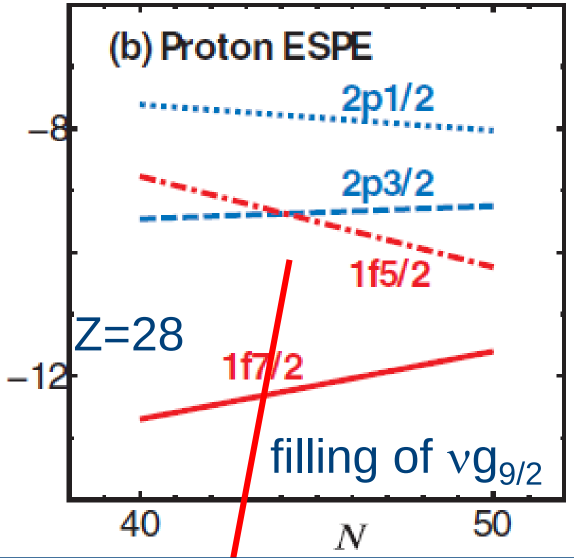
Evolution of single particle orbits: measure ground state spins !

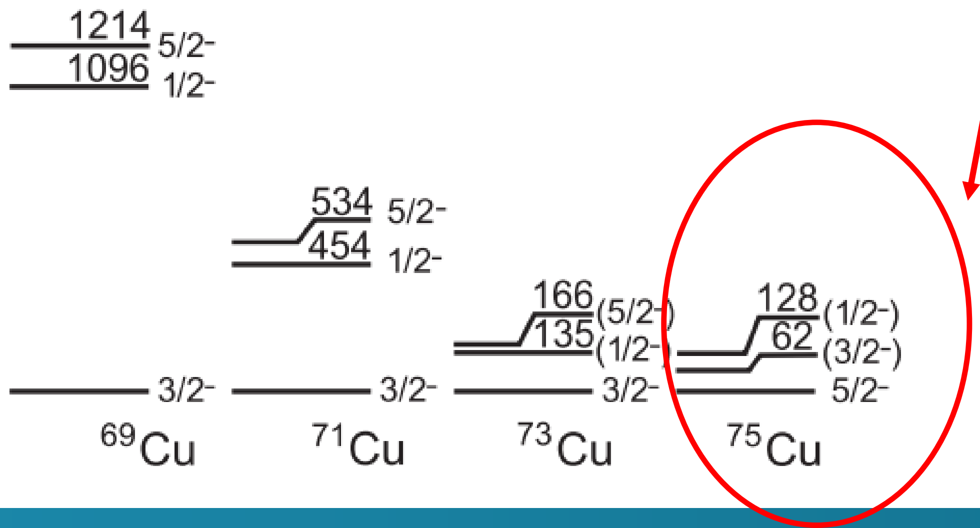
T. Otsuka et al, PRL **95**, 232502 (2005)

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



filling of $\nu g_{9/2}$

Cu-isotopes (Z=29): sensitive to the evolution of proton orbits

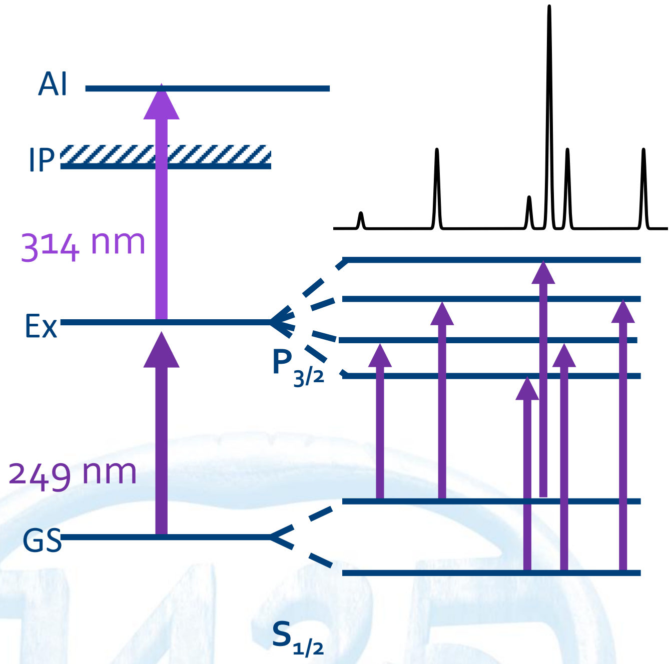


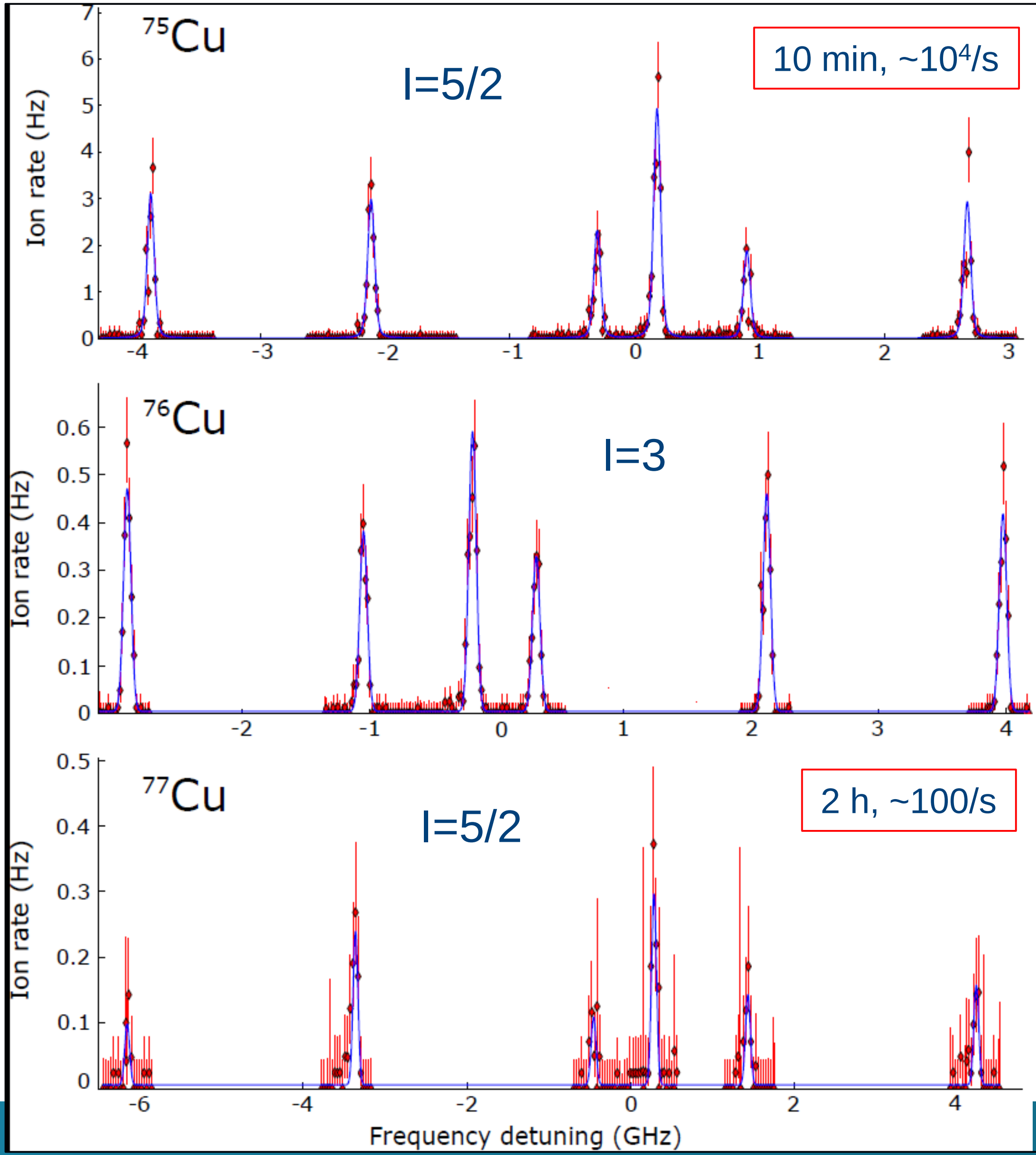
Importance of model-independent
spin measurement
(here: bunched-beam
collinear laser spectroscopy)

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

Extend to ^{77}Cu using high-resolution CRIS

Injection seeded pulsed Ti:Sa laser for 249 nm (Tripled)

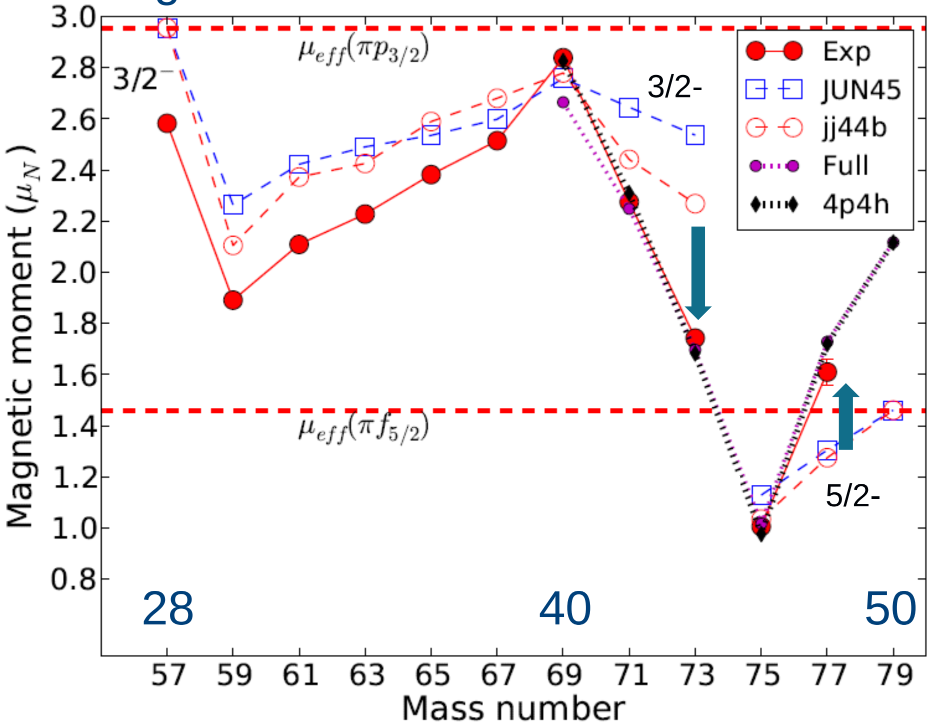


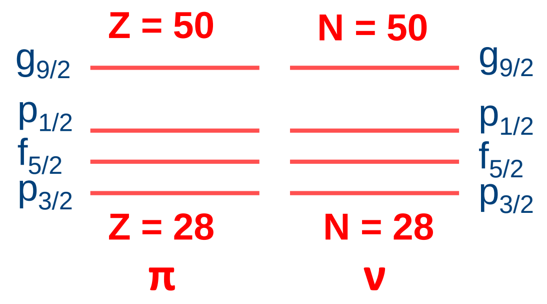


R.P. de Groote et al., In preparation (2016)

Magnetic and Quadrupole moments: probe different correlations (M1/E2)

Magnetic moments from N=28 to N=48



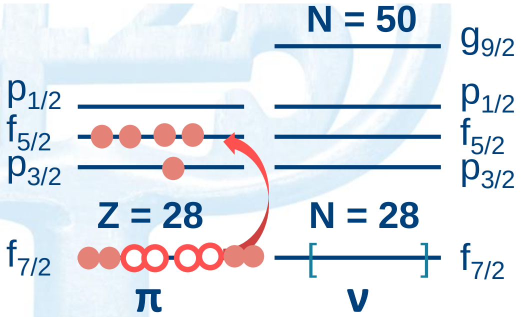


jj44b and JUN45: **f_5pg_9 model space**

→ Overall OK but miss the decrease before and after N=40

→ Z,N=28 not good shell gaps around ^{56}Ni

→ What about magicity of ^{78}Ni ?



