Nuclear structure studies by the measurement of nuclear spins, moments and charge radii

-Using laser spectroscopy- (COLLAPS & CRIS)

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Outline :

- **Introduction**
  - ✓ My group
  - ✓ Regions of interest
  - ✓ Observables (using few examples from COLLAPS experiments)

- **Experimental methods**
  - ✓ COLLAPS (Collinear Laser Spectroscopy) (Ni, Zn as example)
  - ✓ CRIS (Collinear resonance ionization spectroscopy) (Cu as example)

- **COLLAPS results for $^{62-80}$Zn isotopes** ← **Main focus**
  - ✓ Spins, moments and charge radii

- **Further plans in Ni and Ca regions**
  - ✓ Ge experiment approved at COLALPS
  - ✓ K Sc experiments approved at CRIS

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What we do….

Measure nuclear ground/isomeric states properties

- Spins
- Nuclear moment (u,Q)
- Mean square charge radii

To probe…

- Nuclear wave function
- Deformation and collectivity
- ….

By using…

This talk

- Laser spectroscopy at ISOLDE, CERN
  COLLAPS: collinear laser spectroscopy
  CRIS :collinear resonance ionization spectroscopy

- β-NMR at LISE, GANIL

Nuclear Moment group

Prof. Gerda Neyens

We also do…

β-NMR and β-asymmetry measurement of radioactive isotopes polarized by laser technique at **VITO-ISOLDE (New beam line commissioned this year)**

To study.. (near future)

nuclear physics, fundamental interactions, material and life science

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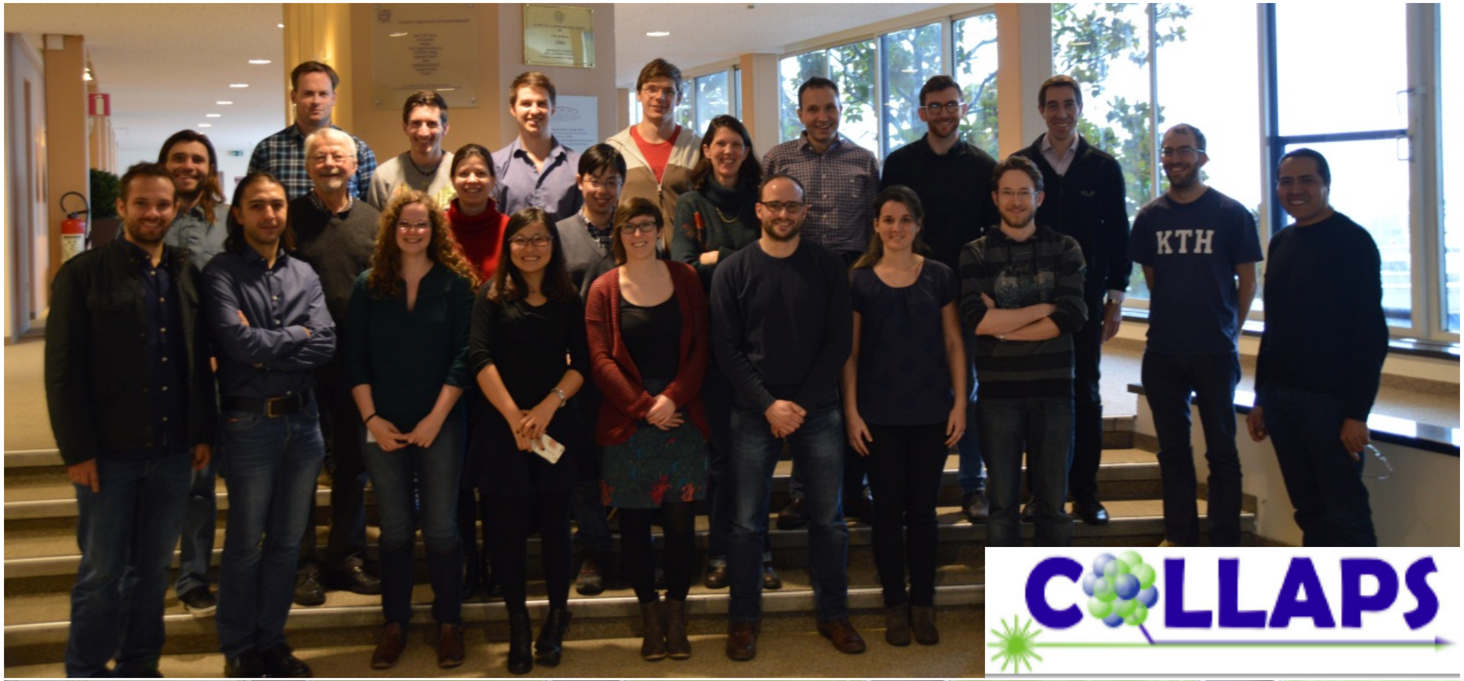
with thanks to the COLLAPS and CRIS collaborations at ISOLDE-CERN



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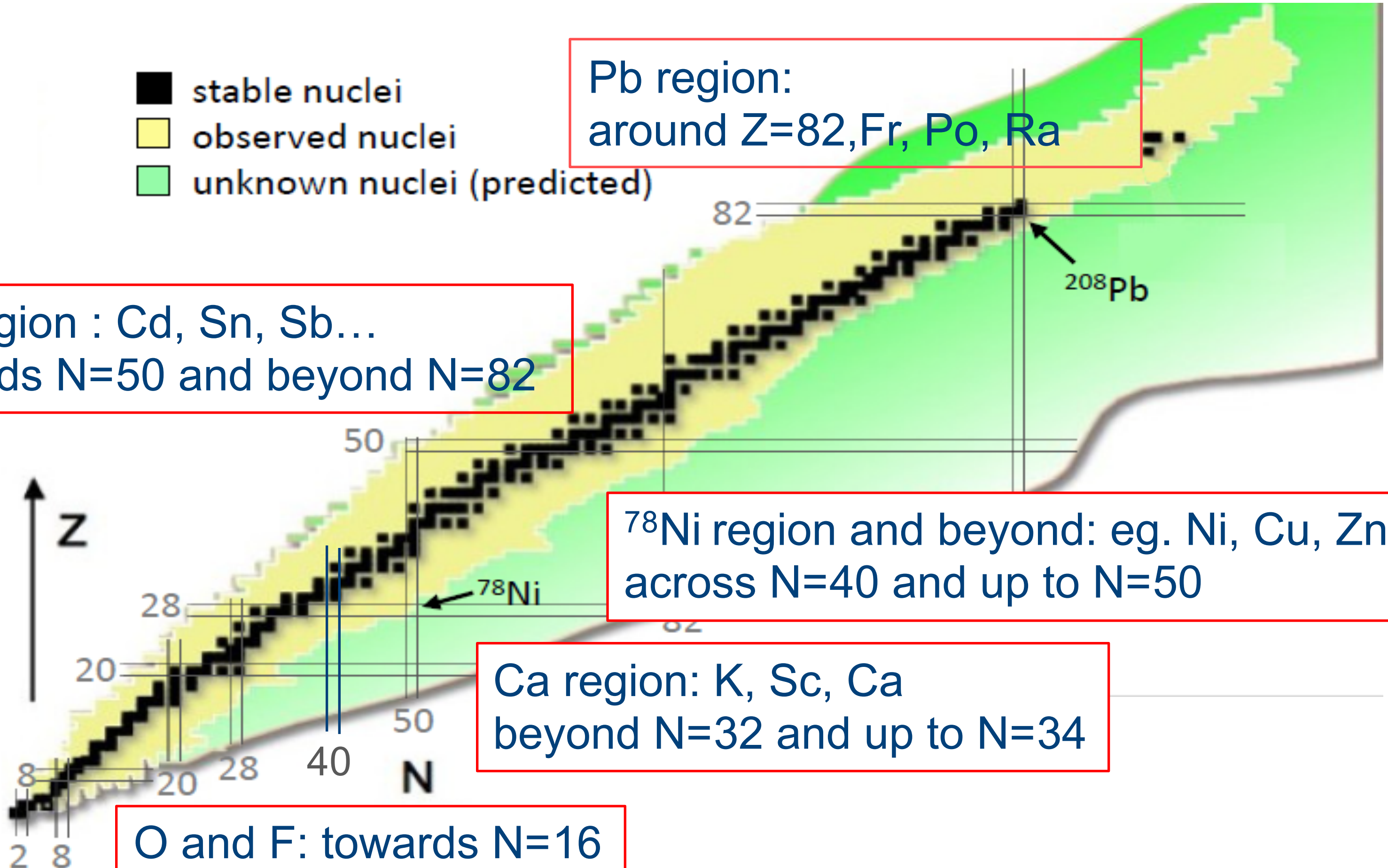
Research interests in our group

Main focus: - transition regions between/towards closed shells
- towards exotic doubly-magic nuclei



Pb region:
around Z=82,Fr, Po, Ra

Sn region : Cd, Sn, Sb…
towards N=50 and beyond N=82

^{78}Ni region and beyond: eg. Ni, Cu, Zn, Ga, Ge….
across N=40 and up to N=50

Ca region: K, Sc, Ca
beyond N=32 and up to N=34

O and F: towards N=16

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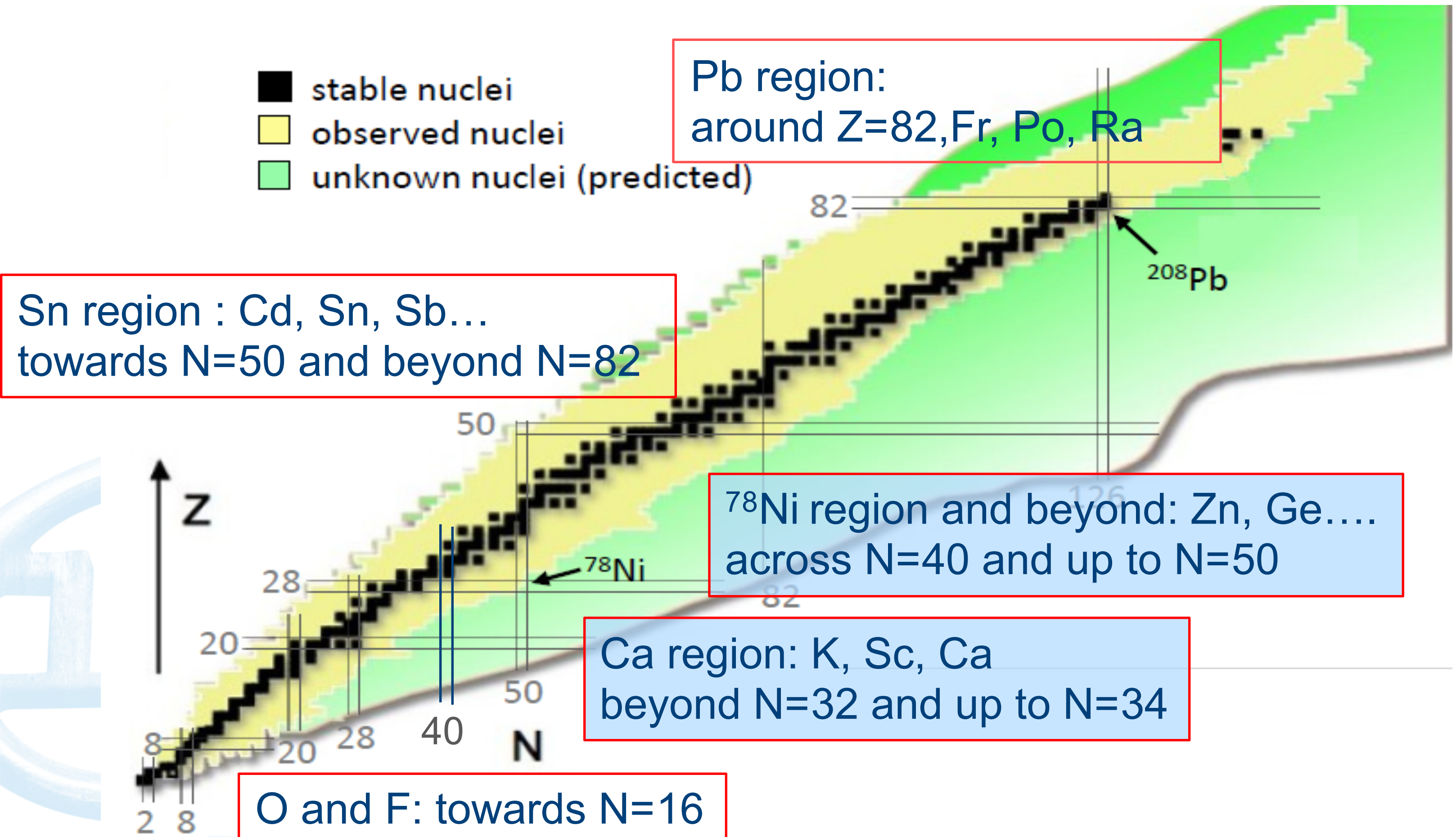
My research focus on…

Main focus:
- transition regions between/towards closed shells
- towards exotic doubly-magic nuclei



How to measure? =>Probe the hyperfine structure

$\Delta E = \mathbf{A} \cdot K/2 + \mathbf{B} \cdot \{3K(K+1)/4 - I(I+1)J(J+1)\}/\{2(2I-1)(2J-1)IJ\}, K=F(F+1)-I(I+1)-J(J+1)$

Atomic parameters

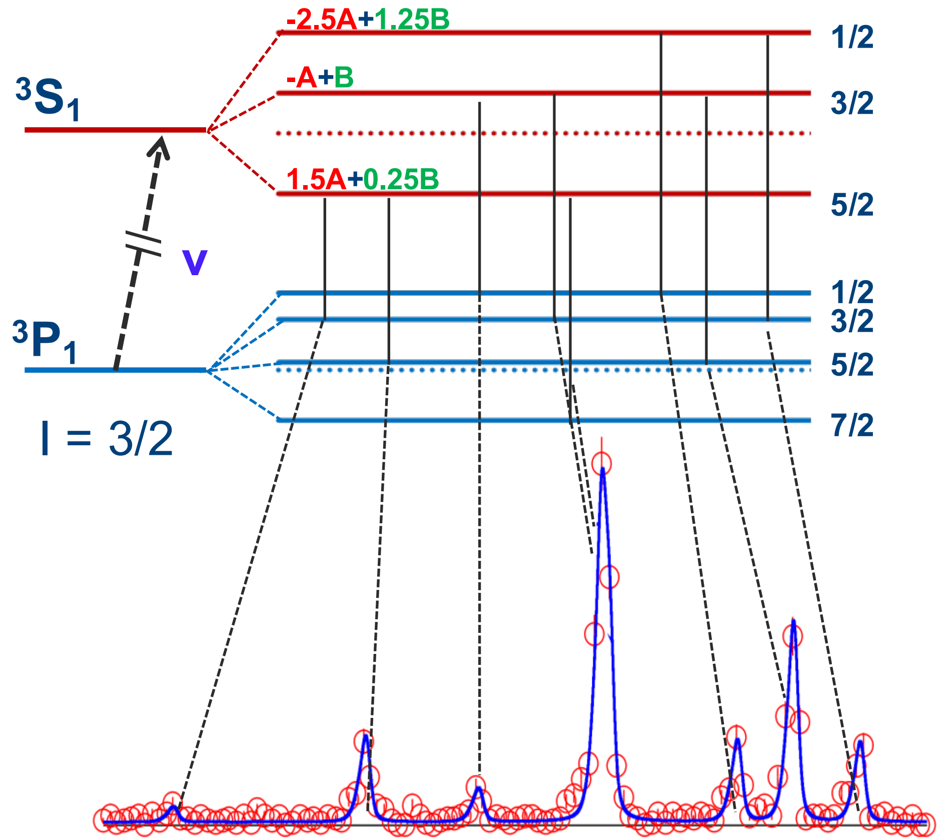
- Magnetic dipole HF parameter

$$A = \frac{\mu_I B_J}{IJ}$$ **I, μ**

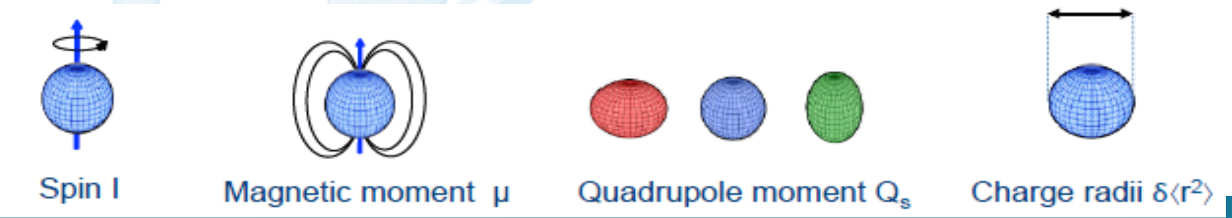
- Electric quadrupole HF parameter

$$B = eQV_{zz}$$ **Q**

- Centroid ν_0
  Isotopes shift **$\langle r^2\rangle^{1/2}$**



What we learn? => few examples will follow.