Sieja et al., PRC81, 061303(R) (2010): include $\pi f_{7/2}$ in model space

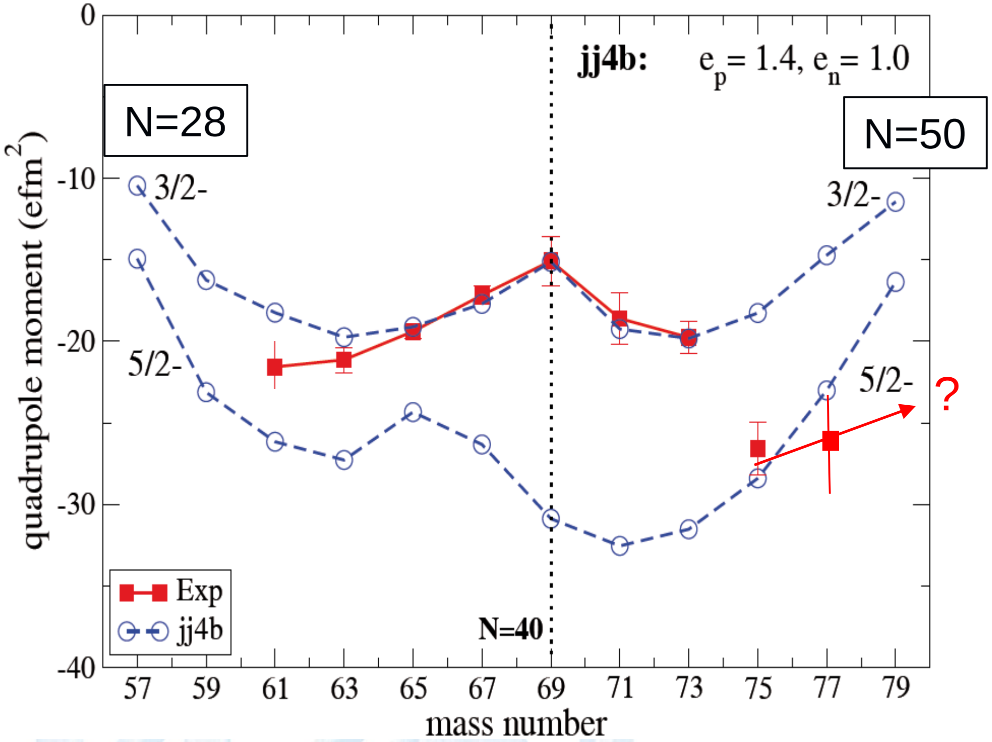
Need **4p-4h proton excitations across Z=28** to reproduce magnetic moments $^{71\text{-}77}$Cu

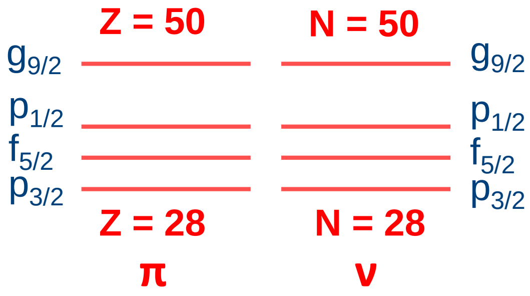
Vingerhoets et al., PRC82, 064311 (2010)

μ(77Cu): Köster et al., PRC 84, 034320 (2011)

Magnetic and Quadrupole moments: probe different correlations (M1/E2)

Quadrupole moments from N=28 to N=48





jj44b and JUN45 model space

→ Good reproduction of n-rich Q-moments !

→ Miss correlations towards N=50 ?

Calculated Q-moments for $^{71-77}$Cu in extended model spaces…

→ Only proton excitations sufficient ?

→ Weakening of N=50 shell gap ? → test magicity of ^{78}Ni

→ Calculations in progress… / more statistic needed !

Vingerhoets et al., PRC82, 064311 (2010)

Ruben de Groote et al., paper in preparation

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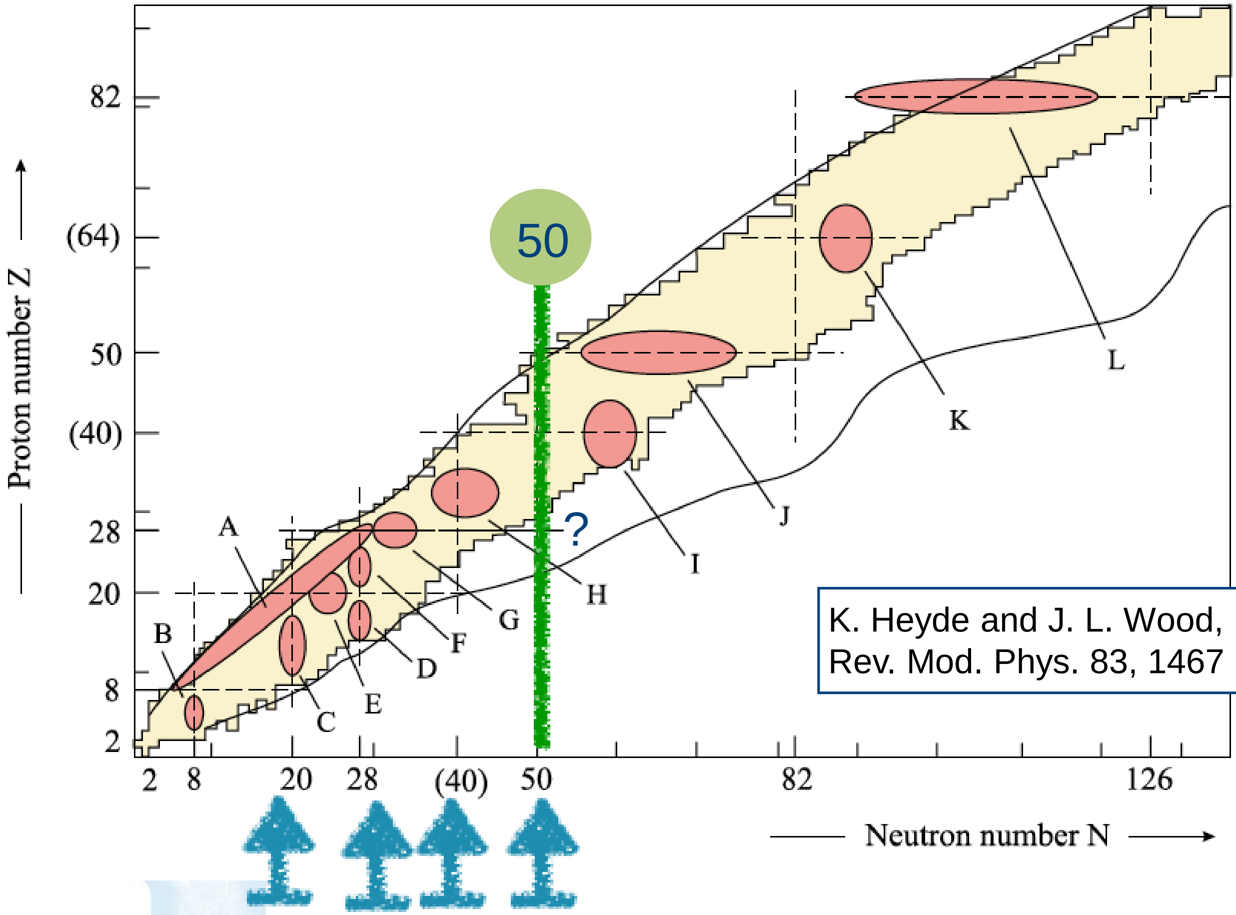
Collinear laser spectroscopy at ISOLDE: New methods and highlights.

Shape coexistence in the chart of nuclei:

- States with different shapes at low energy
- Near one magic shell and one mid-shell for p and n (or vice-versa)



K. Heyde and J. L. Wood,
Rev. Mod. Phys. 83, 1467 (2011).

Laser spectroscopy : a perfect tool to establish shape coexistence:

➔ μ probes wave function (intruder?)

➔ charge radius and Q probes deformation

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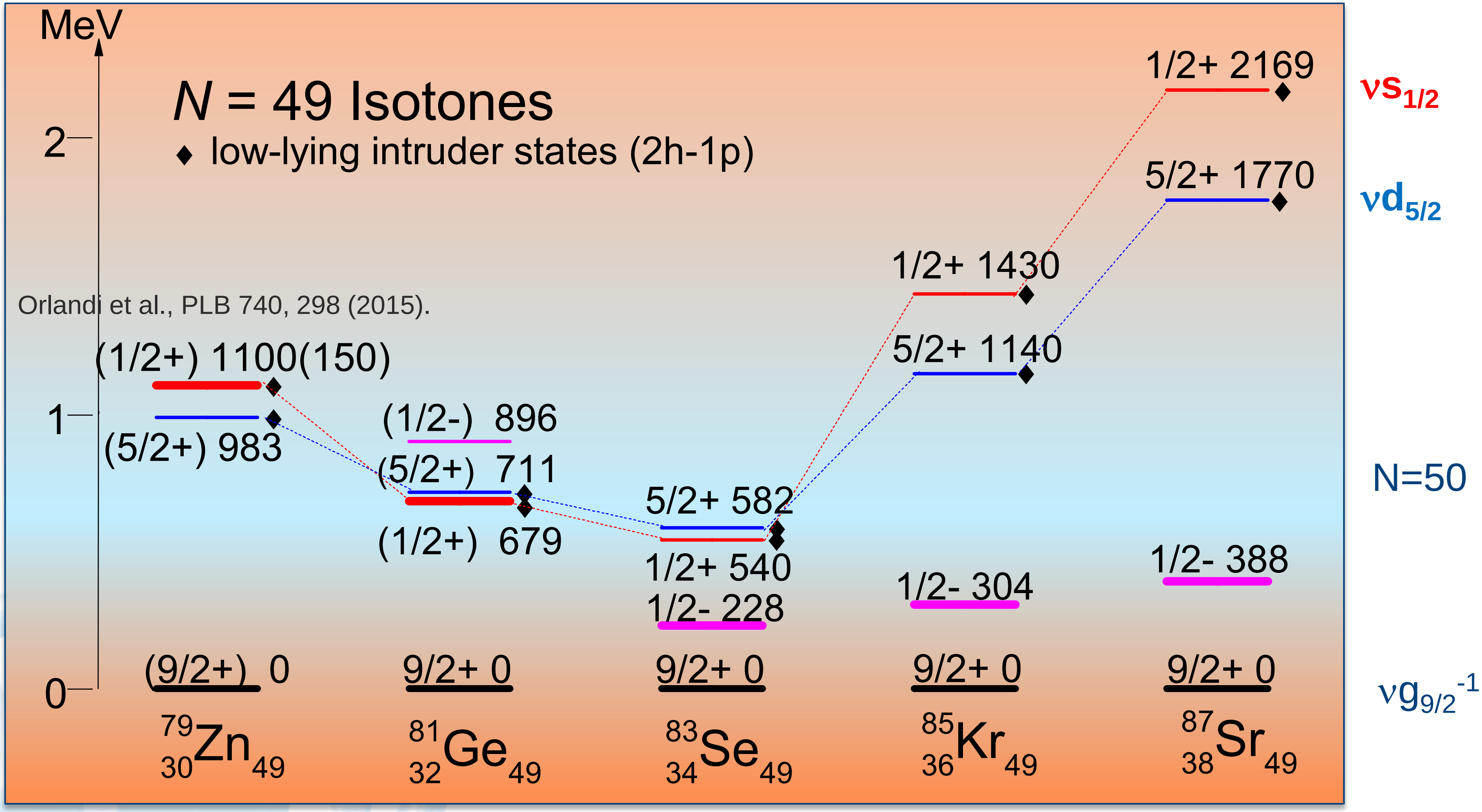
Courtesy Xiaofei Yang

Intruder states along N=49



Orlandi et al., PLB 740, 298 (2015).

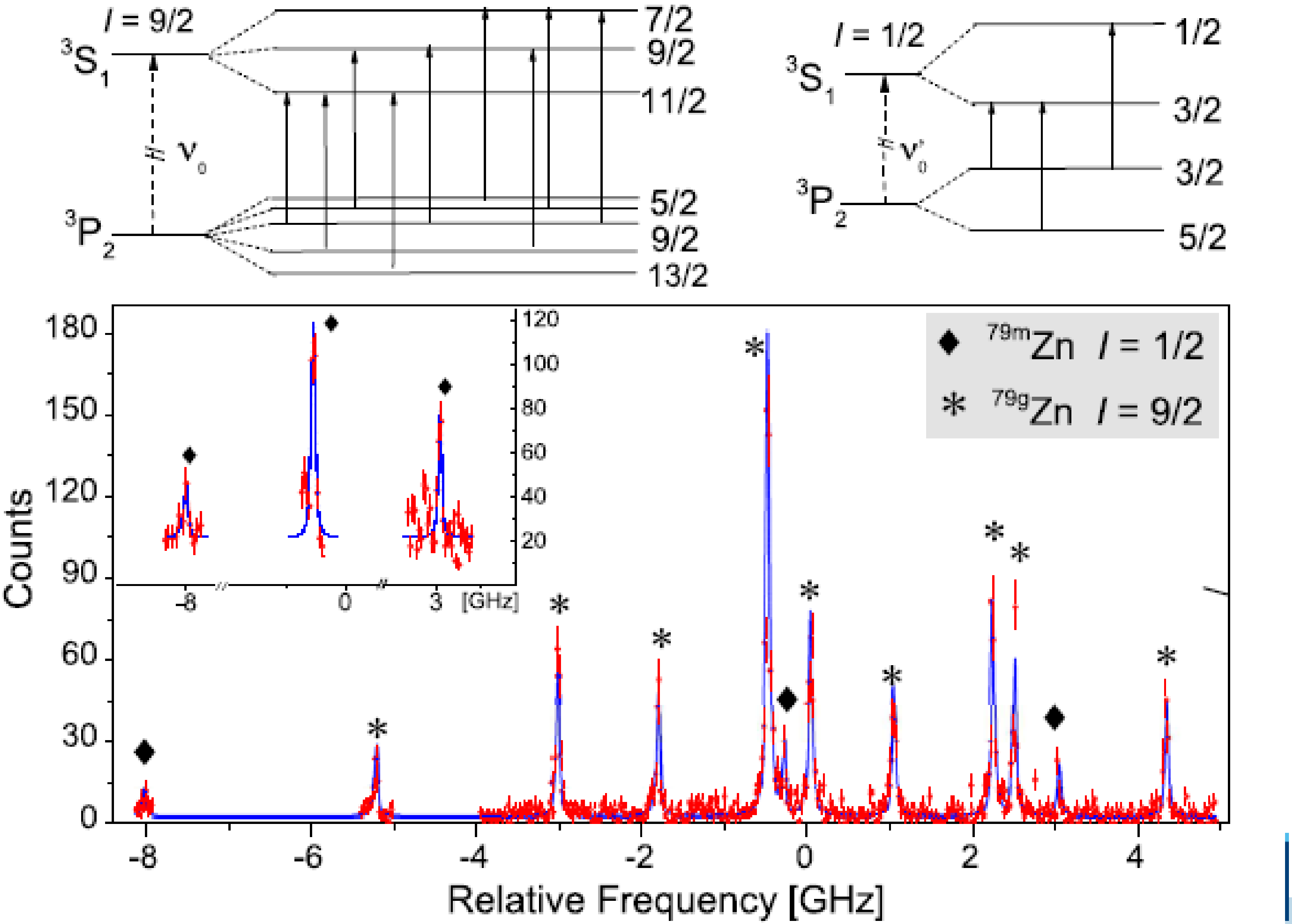
Intruder states confirmed for N = 49 isotones for more than 3 decades

K. Heyde et al., Physics Reports 102, 291 (1983)

Experimental evidence for shape coexistence is still missing!!

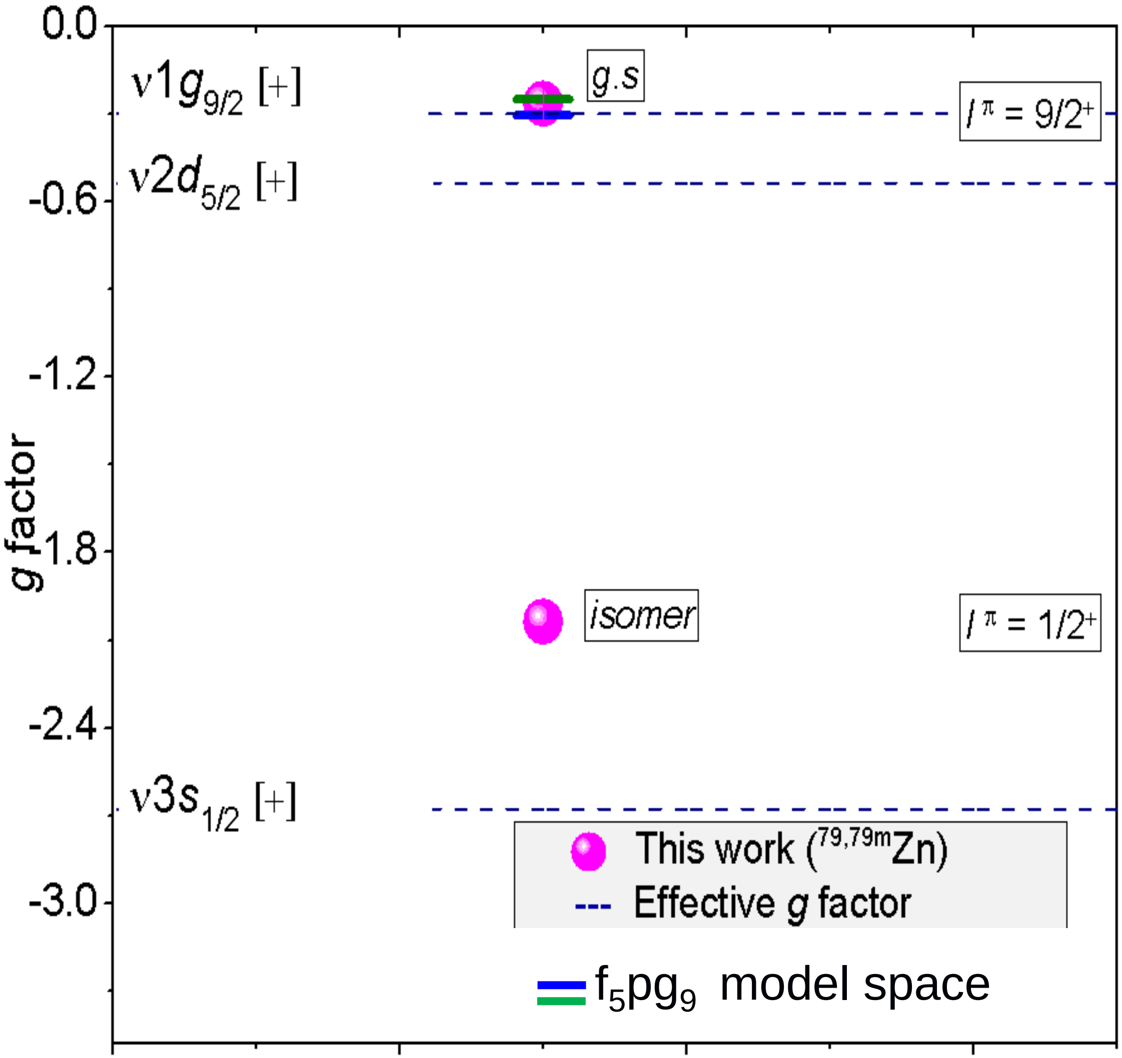
In ^{79}Zn and ^{81}Ge: long-lived ½+ (intruder) isomers → laser spectroscopy !

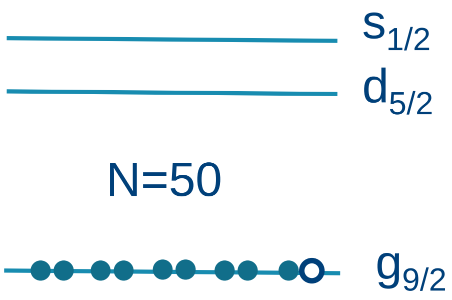
HFS spectra of ^{79g,m}Zn I= 9/2$^+$, 1/2$^+$

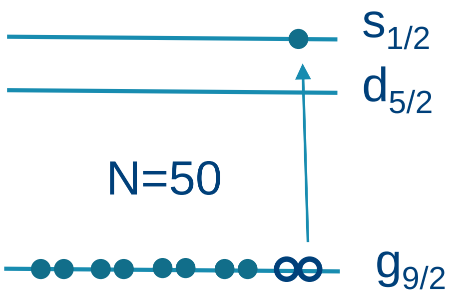


X.F. Yang et al., PRL 116, 182502 (2016)

g-factor of 9/2 g.s. and 1/2 isomeric state in ^{79}Zn







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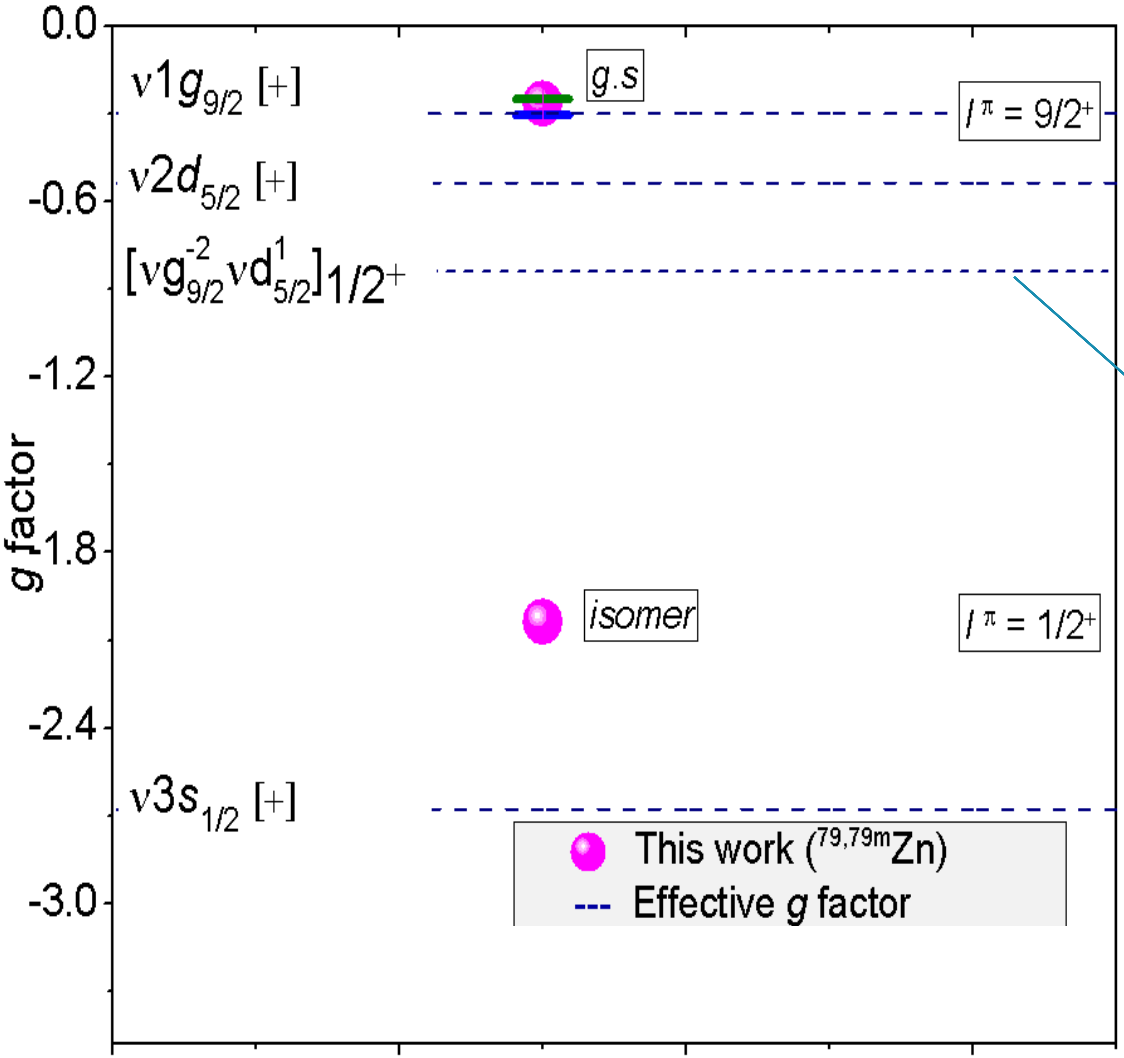