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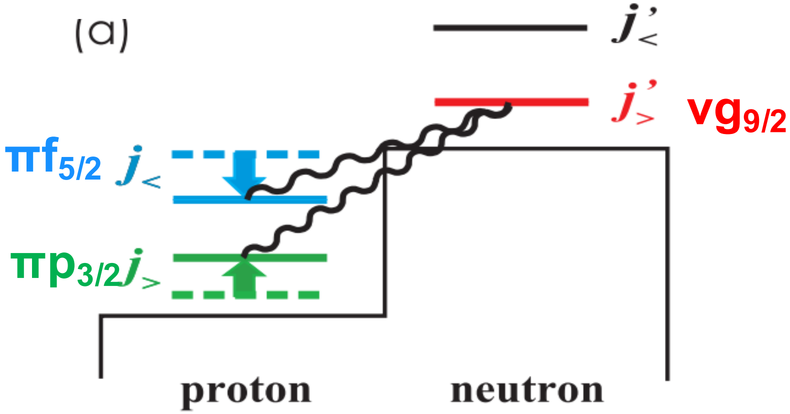
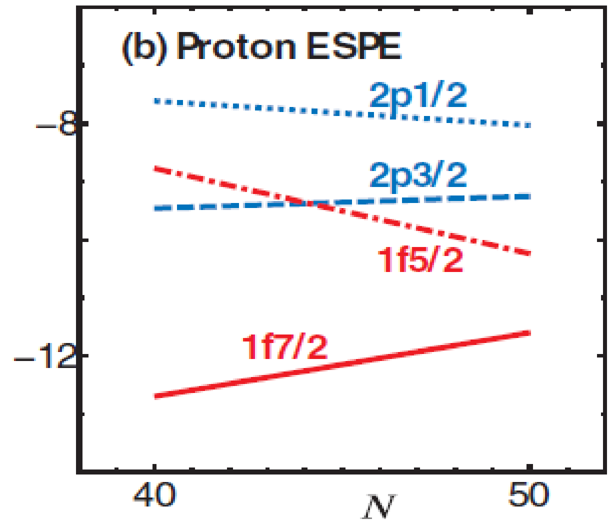
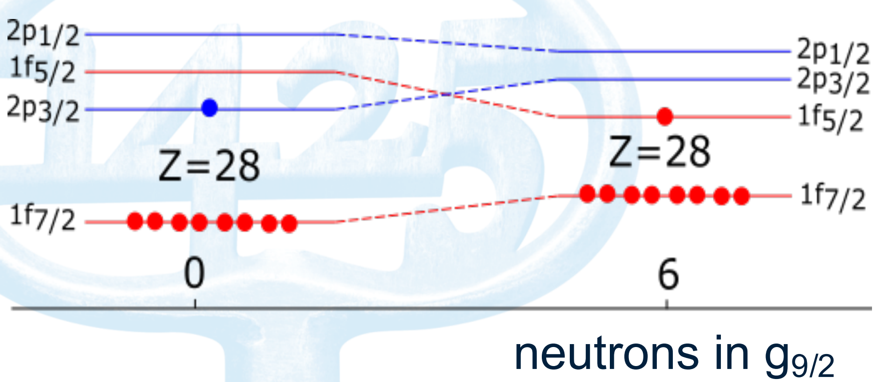
Nuclear spins⇔ shell evolution!

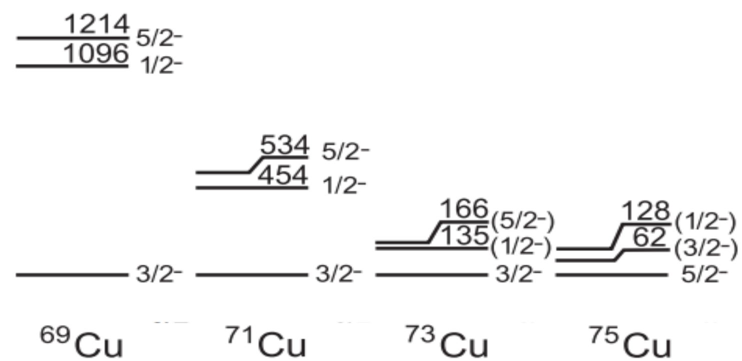




T. Otsuka et al, PRL **95**, 232502 (2005)

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





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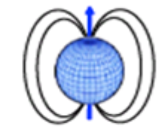
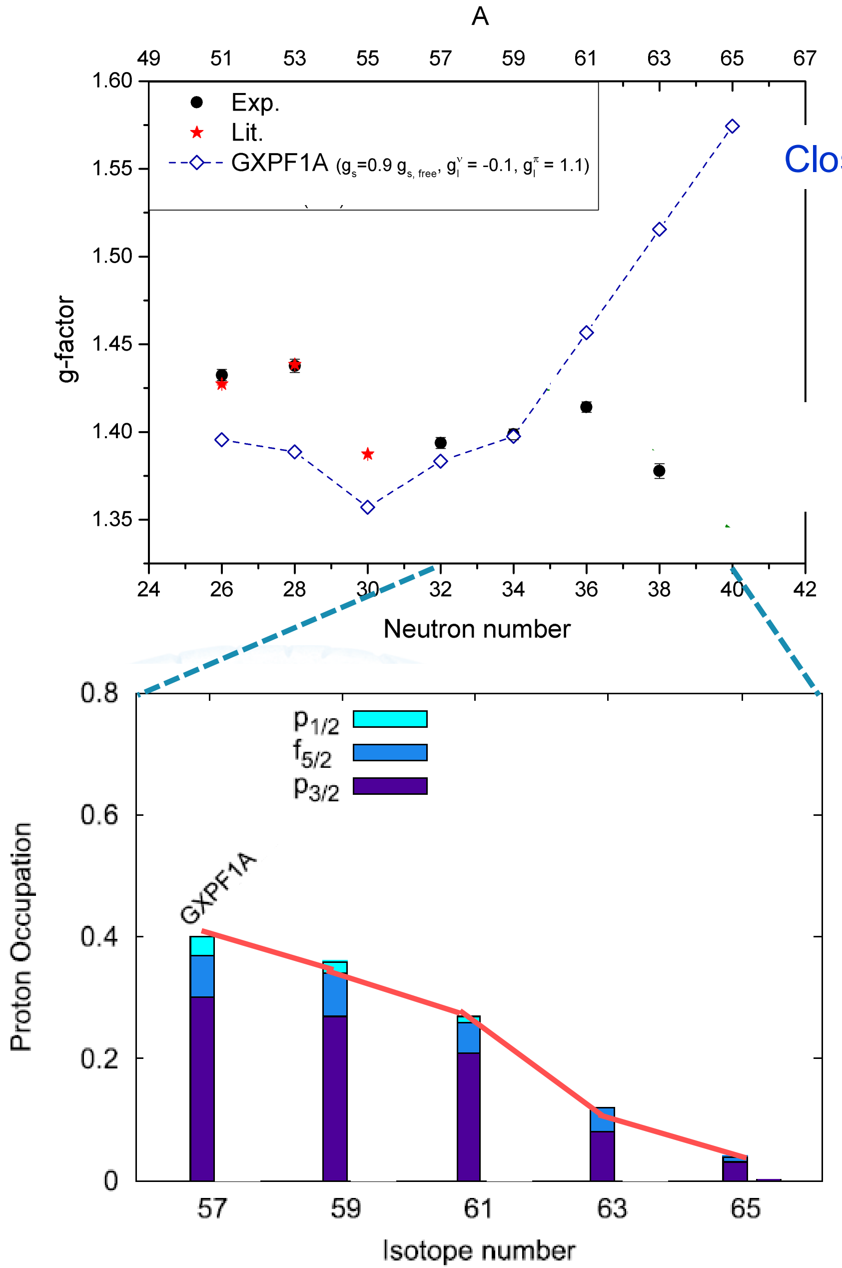
K. T. Flanagan et al., Phys. Rev. Lett. 103, 142501 (2009)

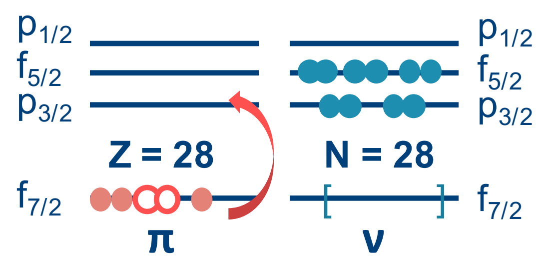
Magnetic moment (g-factor) ⬄ Wave function

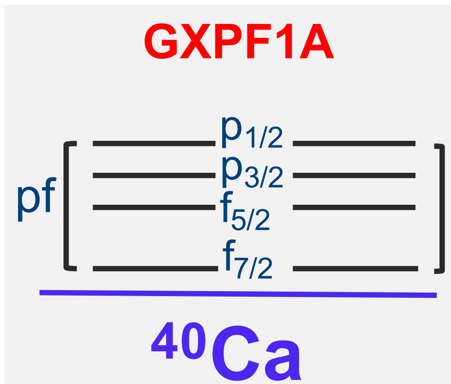




Closed N = 40

Mn isotopes (Z=25)





Honma, PRC65 (2002);

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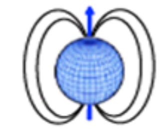
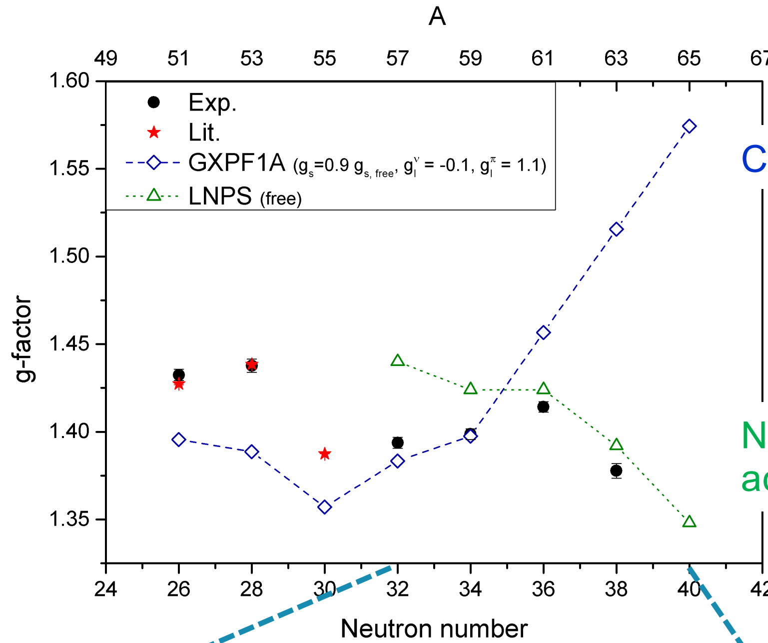
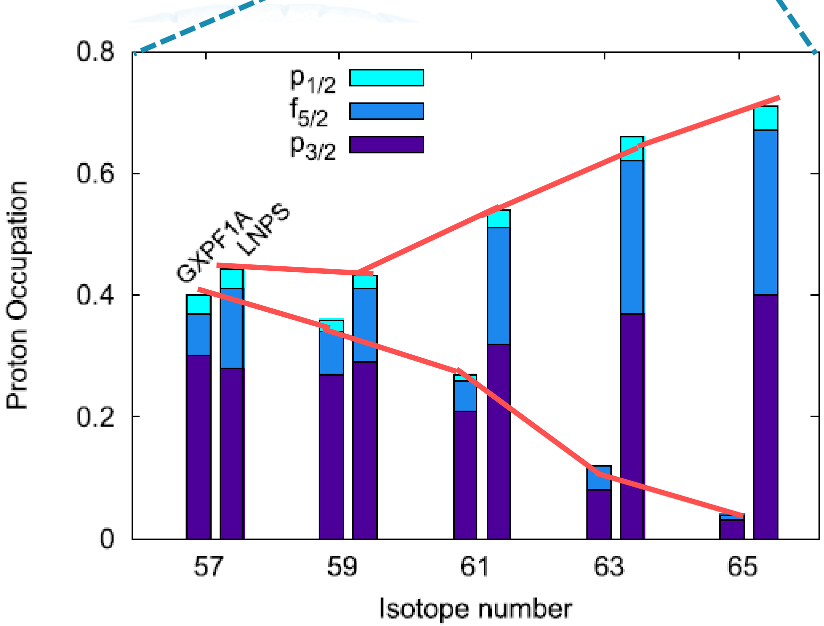
C.Babcock, H. Heylen et al., PLB 750 (2015) 176

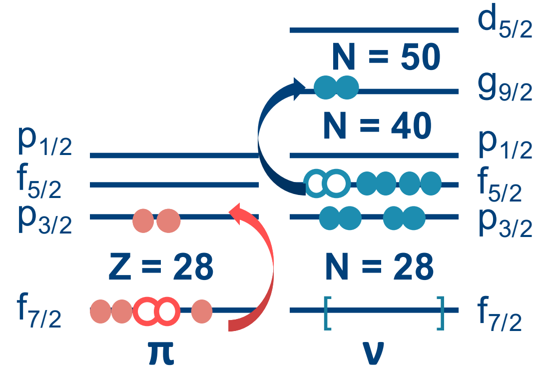
Magnetic moment (g-factor) ⬄ Wave function