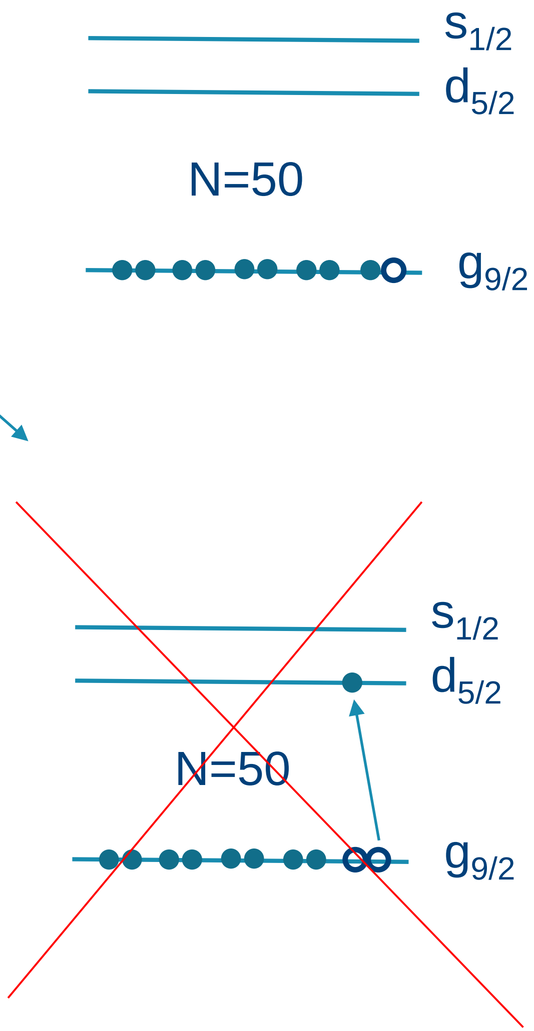

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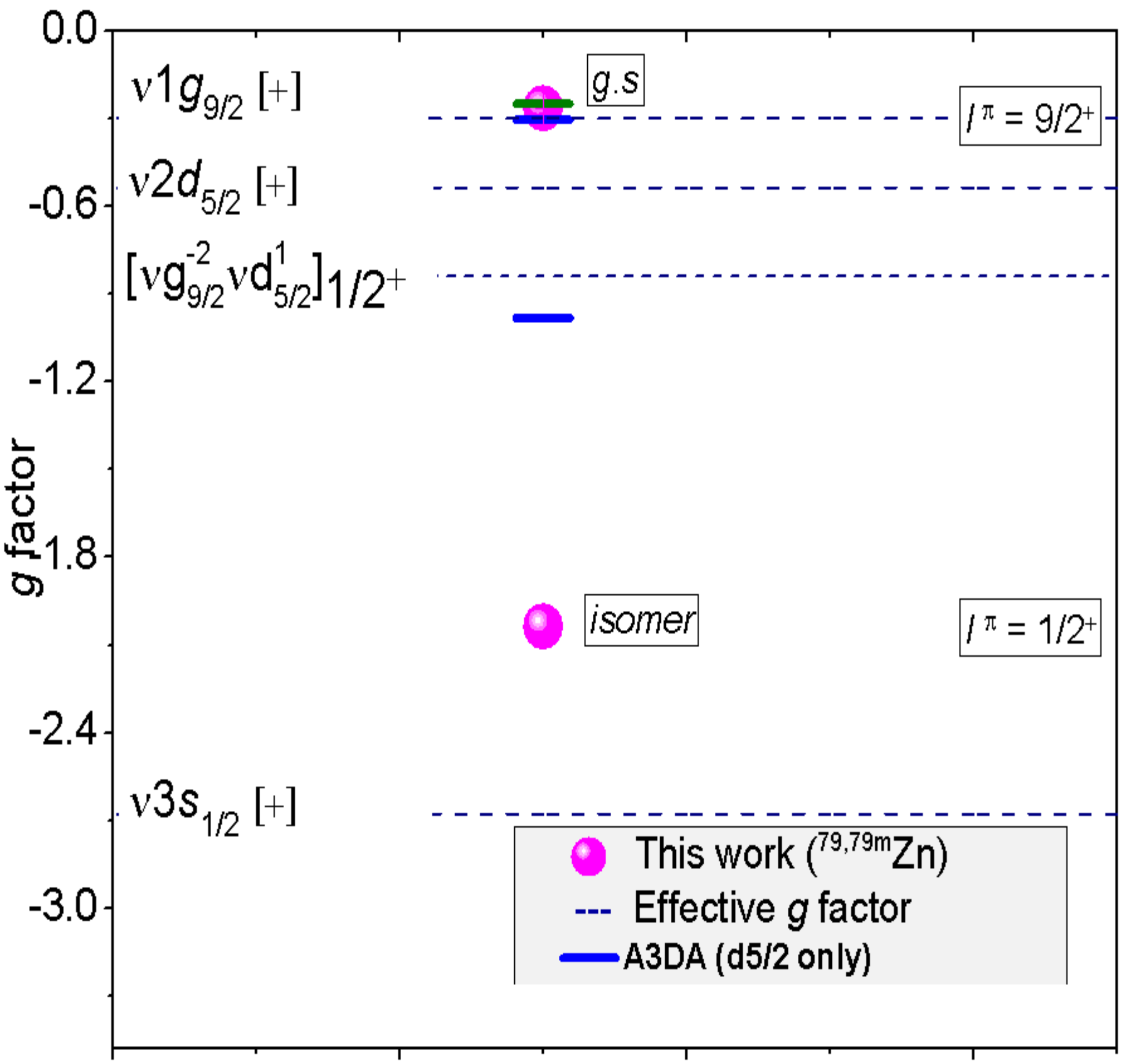
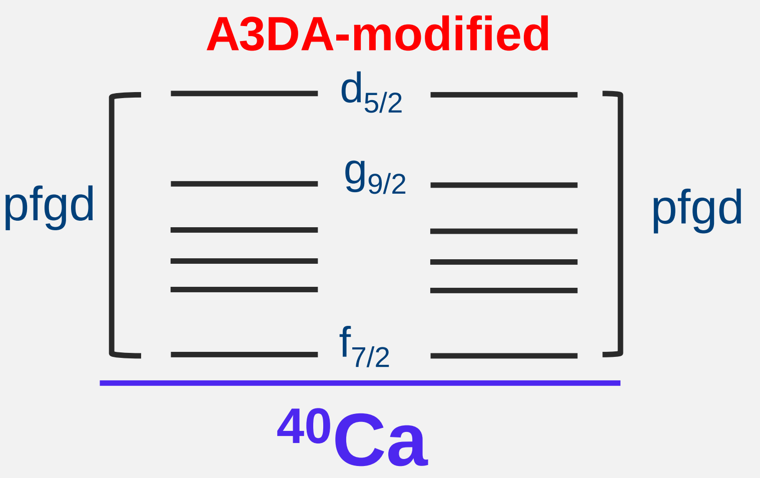




A3DA-modified

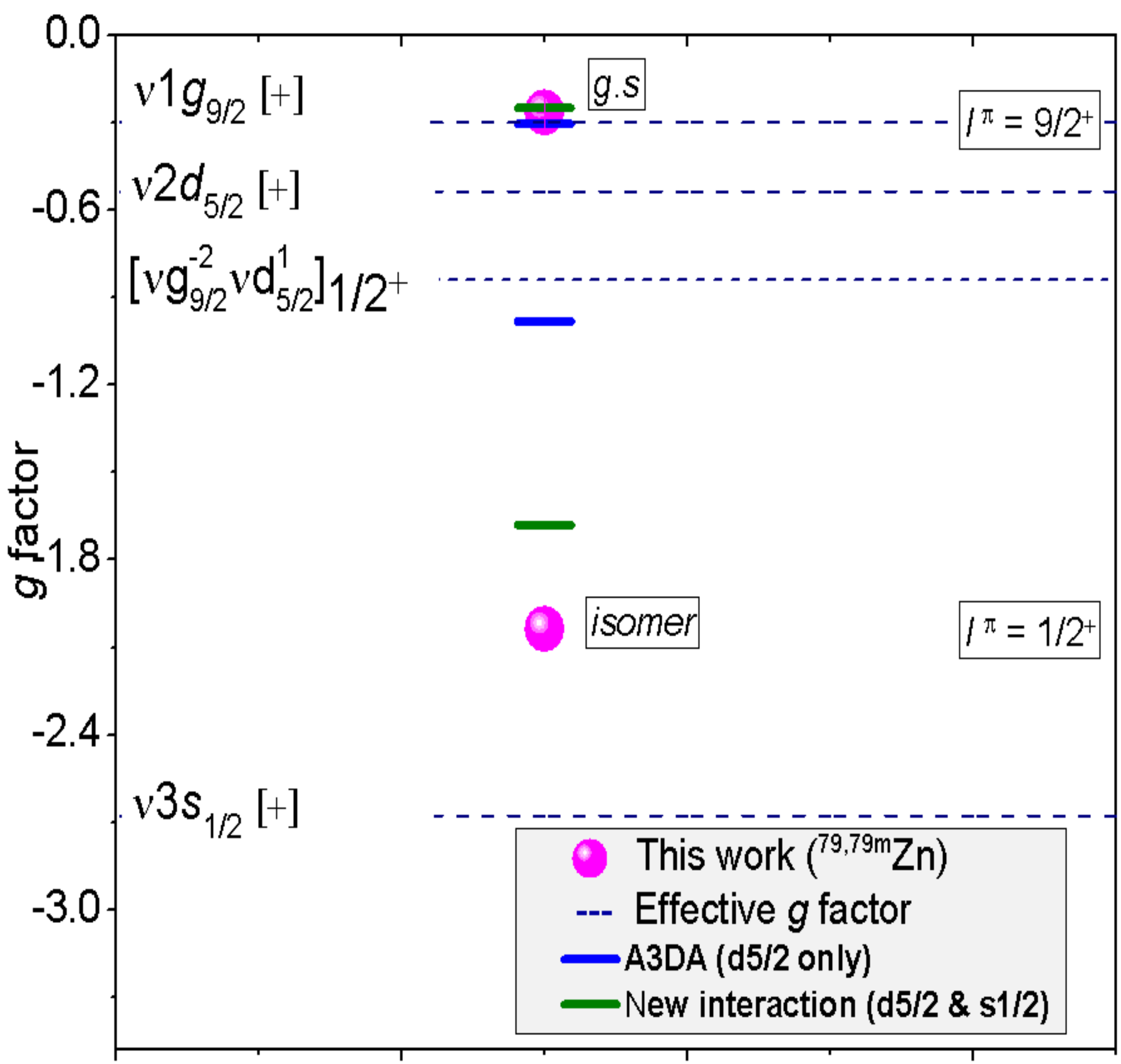
^{40}Ca

Y. Tsunoda et al., PRC 89, 031301(R) (2014)

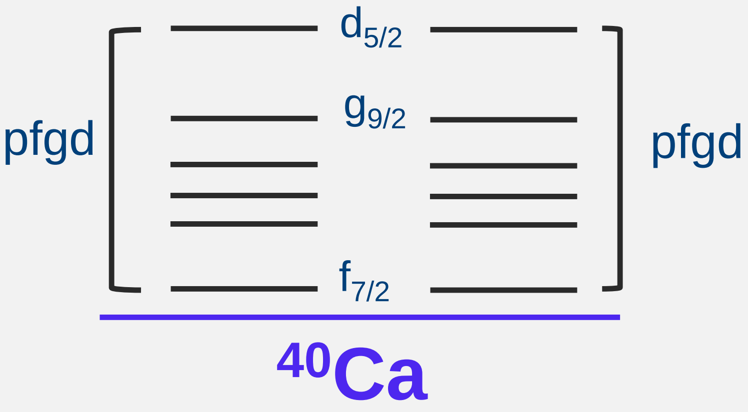
X.F. Yang et al., PRL 116, 182502 (2016)

C. Wright, X.F. Yang et al., in preparation

Established intruder nature of 1/2 isomeric state in ^{79}Zn

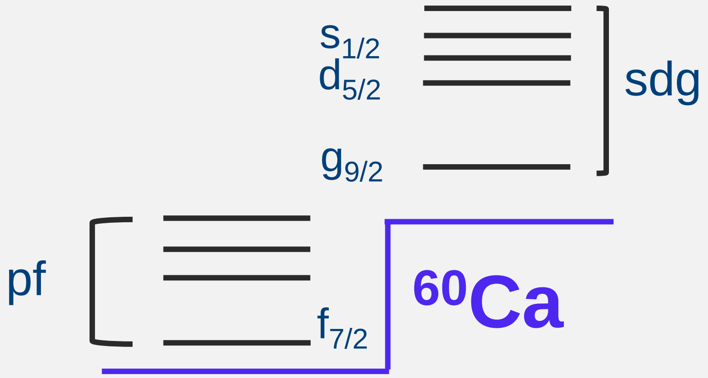


A3DA-modified



Y. Tsunoda et al., PRC 89, 031301(R) (2014)

New interaction

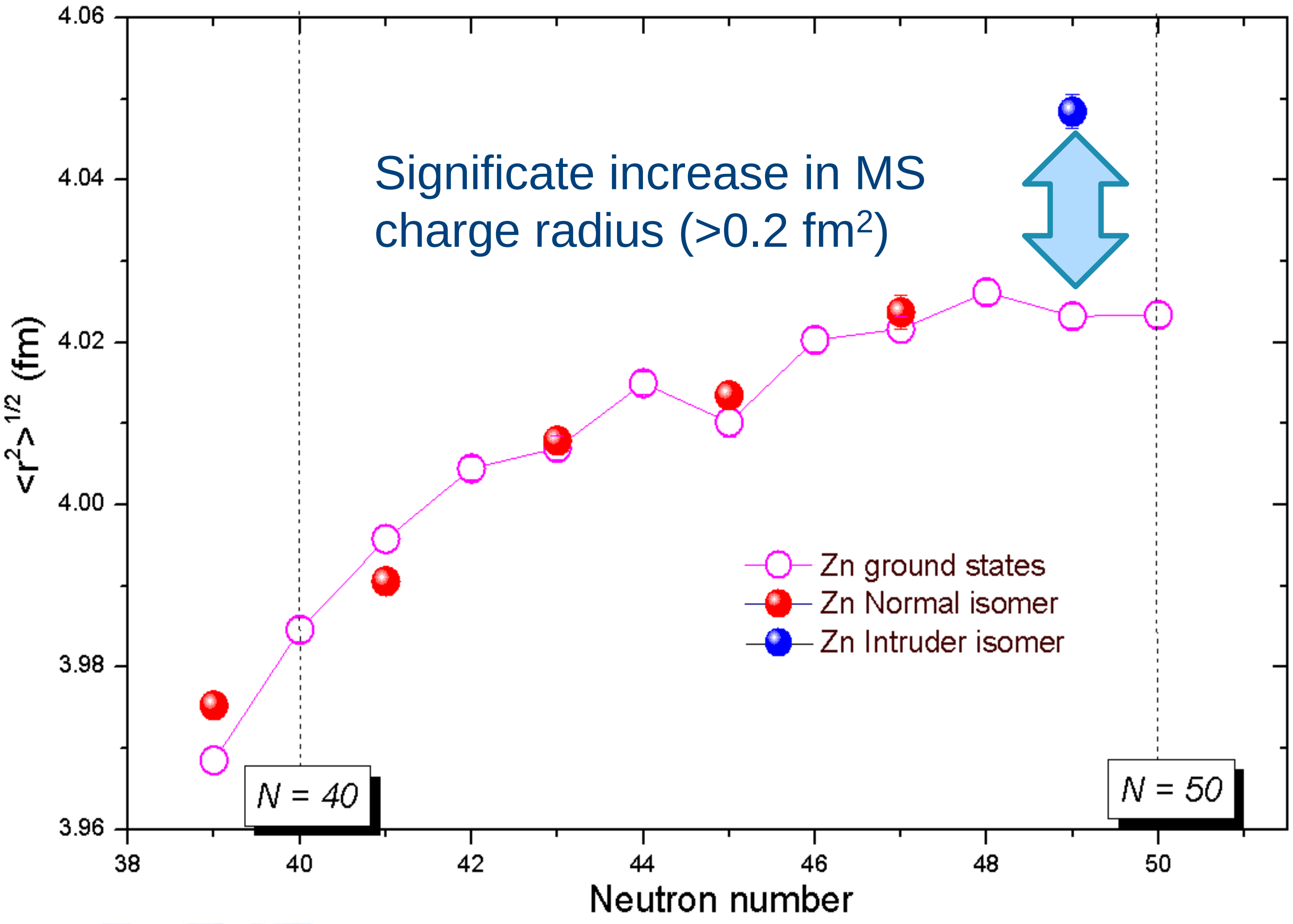


F. Nowacki et al., sdg-pf space

X.F. Yang et al., PRL 116, 182502 (2016)

C. Wright, X.F. Yang et al., in preparation

^{79g,m}Zn radii → isomer shift = signature for shape coexistence



Significate increase in MS charge radius (>0.2 fm^2)

→ Confirm by performing COULEX on the isomeric beam to measure its deformation !

X.F. Yang et al., PRL 116, 182502 (2016)

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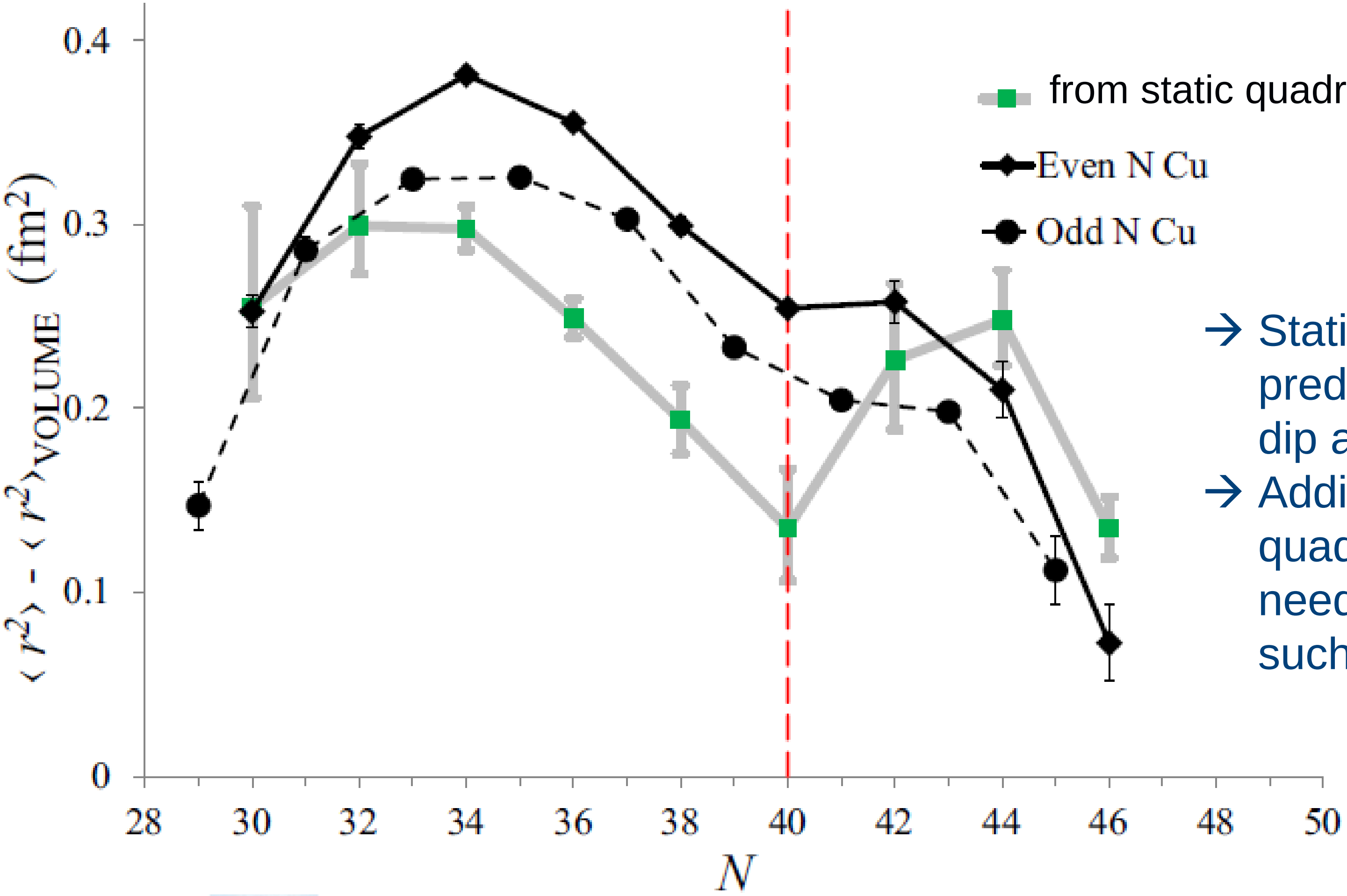
Charge radii: sensitive to shell gaps

Charge radii of Cu isotopes: very weak subshell effect at N=40

→ Data on Ni isotopes up to ^{70}Ni under analysis



→ Static deformation alone predicts much stronger dip at N=40

→ Additional (pairing, quadrupole) correlations needed to reproduce such weak dip

M.L. Bissell et al., PRC **93**, 064318 (2016)

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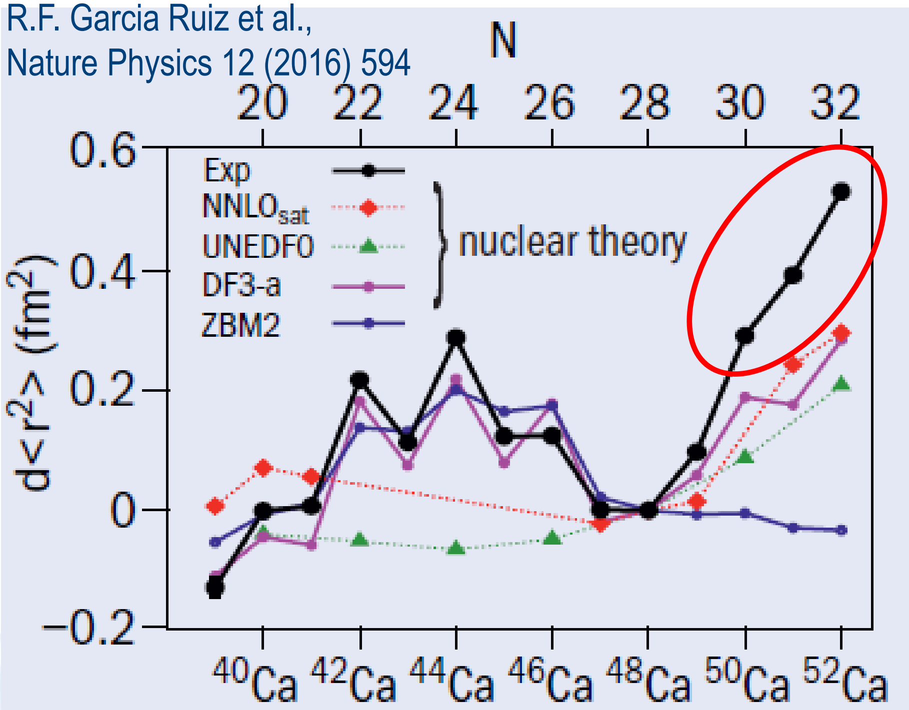
Charge radii and moments of Ca and K: N=32 shell gap ?