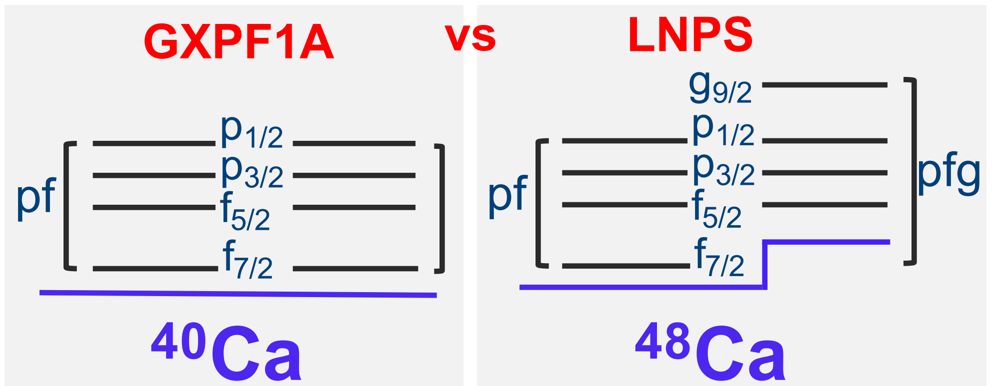






Mn isotopes (Z=25)





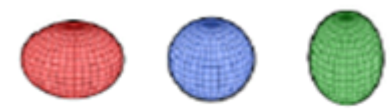
Honma, PRC65 (2002); Lenzi, PRC82 (2010)

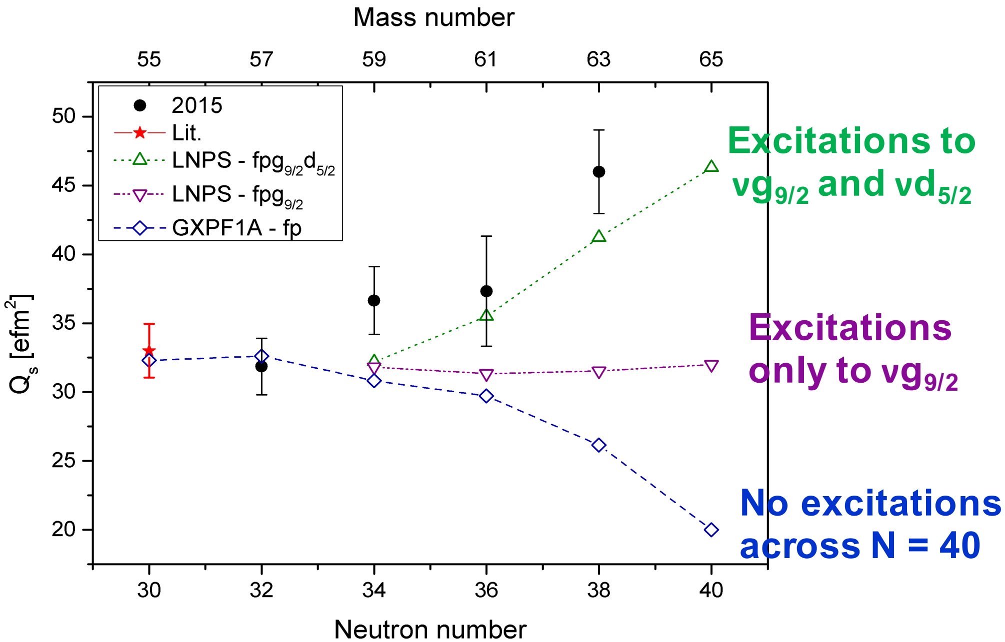
Excitations across *N* = 40 induce increase in proton excitations across *Z* = 28

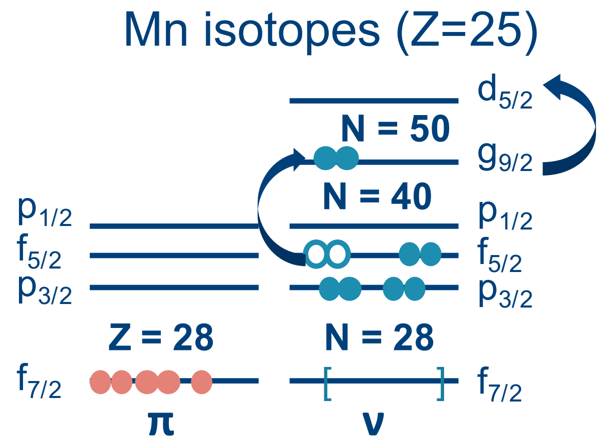
(type-II shell evolution Tsunoda et al., PRC89, 2014)

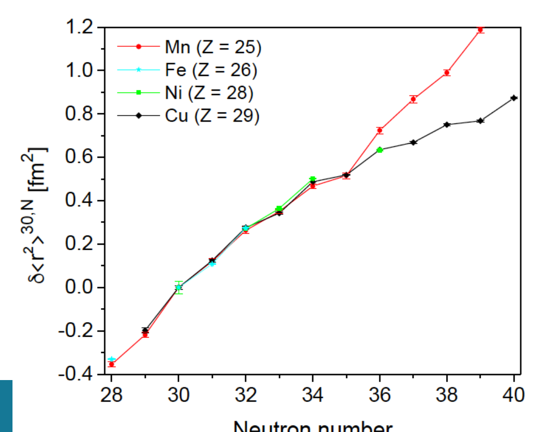
C.Babcock, H. Heylen et al., PLB 750 (2015) 176

Quadrupole moment ⇔ deformation/ correlations









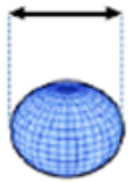
→ neutron excitations are needed from N =36 onwards, into $\nu g_{9/2}$ and $\nu d_{5/2}$!

Onset of deformation

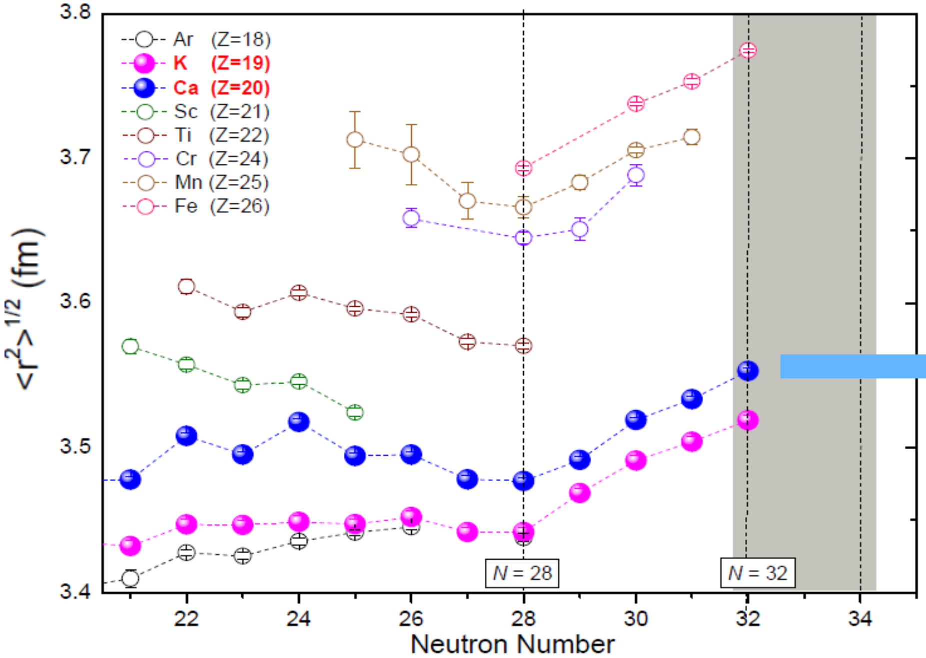
- Particle-hole excitations across N = 40, N=50

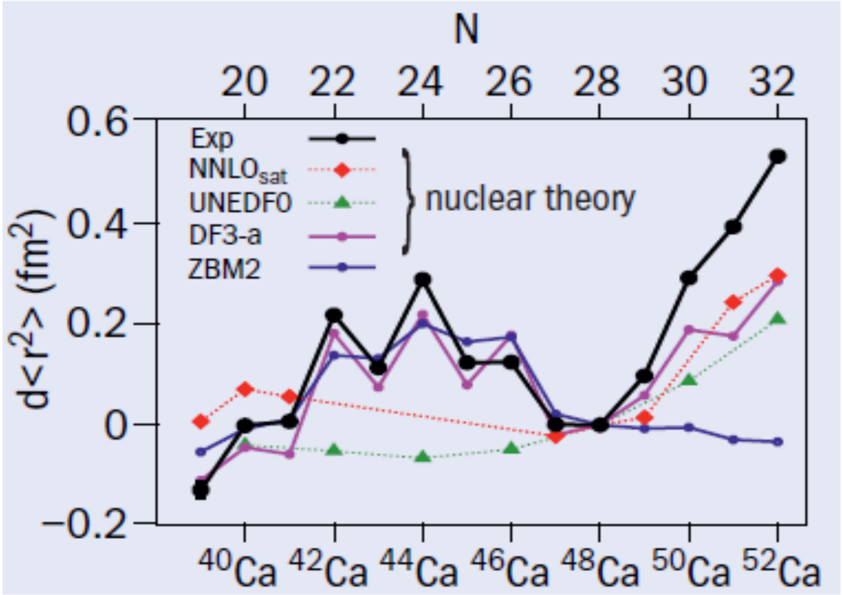
C.Babcock, H. Heylen et al., PLB 760 (2016) 387

Charge radii⇔ shell gap / magic numbers



Charge radii $\delta\langle r^2\rangle$





- ➢ **large charge radii of ^{52}Ca --no signature for shell closure at N=32 ?**
- ➢ **same trend as Fe --no shell closure is expected**

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

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laser spectroscopy techniques:

Collinear laser spectroscopy (COLLAPS)

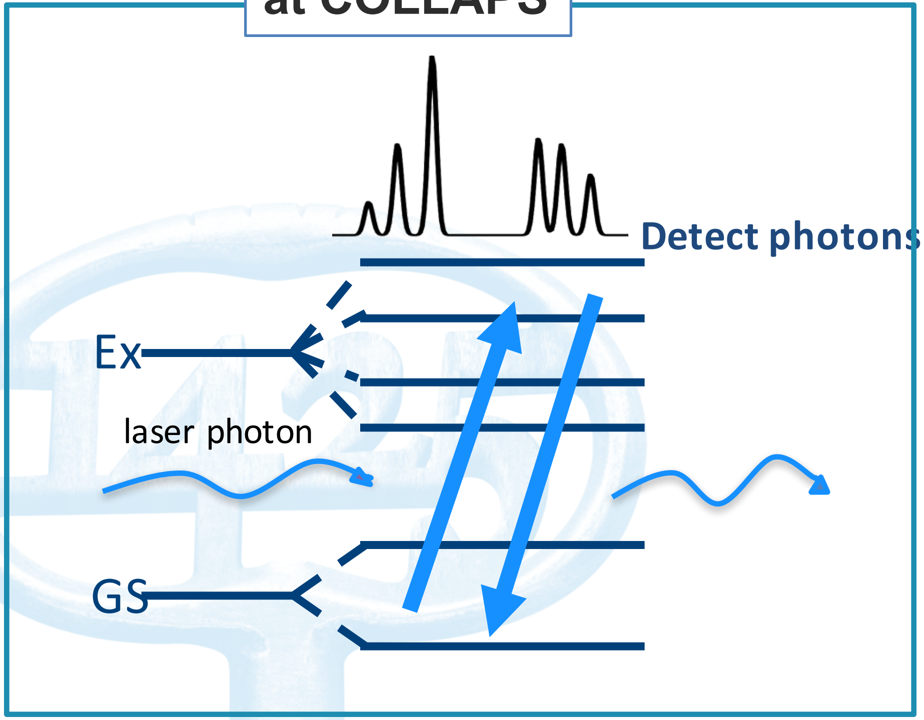
Collinear resonance ionization spectroscopy (CRIS)

In source spectroscopy

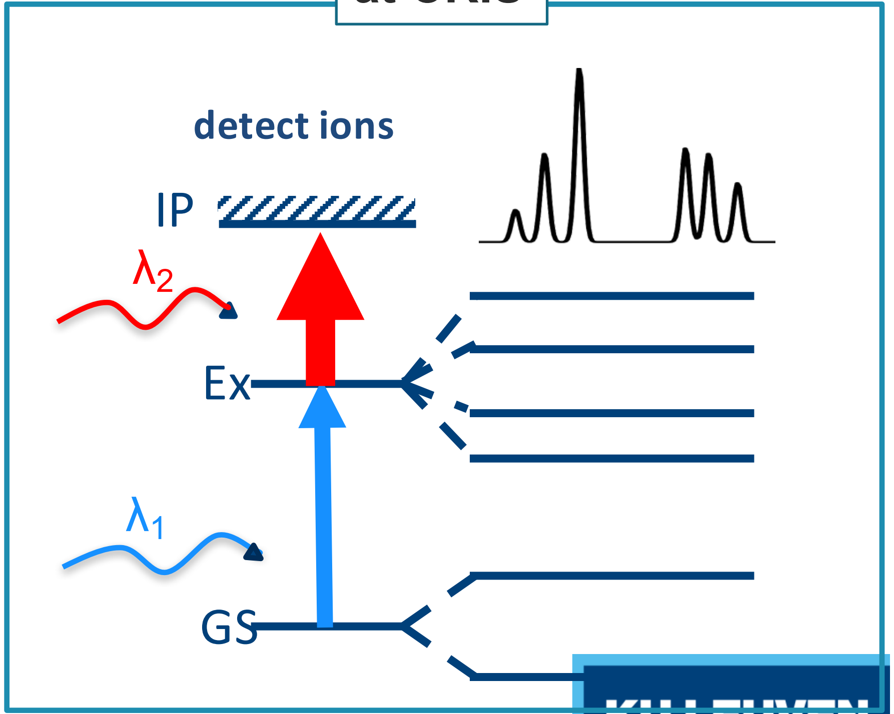
Laser spectroscopy of trapped ions/atoms