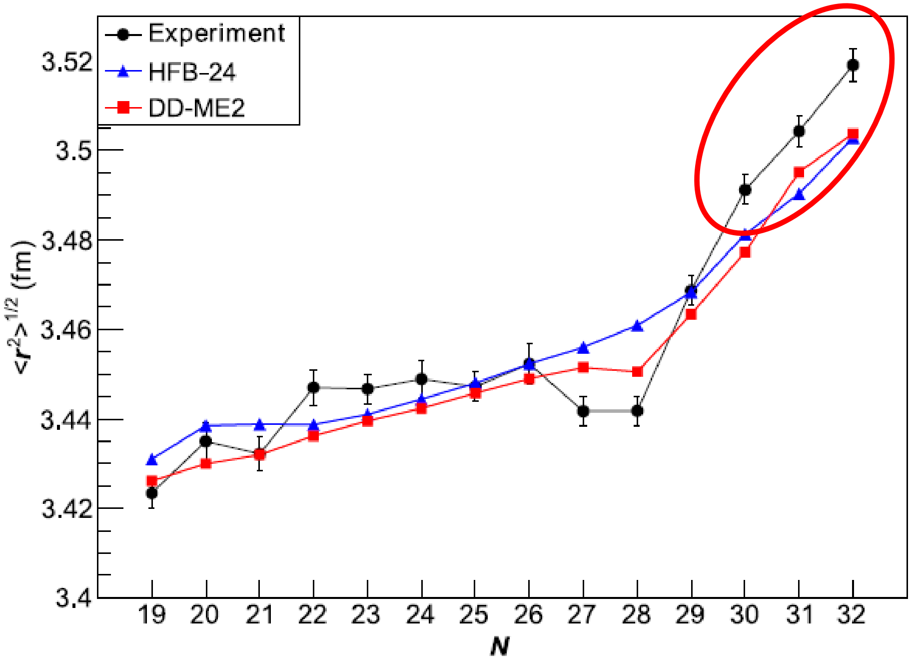
Ca (Z=20) closed proton shell

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



K (Z=19)

K. Kreim et al., PLB 731 (2014) 97



- No signature for a shell gap at N=32 (radii of ^{52}Ca and ^{51}K are increasing)
- From nuclear moments of Ca isotopes: excitations across N=32 needed to reproduce magnetic moment of ^{51}Ca (R. Garcia-Ruiz et al., 91, 041304(R) (2015))

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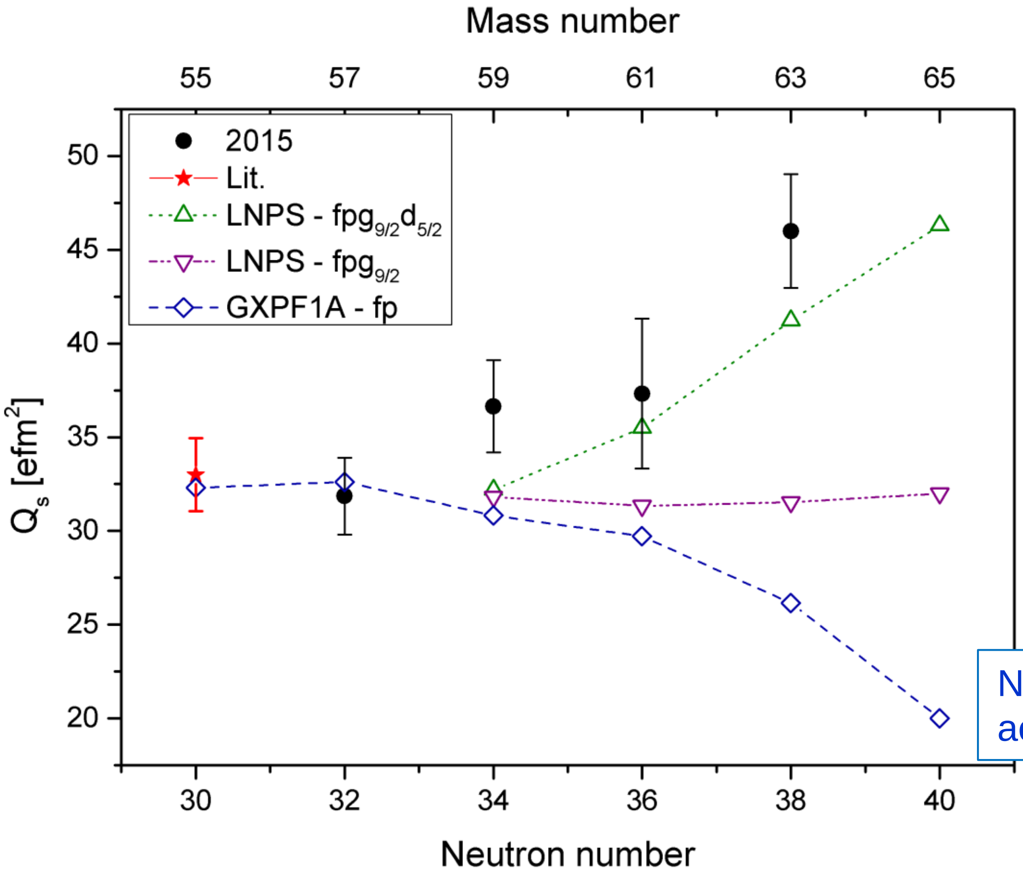
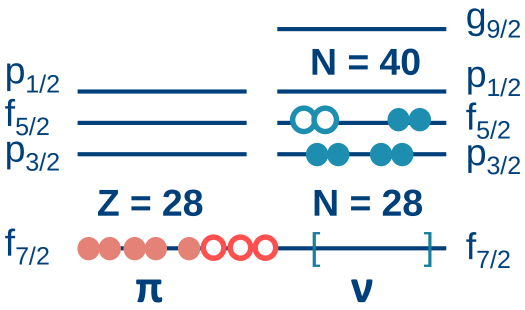
Quadrupole moments: sensitive to correlations and deformation

Mn isotopes (Z=25)



No excitations across N = 40



GXPF1A

Honma, PRC65 (2002);

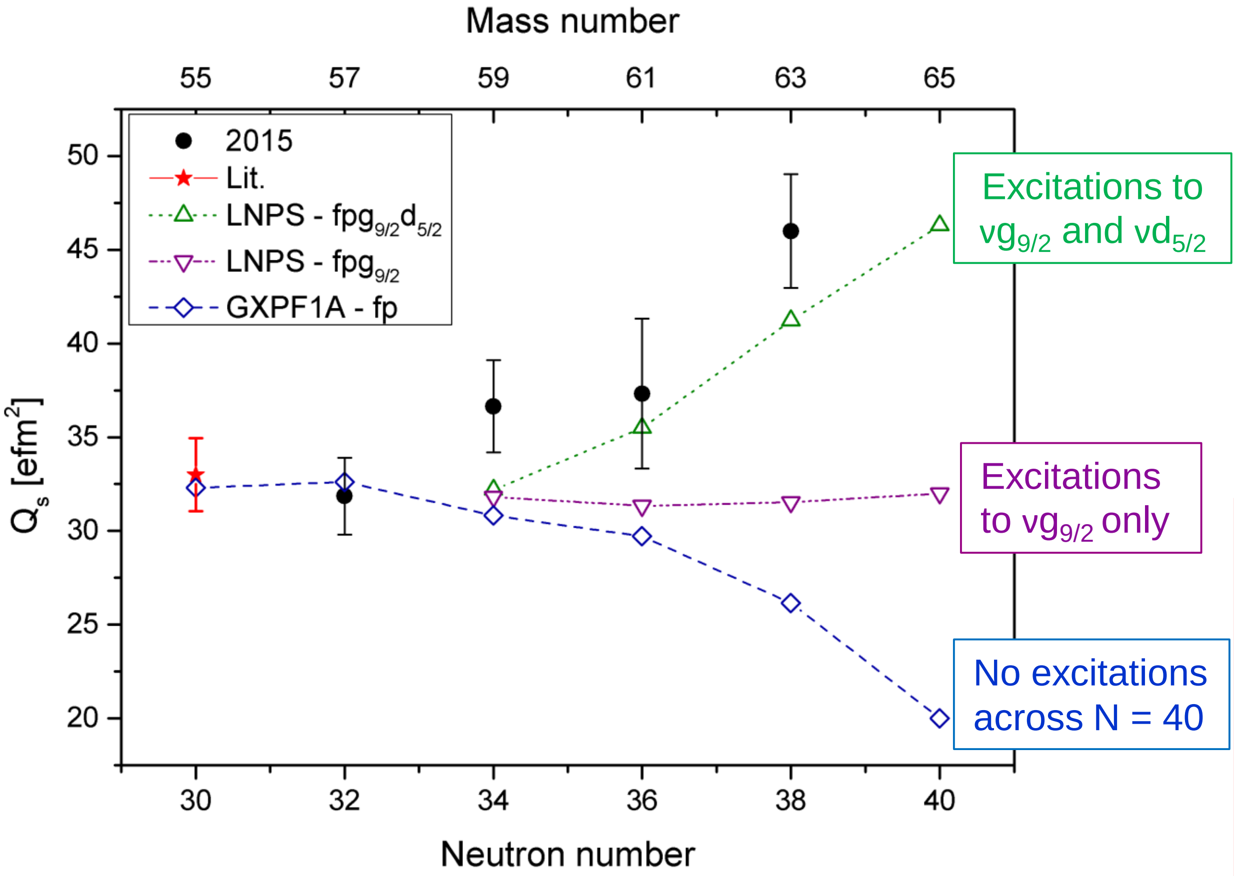
40Ca core

π and ν in fp-shell

All isotopes have I=5/2
except ^{53}Mn (at N=28) has normal I=7/2

C.Babcock, H. Heylen et al., PLB 760 (2016) 387

Quadrupole moments: sensitive to correlations and deformation

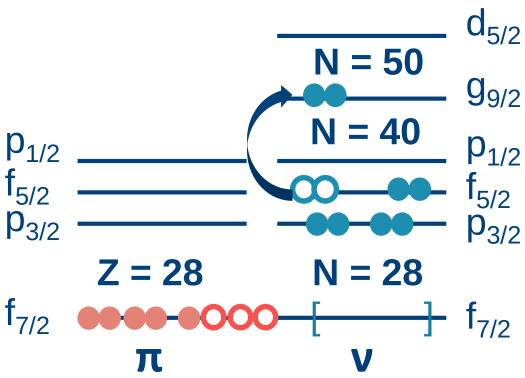


Excitations to $\nu g_{9/2}$ and $\nu d_{5/2}$

Excitations to $\nu g_{9/2}$ only

No excitations across N = 40

Mn isotopes (Z=25)