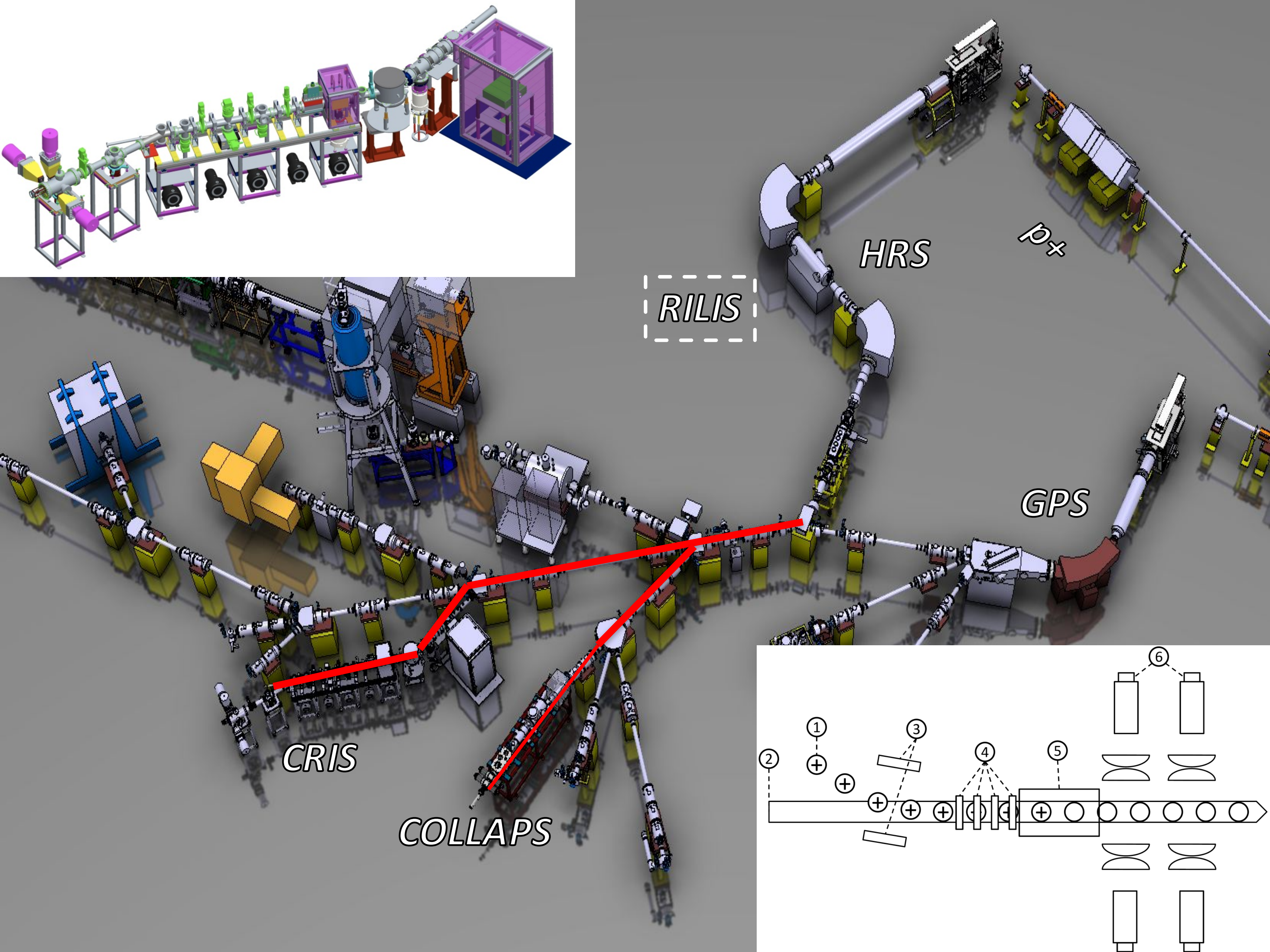
@ ISOLDE and using Cooled bunched beam

at COLLAPS

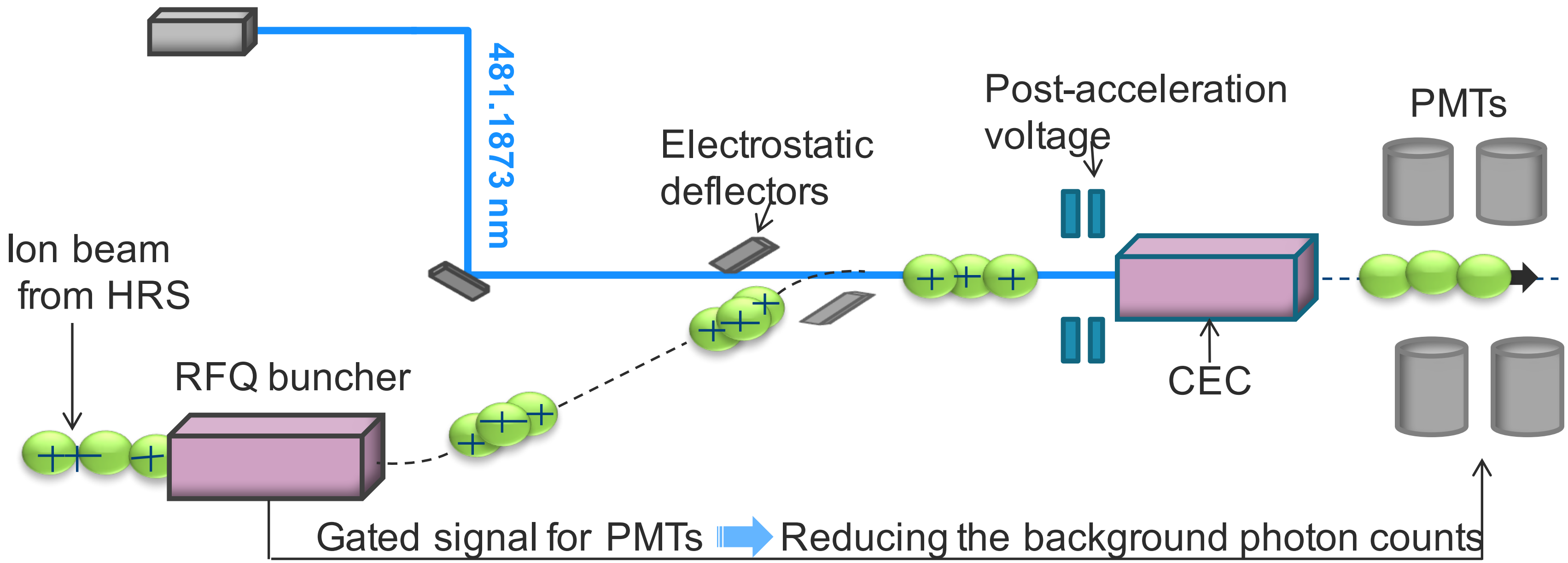


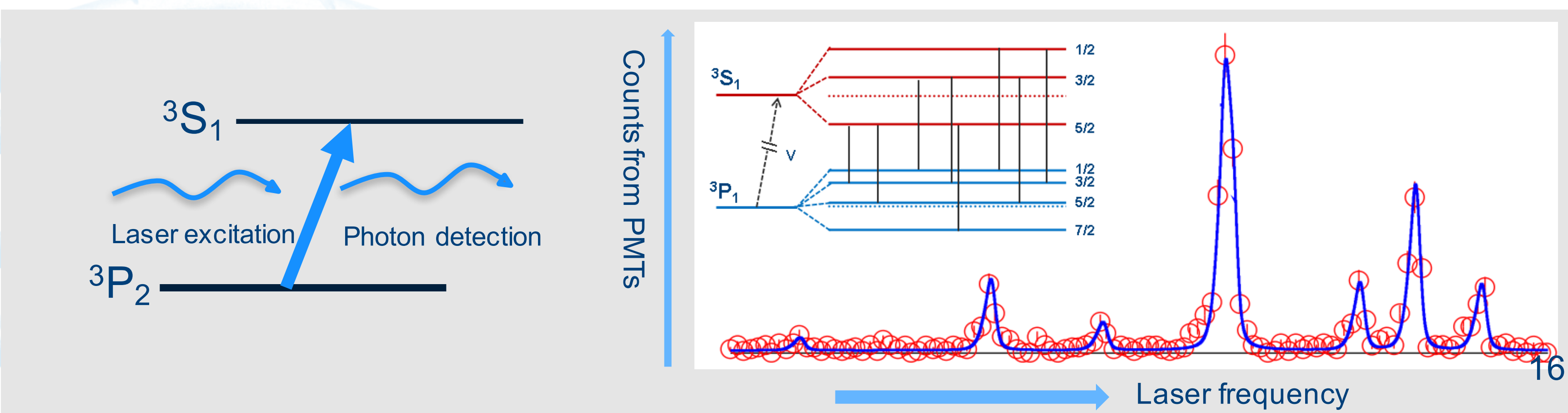
at CRIS




HRS
p+
RILIS
GPS
CRIS
COLLAPS
1
2
3
4
5
6

Collinear Laser Spectroscopy @ISOLDE-CERN





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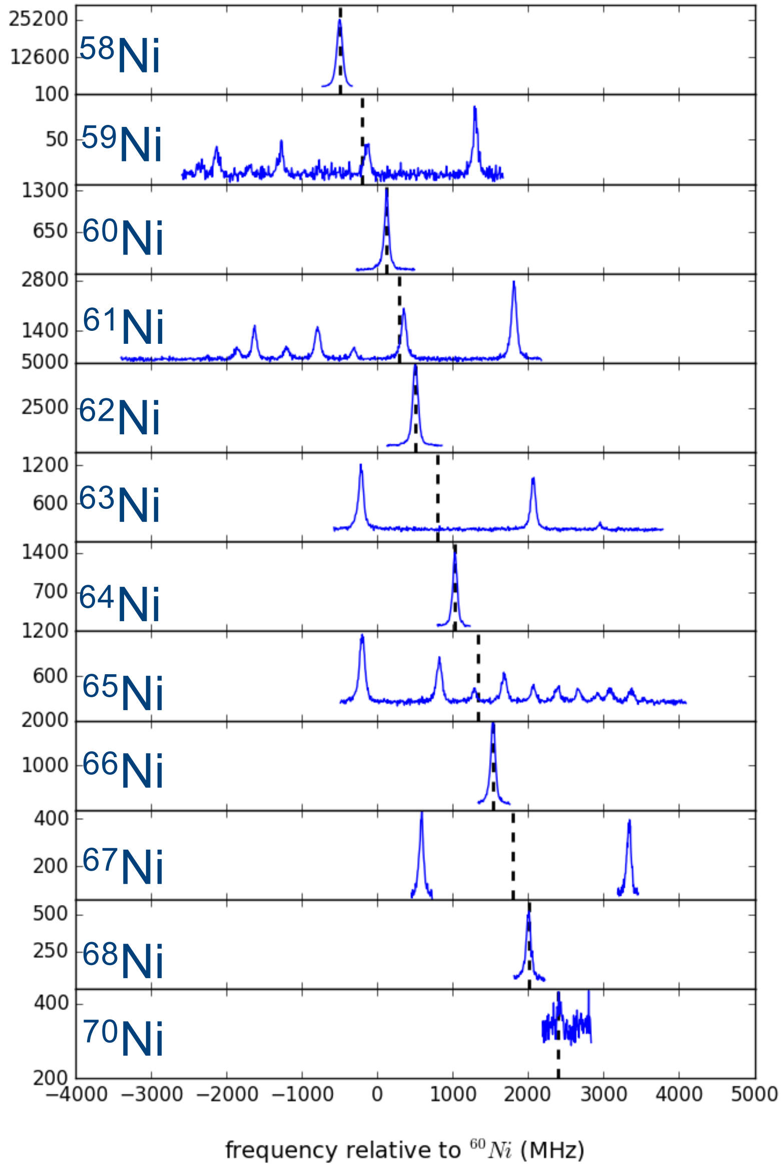
Well demonstrated technique for high resolution

HFS of Ni isotopes across N = 40



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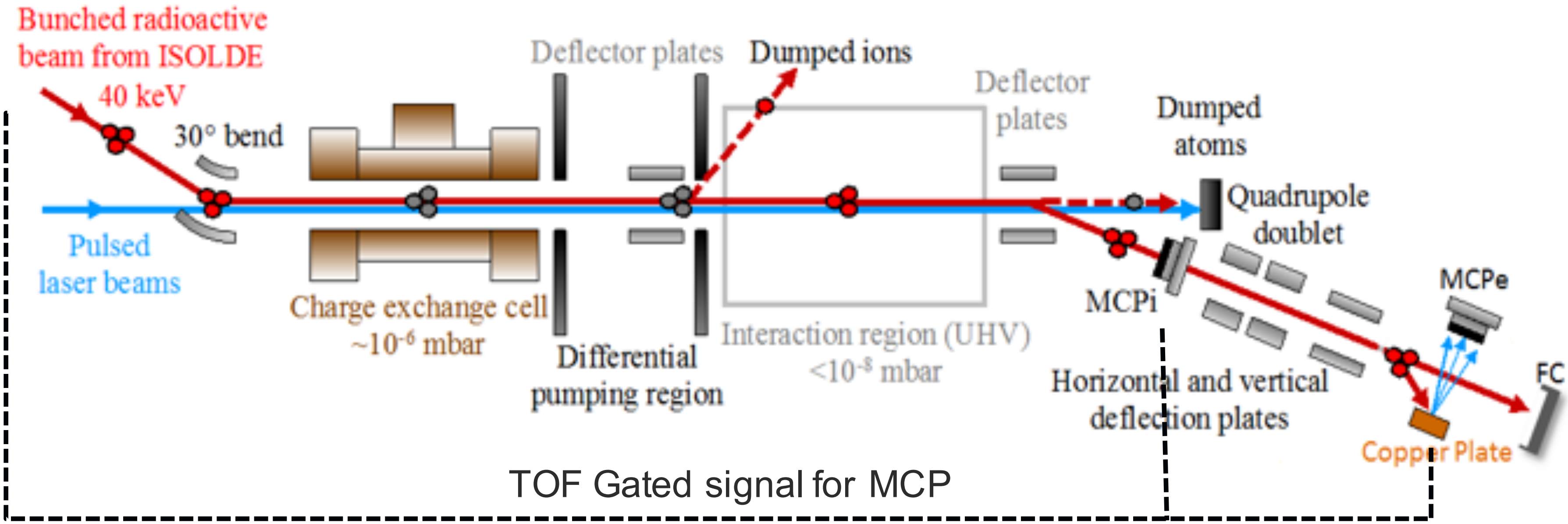
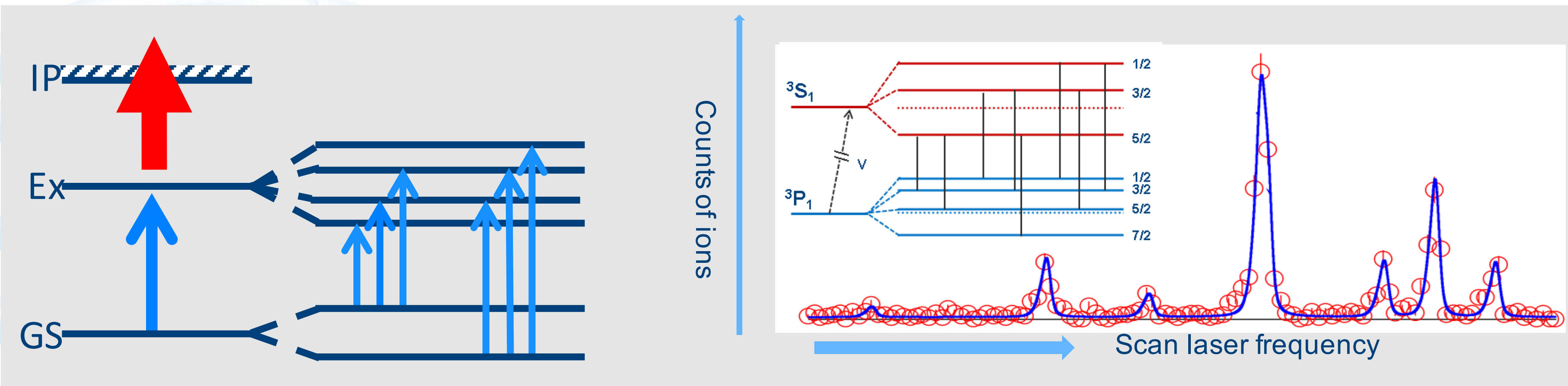
Pictures courtesy Liang Xie (ISOLDE workshop 2016)

Collinear resonance ionization spectroscopy @ISOLDE - CERN





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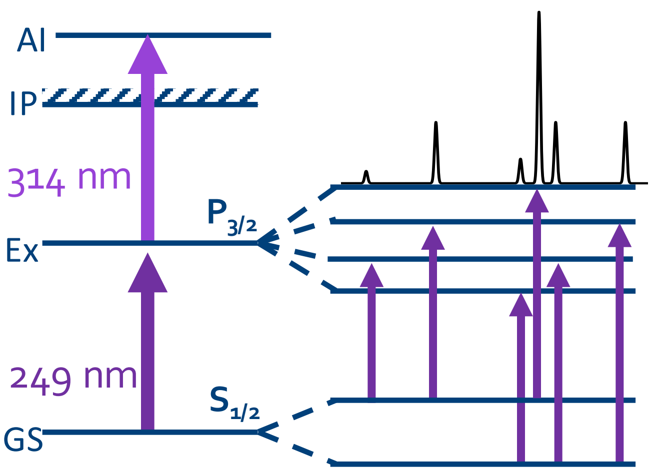
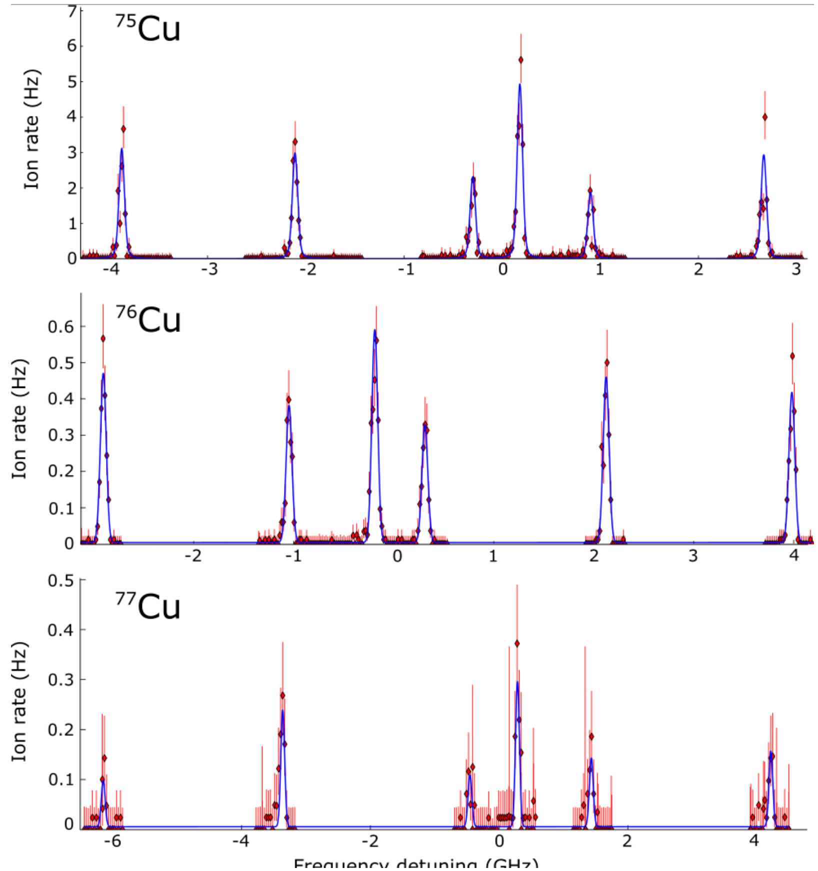
Pictures courtesy of Kara Lynch

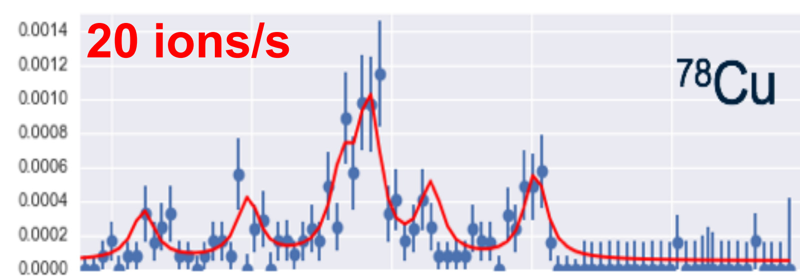
HFS of Cu isotopes

--with high-resolution (70MHz) and high efficiency (1%)





Injection locked pulsed Ti:Sa laser for 249 nm (Tripled) and Pulse dye laser (doubled)



New data

^{76}Cu: 3-, u, Q moments, $<r^2>^{1/2}$

^{77}Cu: Q , $<r^2>^{1/2}$

^{78}Cu: (6-), u, Q moments, $<r^2>^{1/2}$

Pictures courtesy of R.P. de Groote (ISOLDE workshop 2016)

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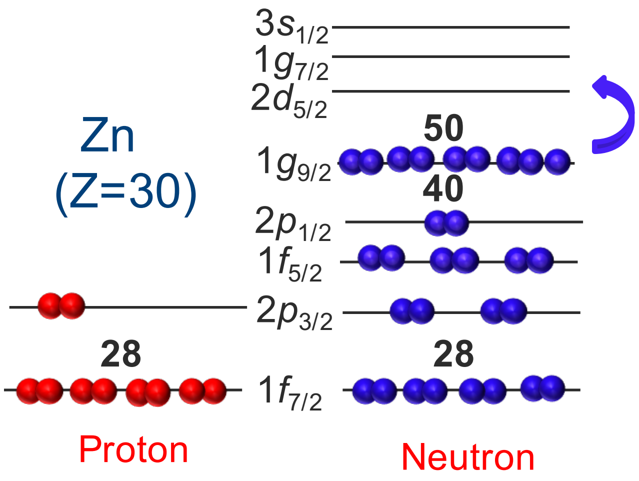
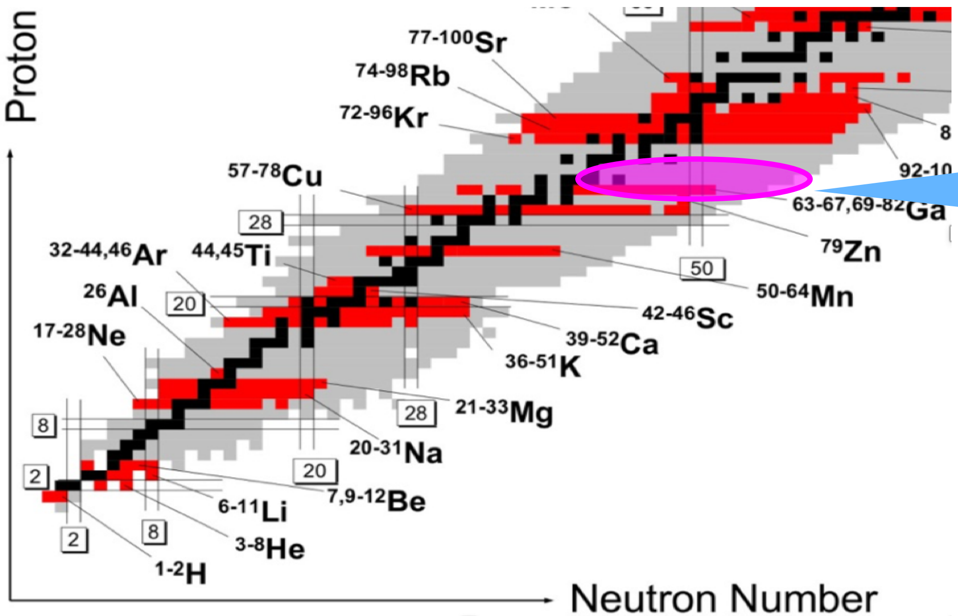
$^{62-80}$Zn experiment

Spins, moments, charge radii





Ni Regions

- Role of tensor force
- Sub/shell closure $N = 40$, 50
- Collectivity above $N = 40$,
- ……..

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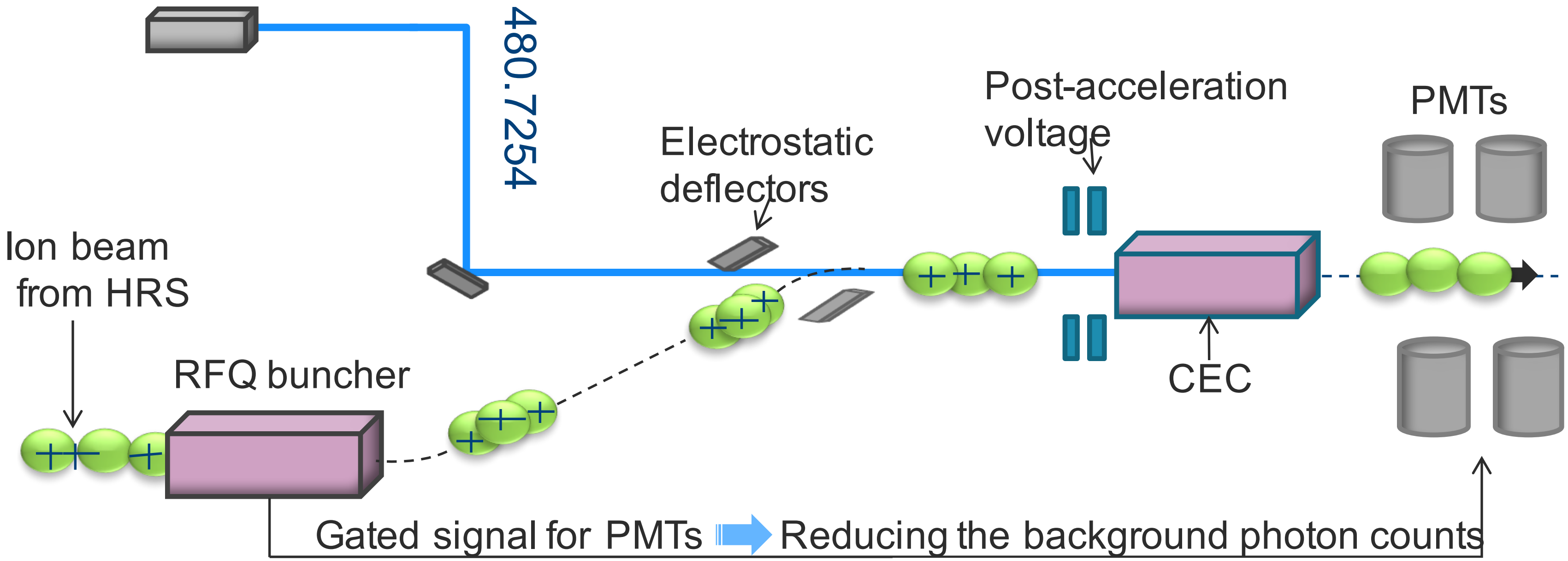
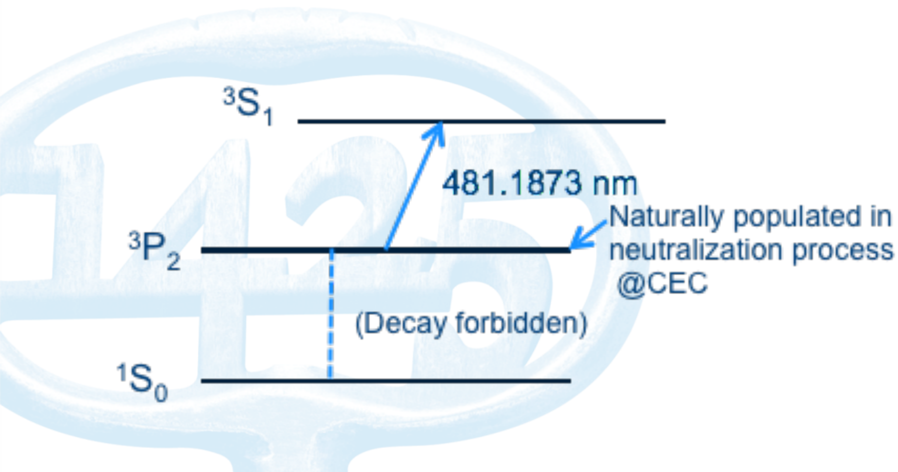
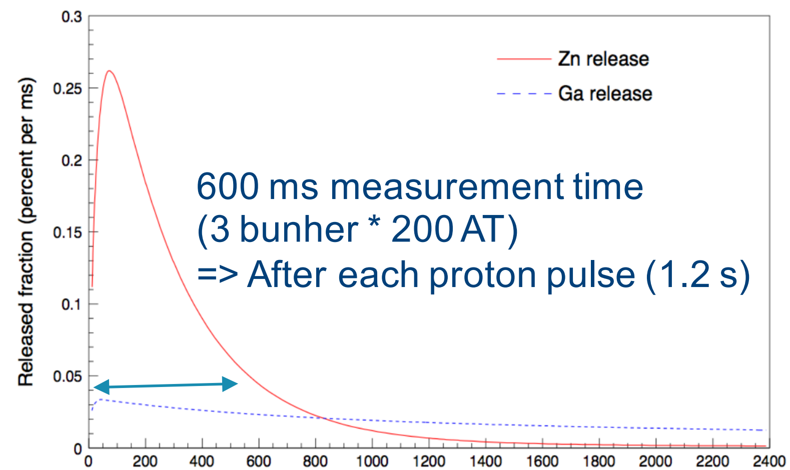
Collinear Laser Spectroscopy (Zn)



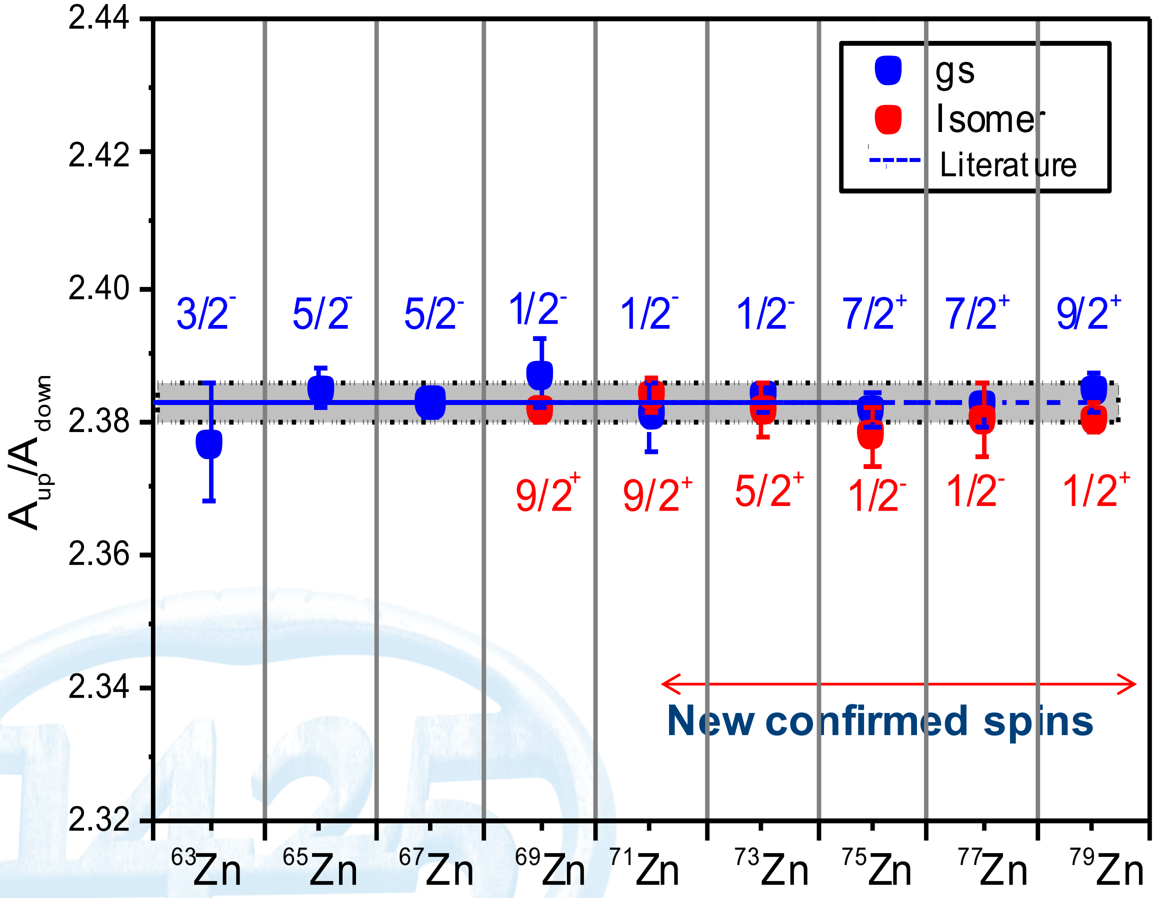


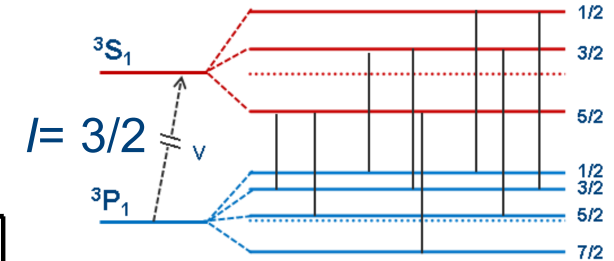


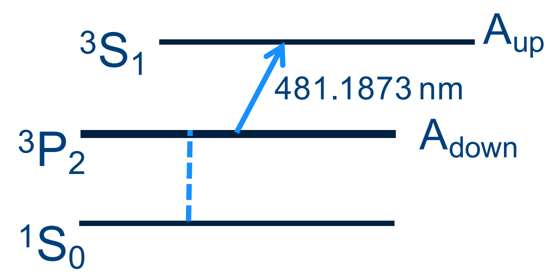
Doppler tuning: $\nu_{transition} = \nu_{laser} \dfrac{1-\beta}{\sqrt{1-\beta^2}}$