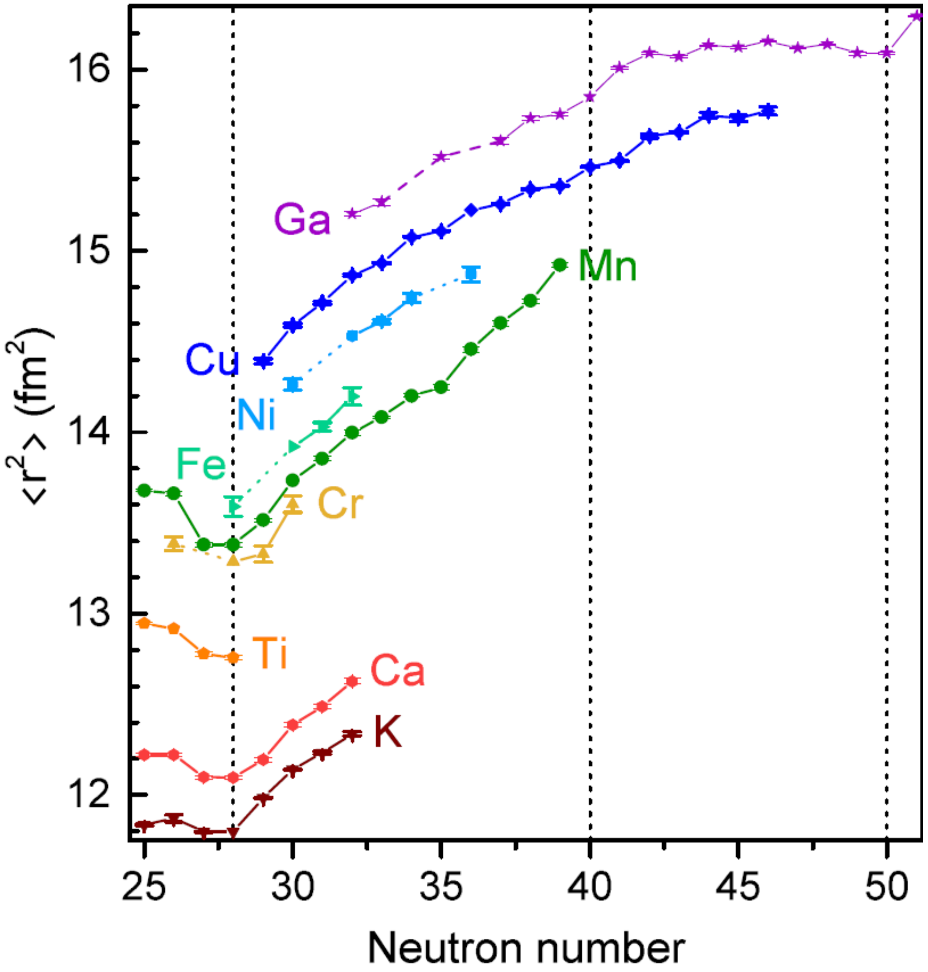


GXPF1A	LNPS
Honma, PRC65 (2002);	Lenzi, PRC82 (2010)
40Ca core	48Ca core
π fp-shell	π fp-shell
ν fp-shell	ν upper fp + $g_{9/2}d_{5/2}$

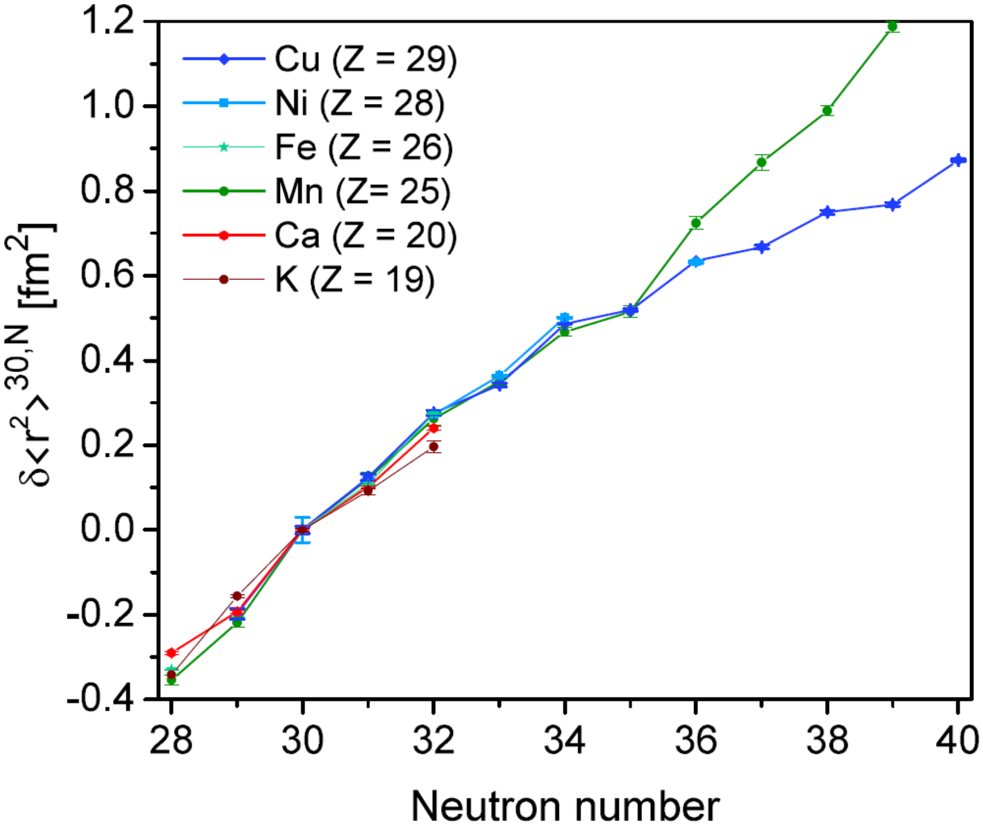
→ neutron excitations are needed from N=36 onwards, into $\nu g_{9/2}$ and $\nu d_{5/2}$!

C.Babcock, H. Heylen et al., PLB 760 (2016) 387

Radii of Mn isotopes



Consistent with conclusion from Q-moments



Onset of deformation from N=36 onwards

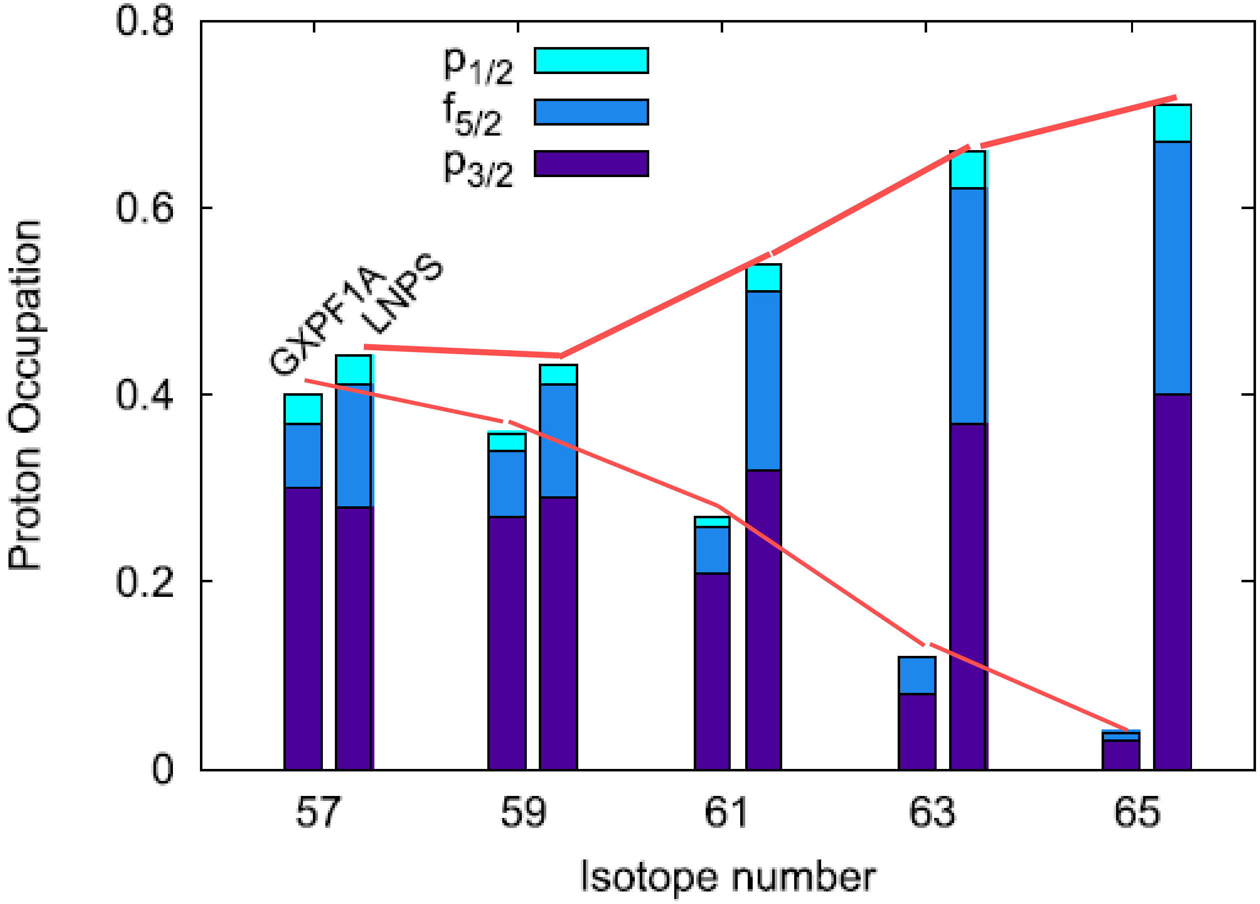
KU LEUVEN

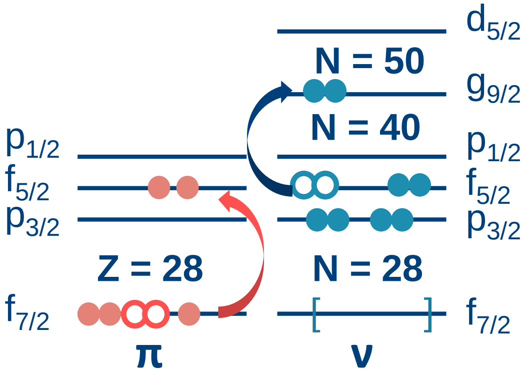
H. Heylen, C.Babcock, et al., PRC 94, 054321 (2016)

Moments: probing the wave function

Mn isotopes (Z=25)