$$\beta = \sqrt{1 - \frac{M_0^2 c^4}{(Uq + M_0 c^2)^2}}$$

Spins assignments







Ratio A_{up}/A_{down}:constant （hyperfine anomaly is negligible）

$A(S_1) / A(P_2) = 2.383(2)$

➔depends on nuclear spin assumed in fitting procedure

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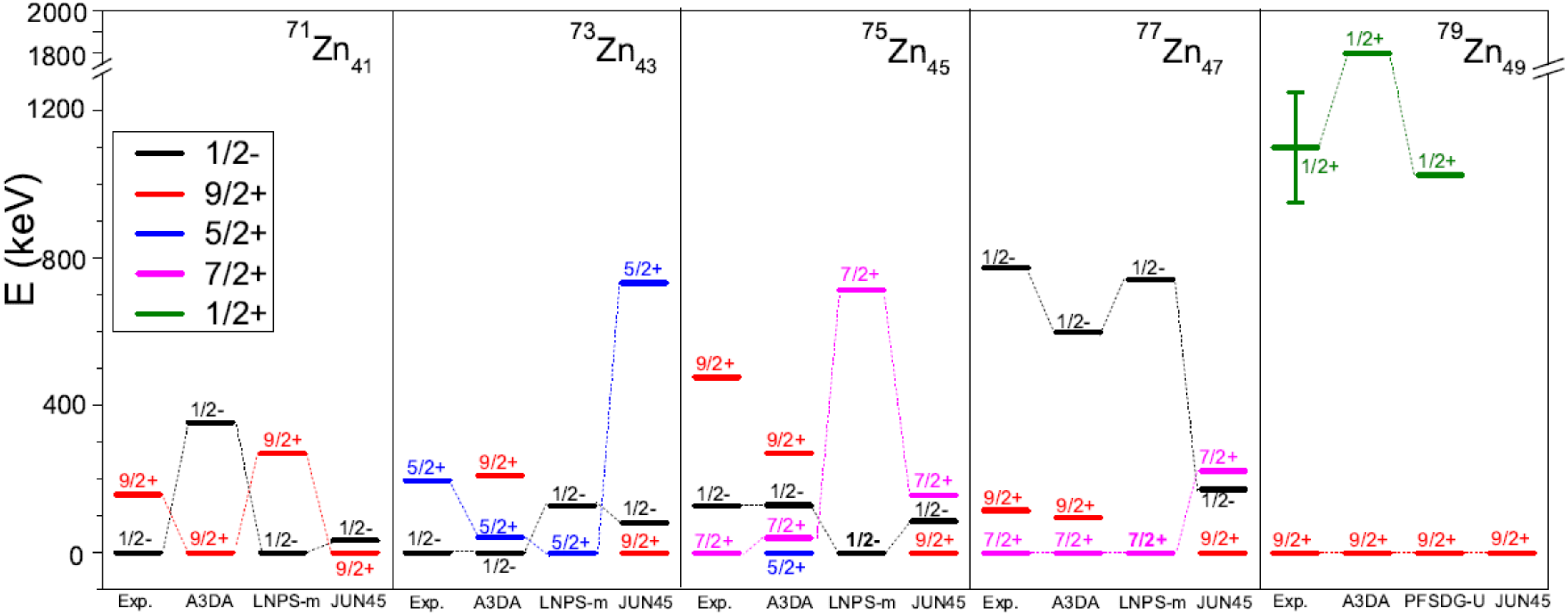
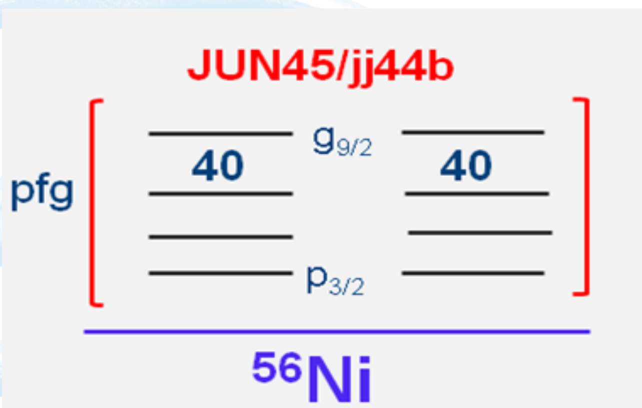
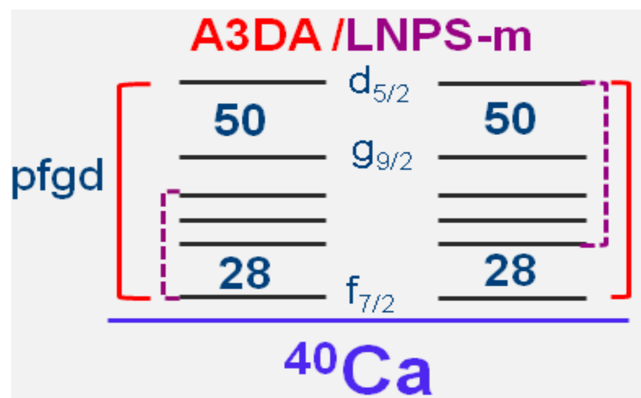
C. Wraith, X.F. Yang et al., to be submitted to Phys. Lett. B (2016)

Spins assignments







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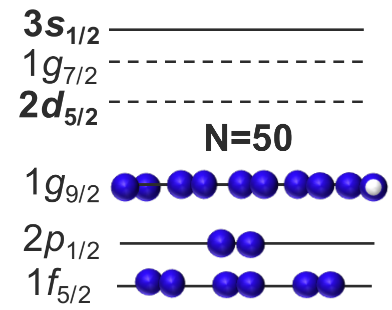
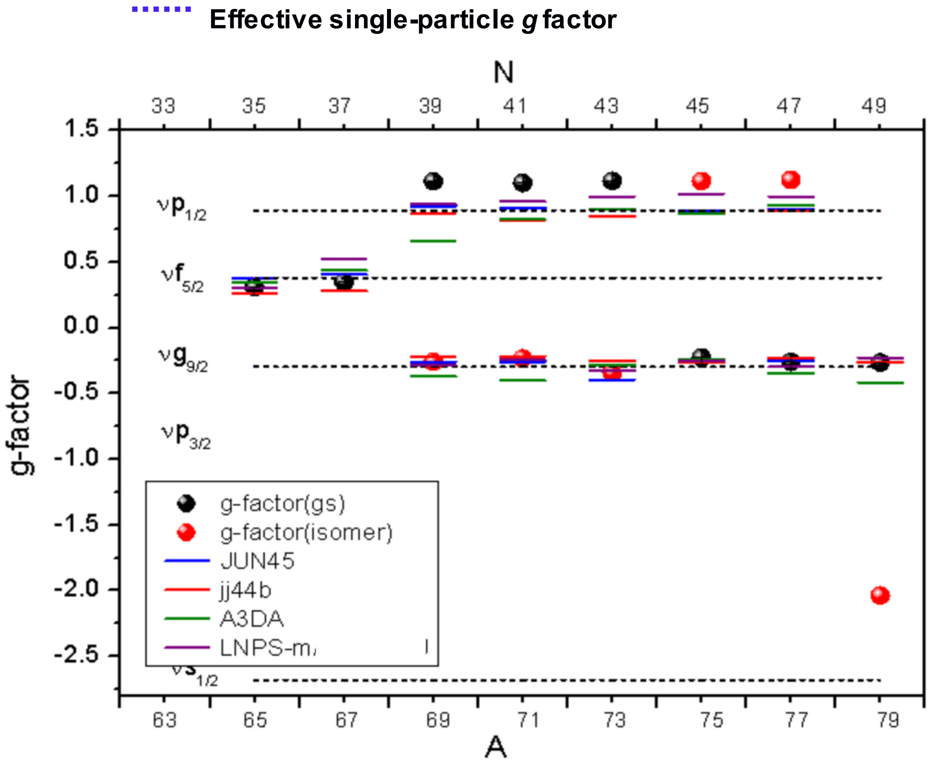
D. Verney et al., Phys. Rev. C 76, 054312 (2007)
M. Honma et al., Phys. Rev. C 80, 064323 (2009)
Y. Tsunoda et al., PRC 89, 031301(R) (2014)
F. Nowacki et al., http://arxiv.org/abs/1605.05103 (2016)

g-factors (magnetic moment)

Information on the orbit occupied by unpaired neutron(s):
compare data to effective single particle g-factors (0.7 g_s^{free})



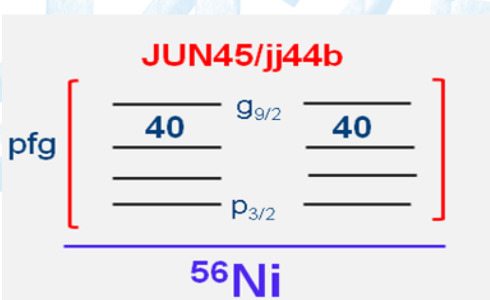


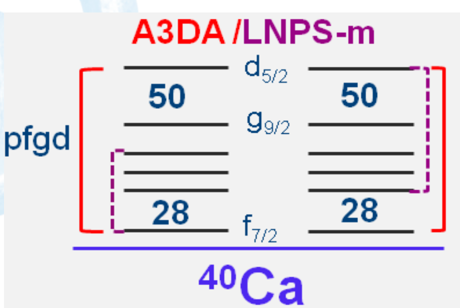
✓ the ½- states have a hole in $\nu p_{1/2}$

✓ all high-spin isomers have hole(s) in $\nu g_{9/2}$

✓ positive parity of the ½ isomer in ^{79}Zn confirmed → only $\nu s_{1/2}$ has strong negative g-factor

----will be discussed in details later





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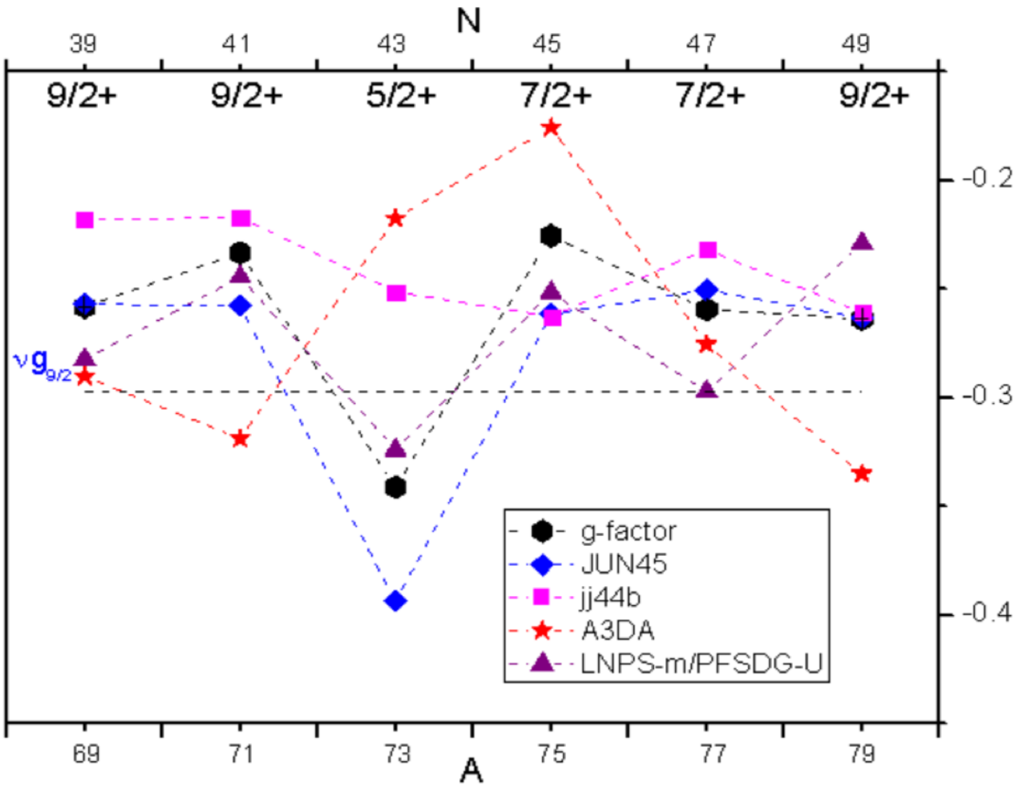
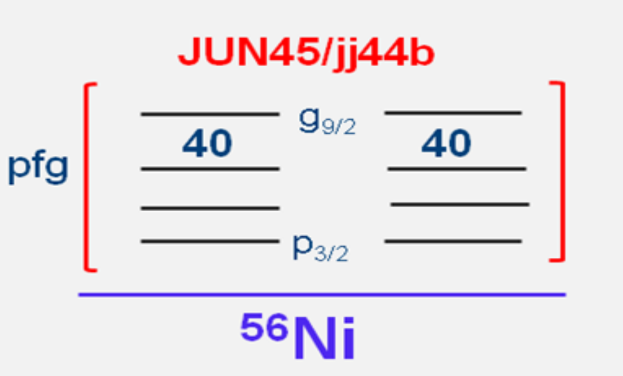
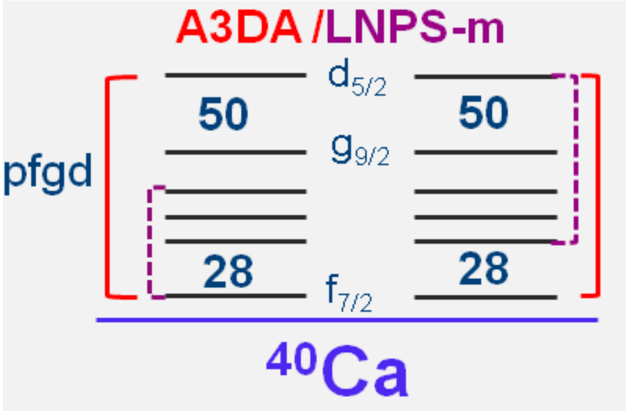
g-factors (magnetic moment)







→ well reproduced by the JUN45/LNPS-m interaction
→ the 5/2+ state in ^{73}Zn has more mixing

	JUN45		jj44b	
^{73}Zn	$f_{5/2}^{+2} \otimes p_{3/2}^{+4} f_{5/2}^{+4} p_{1/2}^{+2} g_{9/2}^{+5}$	8.3189	$f_{5/2}^{+2} \otimes p_{3/2}^{+4} f_{5/2}^{+4} p_{1/2}^{+2} g_{9/2}^{+5}$	14.04
(5/2+)	$p_{3/2}^{+2} \otimes p_{3/2}^{+4} f_{5/2}^{+6} p_{1/2}^{+2} g_{9/2}^{+3}$	8.1002	$p_{3/2}^{+2} \otimes p_{3/2}^{+4} f_{5/2}^{+4} p_{1/2}^{+2} g_{9/2}^{+5}$	12.56
	$p_{3/2}^{+2} \otimes p_{3/2}^{+4} f_{5/2}^{+4} p_{1/2}^{+2} g_{9/2}^{+5}$	7.9829	$p_{3/2}^{+1} f_{5/2}^{+1} \otimes p_{3/2}^{+4} f_{5/2}^{+4} p_{1/2}^{+2} g_{9/2}^{+5}$	9.56
	$p_{3/2}^{+1} f_{5/2}^{+1} \otimes p_{3/2}^{+4} f_{5/2}^{+4} p_{1/2}^{+2} g_{9/2}^{+5}$	5.9277	$f_{5/2}^{+1} p_{1/2}^{+1} \otimes p_{3/2}^{+4} f_{5/2}^{+4} p_{1/2}^{+2} g_{9/2}^{+5}$	8.91

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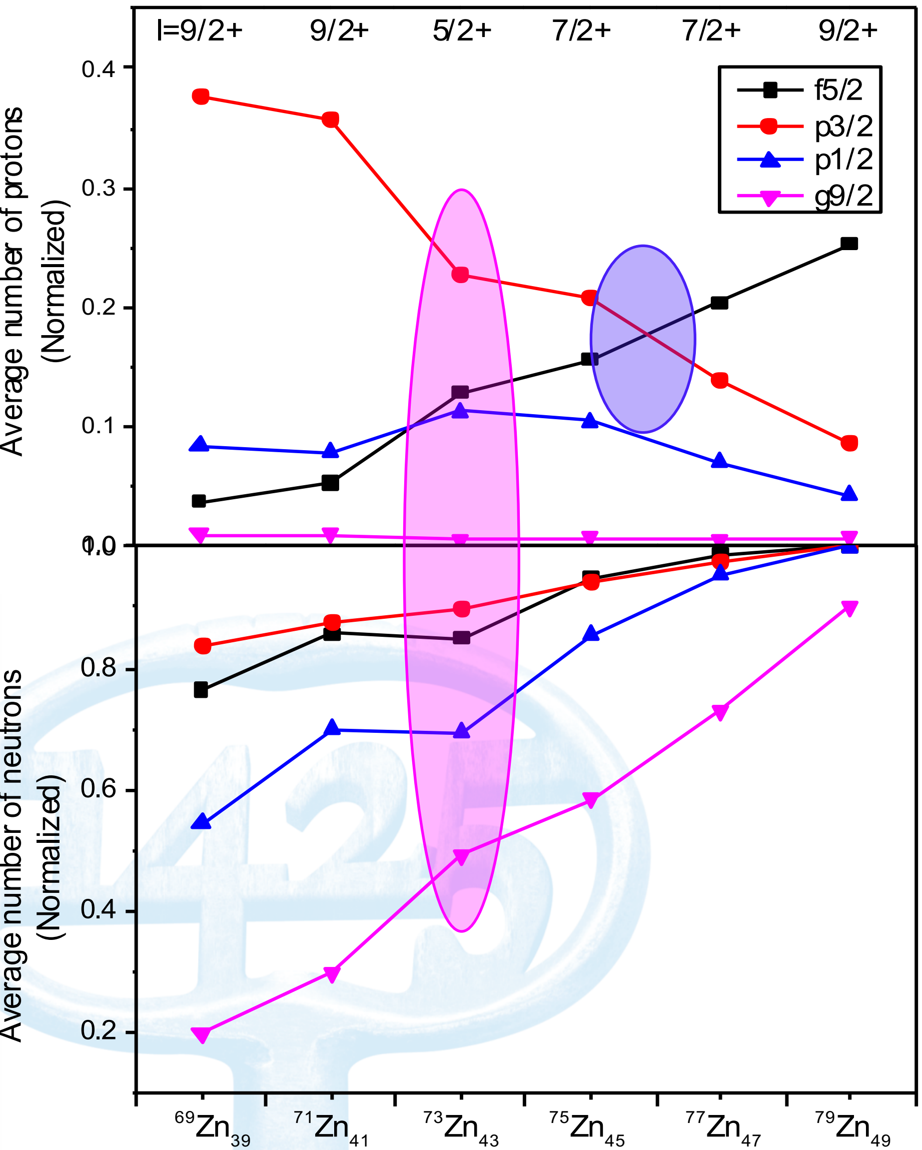
C. Wraith, X.F. Yang et al., to be submitted to Phys. Lett. B (2016)

Occupation numbers of proton/neutron

for the positive parity high-spin levels calculated by JUN45



- As neutrons are added to the $g_{9/2}$, the occupation number in $\pi f_{5/2}$ increase but decrease in $\pi p_{3/2}$.
- An inversion of occupation occurs in $\pi p_{3/2}$ / $\pi f_{5/2}$ around $^{76}Zn_{46}$(Z=30), which is consistent **with the inversion of the proton orbit due to tensor effect**. It is known to occur in $^{75}Cu_{46}$ (Z = 29) and $^{79}Ga_{48}$ (Z = 31).
- A kink appear around ^{73}Zn, suggesting an increase of configuration mixing for the $5/2^+$ isomer in ^{73}Zn
- P-h excitations across N = 40 in $^{69-77}Zn$

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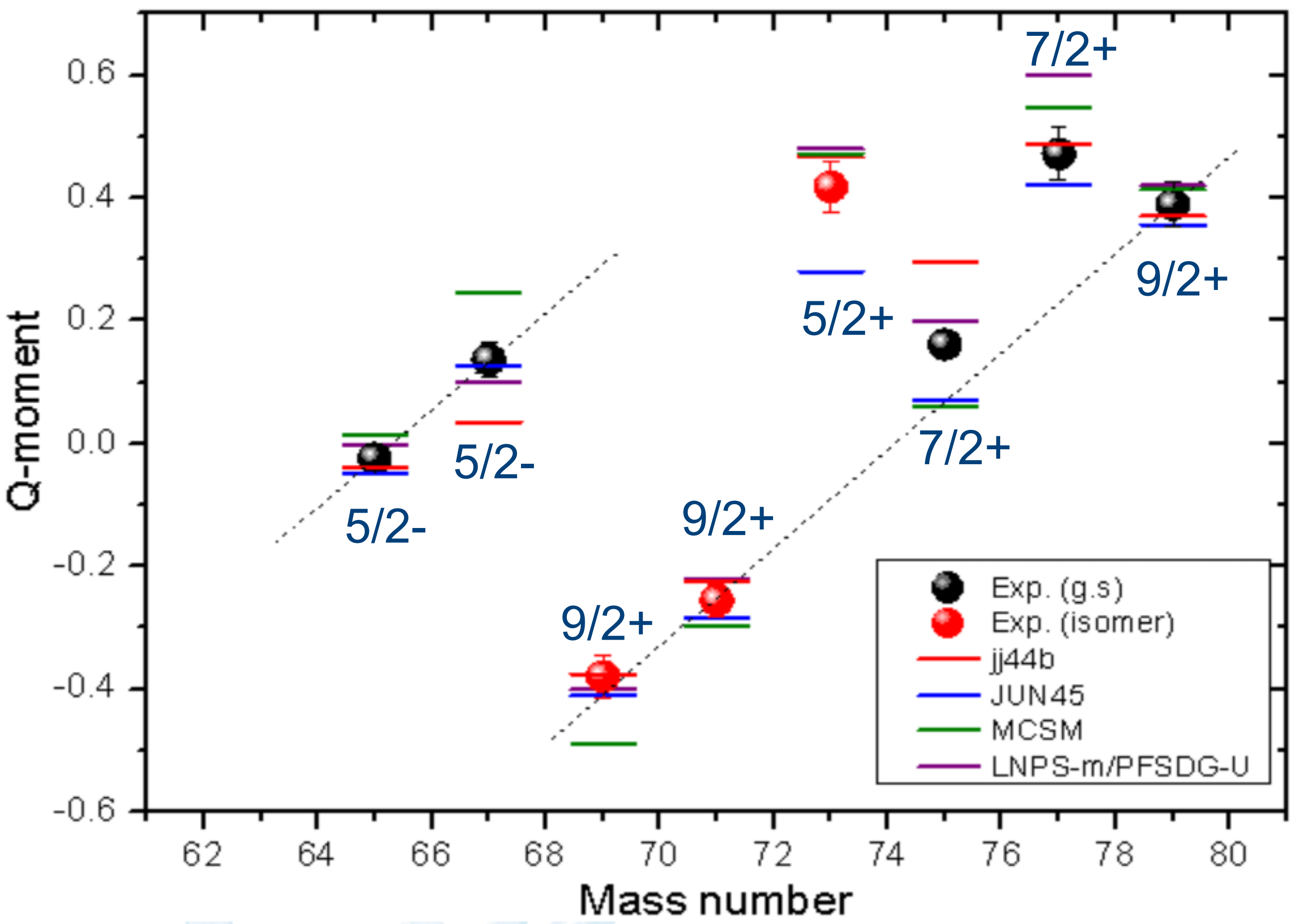
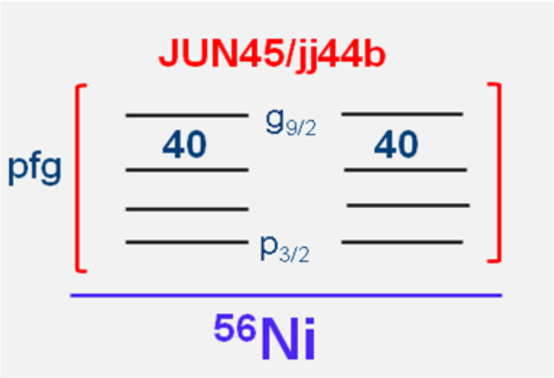
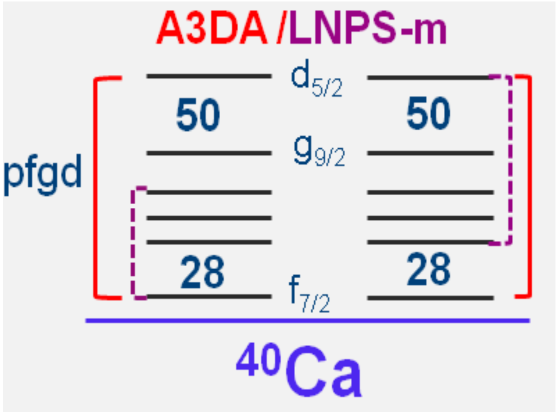
C. Wraith, X.F. Yang et al., to be submitted to Phys. Lett. B (2016)

Quadrupole moments







Quadrupole moments could be well produced from all shell motel interactions

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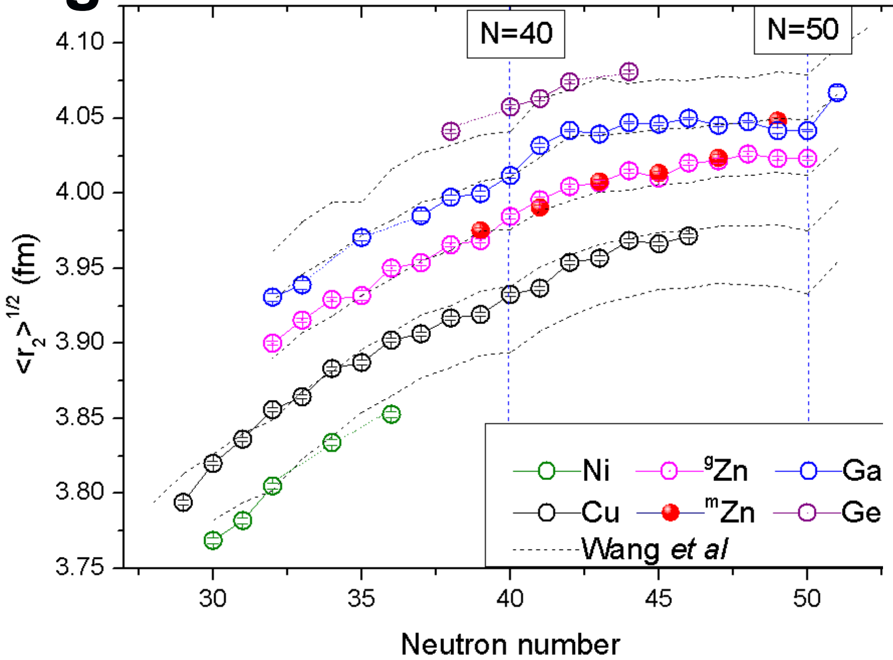
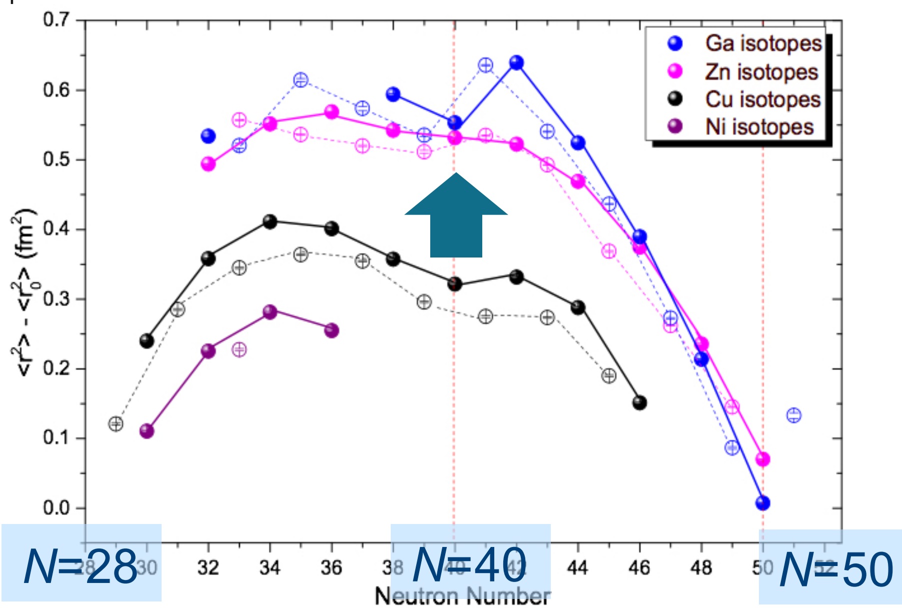
C. Wraith, X.F. Yang et al., to be submitted to Phys. Lett. B (2016)

Charge radii of Zn



Preliminary results



- Charge radii of Zn isotopes follows the general trend in Ni region
- The effect of N = 40 sub shell closure becomes weaker as the increase of Z

M. L. Bissell *et al.*, "Phys. Rev. C," (2016); T. J. Procter *et al.*, Phys. Rev. C **86**, 034329 (2012).
N. Wang and T. Li, Phys. Rev. C **88**, 011301 (2013). I. Angelia et al, At. Data Nucl. Data Tables**99**, 69 (2013).