LNPS reproduces the moments → correct wave function



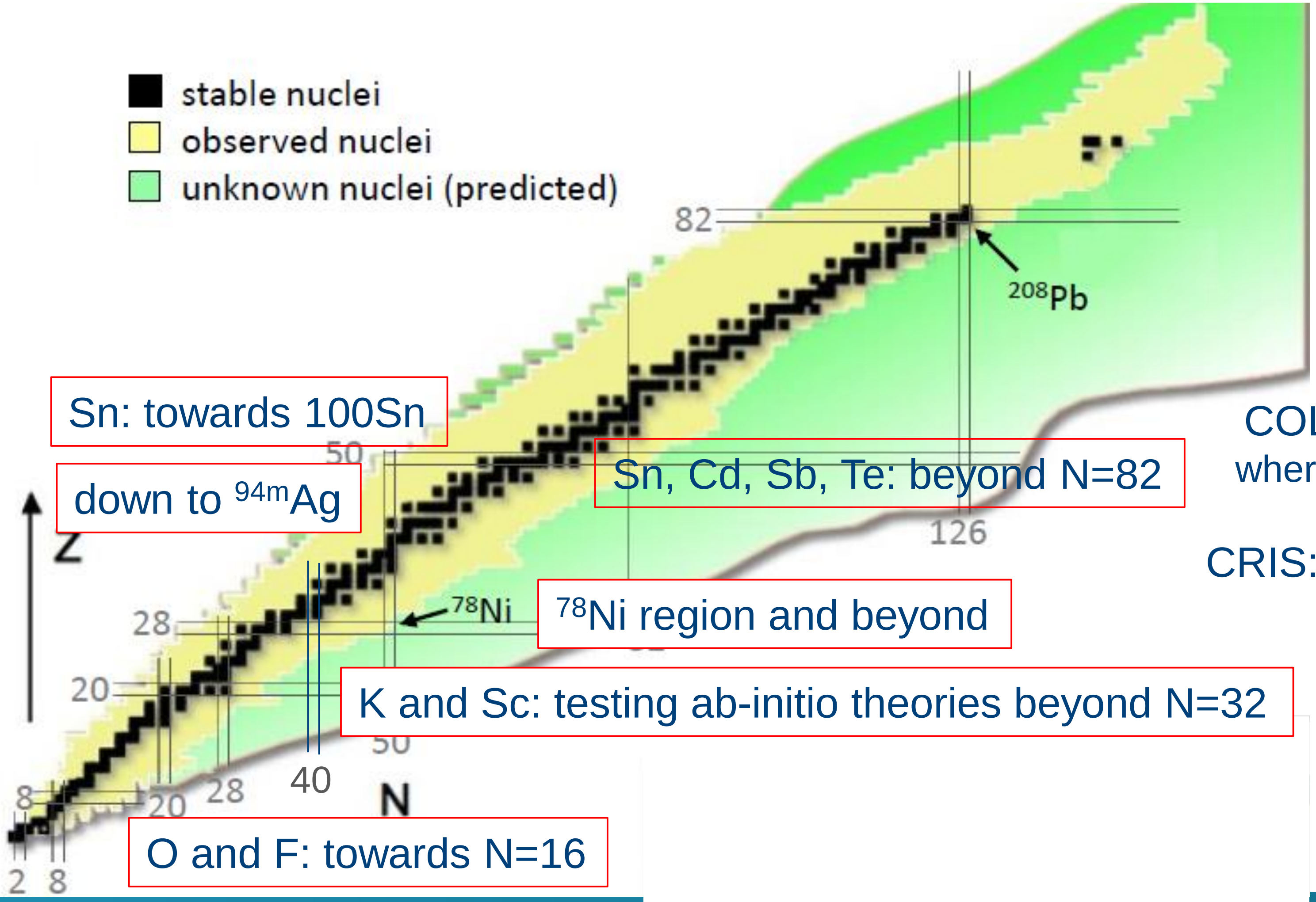


Excitations across N = 40 induce increase in proton excitations across Z=28
(type-II shell evolution Tsunoda et al., PRC89, 2014)

C.Babcock, H. Heylen et al., PLB 750 (2015) 176

Future cases

Main focus:
- transition regions between/towards closed shells
- towards exotic doubly-magic nuclei
- neutron-deficient proton emitters



Sn: towards 100Sn

down to ^{94m}Ag

Sn, Cd, Sb, Te: beyond N=82

^{78}Ni region and beyond

K and Sc: testing ab-initio theories beyond N=32

O and F: towards N=16

COLLAPS: preferred where possible (easier)

CRIS: towards very exotic regions

CONCLUSIONS

Nuclear spins, moments and radii are complementary probes to study nuclear structure far from stability

Complementary laser spectroscopy methods are needed:

- related to production method
- related to sensitivity/efficiency
- related to resolution
- related to ‘easiness’

(each method has its pro’s and contra’s)

Other probes are needed to complement the physics interpretation:
each observable probes different aspects of the nuclear structure

- coulex and transfer reactions
- masses
- decay spectroscopy
- lifetime measurements
- moments of exited states

R. Neugart et al., ISOLDE Laboratory Report, Nov. 2016

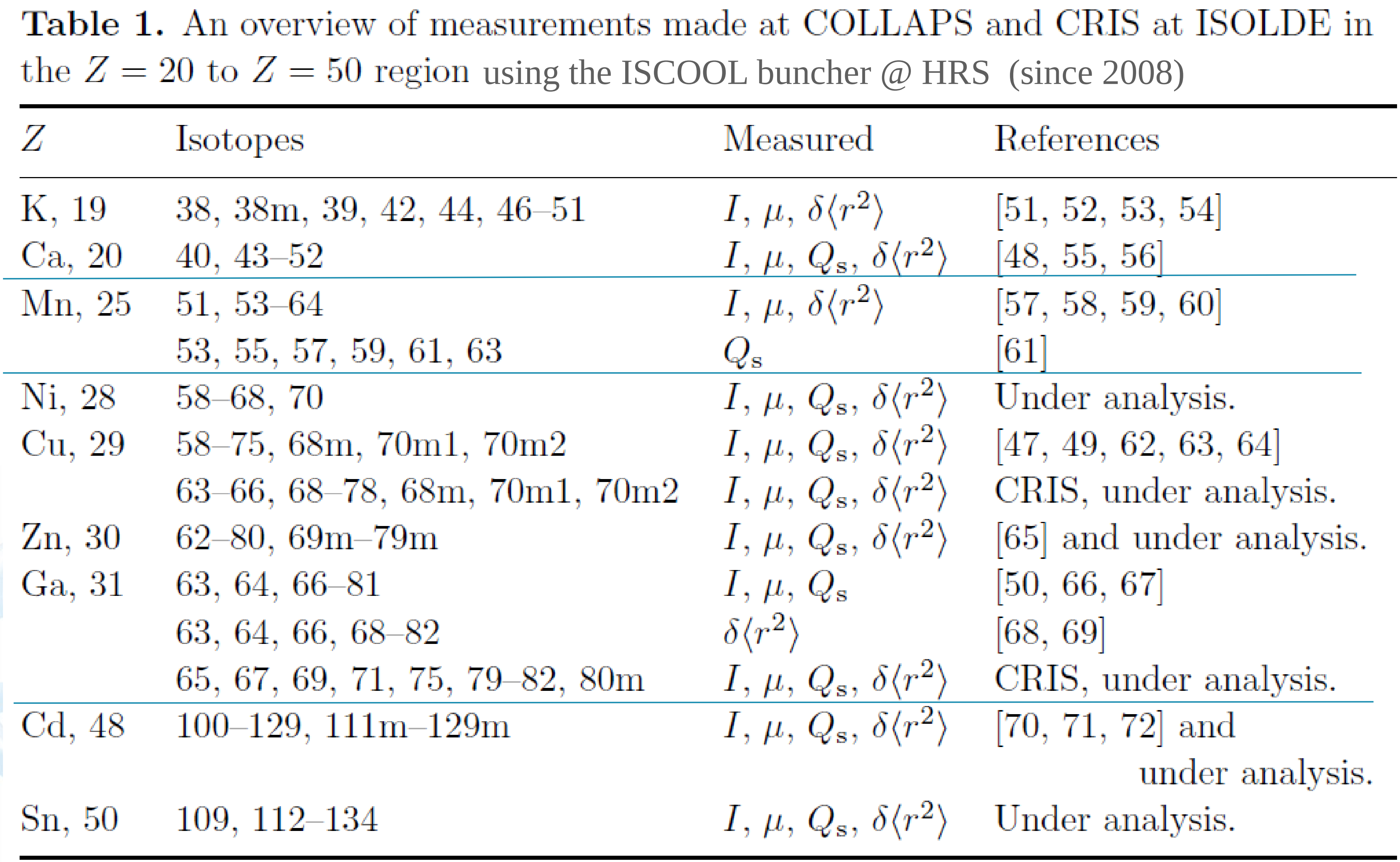


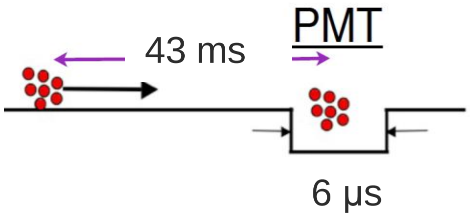
Table 1. An overview of measurements made at COLLAPS and CRIS at ISOLDE in the $Z = 20$ to $Z = 50$ region using the ISCOOL buncher @ HRS (since 2008)

Z	Isotopes	Measured	References
K, 19	38, 38m, 39, 42, 44, 46–51	I, μ, $\delta\langle r^2\rangle$	[51, 52, 53, 54]
Ca, 20	40, 43–52	I, μ, Q_s, $\delta\langle r^2\rangle$	[48, 55, 56]
Mn, 25	51, 53–64	I, μ, $\delta\langle r^2\rangle$	[57, 58, 59, 60]
	53, 55, 57, 59, 61, 63	Q_s	[61]
Ni, 28	58–68, 70	I, μ, Q_s, $\delta\langle r^2\rangle$	Under analysis.
Cu, 29	58–75, 68m, 70m1, 70m2	I, μ, Q_s, $\delta\langle r^2\rangle$	[47, 49, 62, 63, 64]
	63–66, 68–78, 68m, 70m1, 70m2	I, μ, Q_s, $\delta\langle r^2\rangle$	CRIS, under analysis.
Zn, 30	62–80, 69m–79m	I, μ, Q_s, $\delta\langle r^2\rangle$	[65] and under analysis.
Ga, 31	63, 64, 66–81	I, μ, Q_s	[50, 66, 67]
	63, 64, 66, 68–82	$\delta\langle r^2\rangle$	[68, 69]
	65, 67, 69, 71, 75, 79–82, 80m	I, μ, Q_s, $\delta\langle r^2\rangle$	CRIS, under analysis.
Cd, 48	100–129, 111m–129m	I, μ, Q_s, $\delta\langle r^2\rangle$	[70, 71, 72] and under analysis.
Sn, 50	109, 112–134	I, μ, Q_s, $\delta\langle r^2\rangle$	Under analysis.

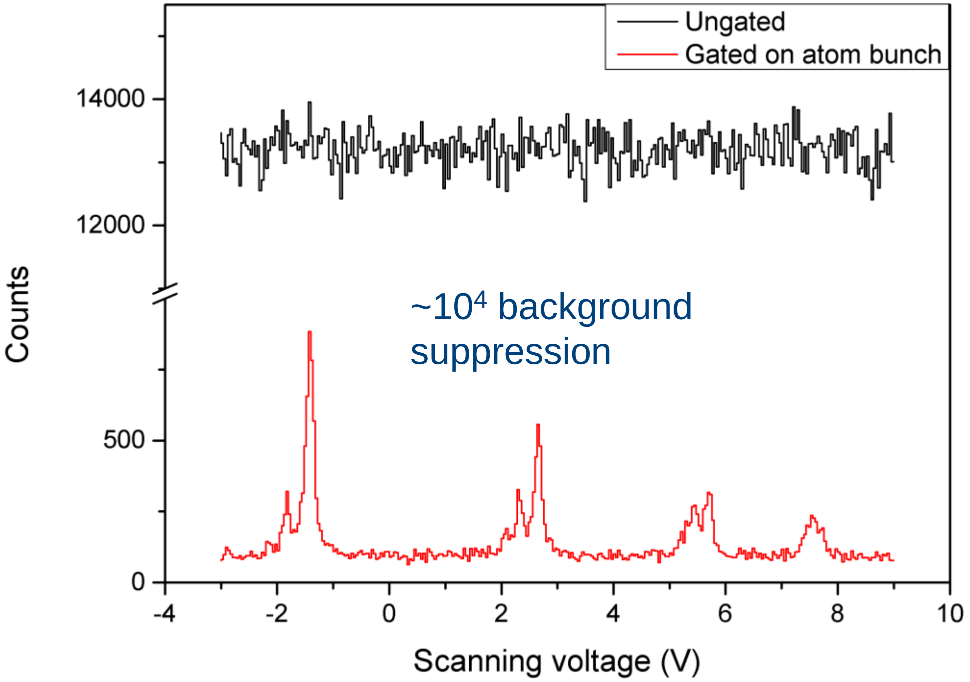
26 papers since 2009: 10 PRL, 4 PLB, 1 Nature Physics

Use of ‘bunched’ beams from RFQ (ISCOOL) is crucial

at COLLAPS (CW lasers)



measure photons
only during the bunch length



~10^4 background suppression

at CRIS (pulsed lasers)

✓ efficiency (duty-cycle) enhanced by factor 1000 by time-overlap between the ion bunch and the laser pulses

CRIS with CW atom beam:
(Schulz et al., J. Phys. B 24, 1991)
efficiency = 0.001 %

CRIS with bunched atom beam:
(Flanagan et al., Phys. Rev. Lett. 111, 212501 (2013)
efficiency = 1 %
(De Groote et al. Phys. Rev. Lett. 115, 132501 (2015))
resolution = 20 MHz !