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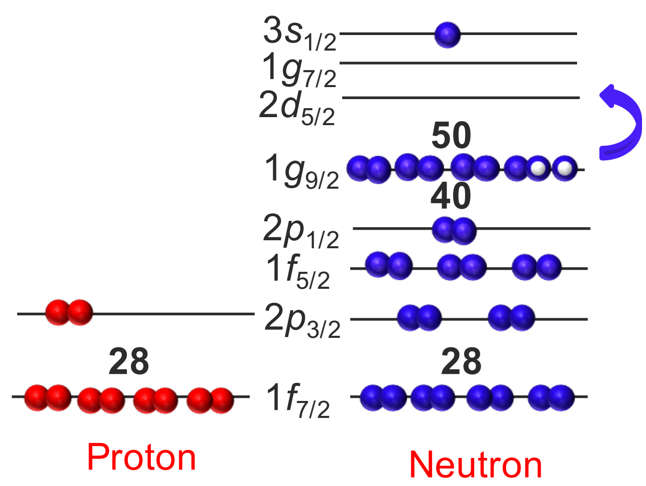
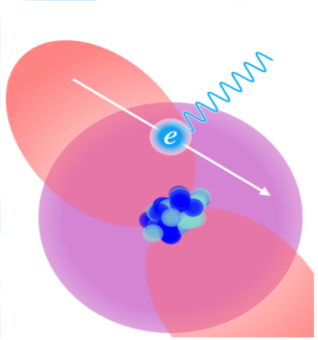
X. Liang, X.F. Yang et al., in preparation(2016)

- **½+ intruder isomer in ^{79}Zn**

  --- spins, moments, charge radii

  --- half-live, energy levels





EDITORS' SUGGESTION

Shape Coexistence Near ^{78}Ni

Two different experiments observe nuclei with excited nuclear state that differ in shape from their ground states, so called shape coexistence. These nuclei lie close to the neutron-rich doubly-mag ^{78}Ni region of the nuclear chart.

A. Gottardo *et al*.
Phys. Rev. Lett. **116**, 182501 (2016)

X.F. Yang *et al*.
Phys. Rev. Lett. **116**, 182502 (2016)

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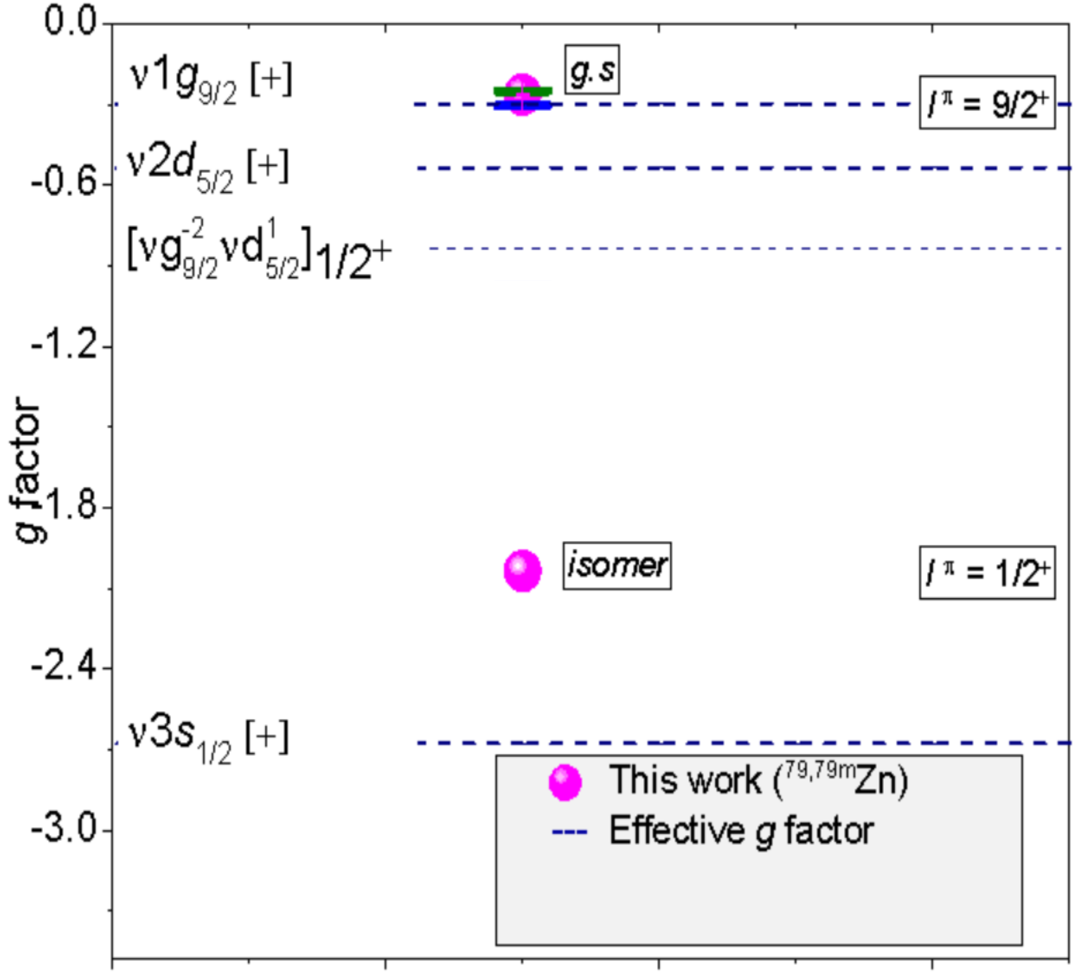
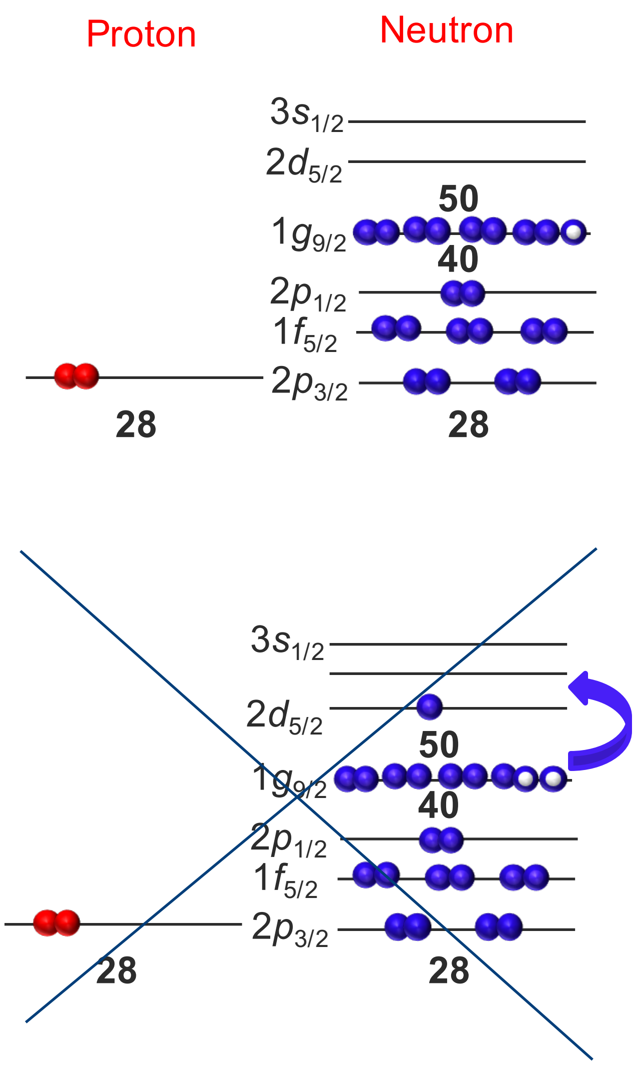
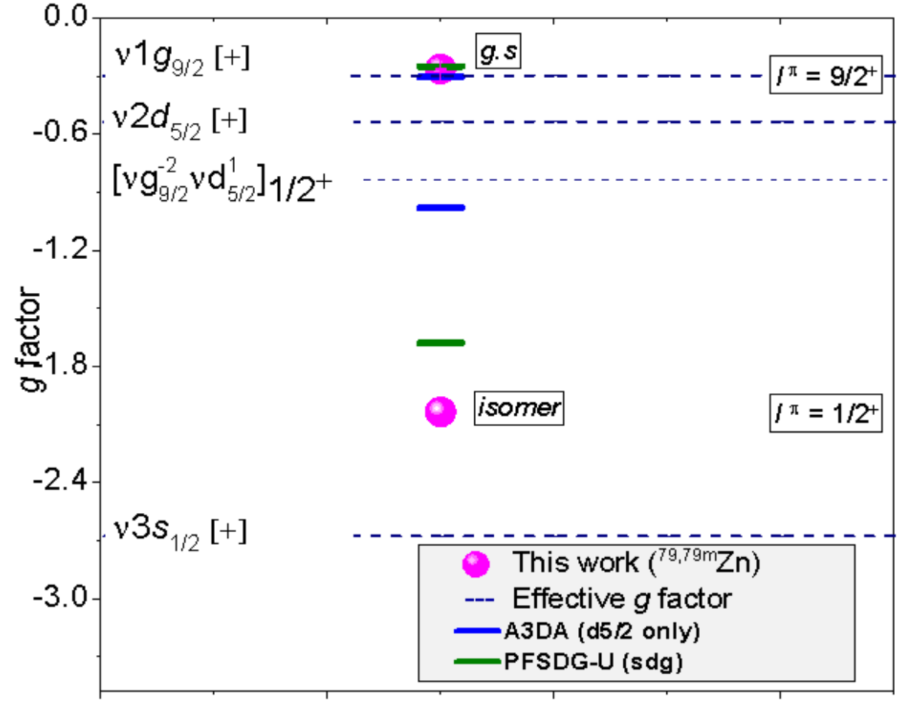
g-factor & wave function of $^{79}Zn^{g,m}$

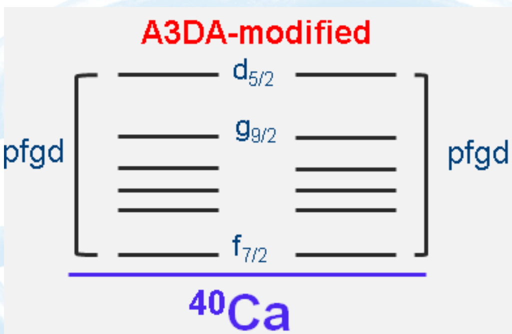


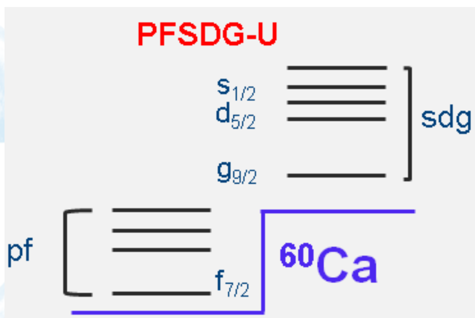


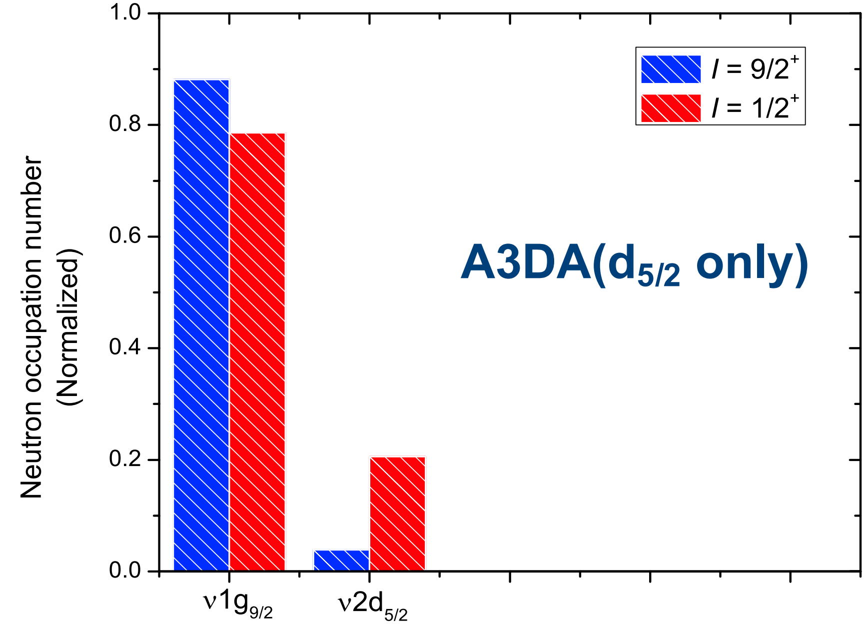
X.F. Yang et al., PRL 182501 (2016);

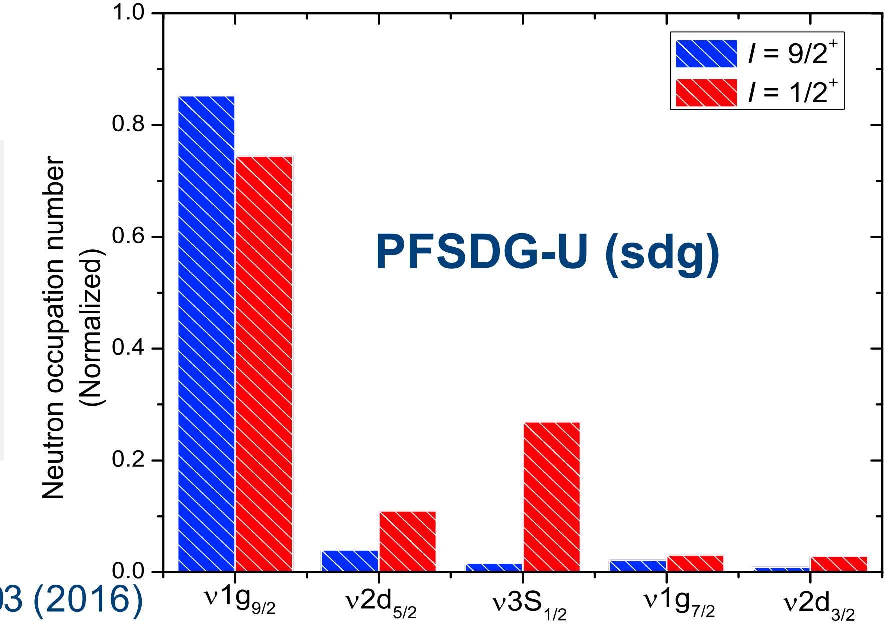
g-factor & wave function of $^{79}Zn^{g,m}$









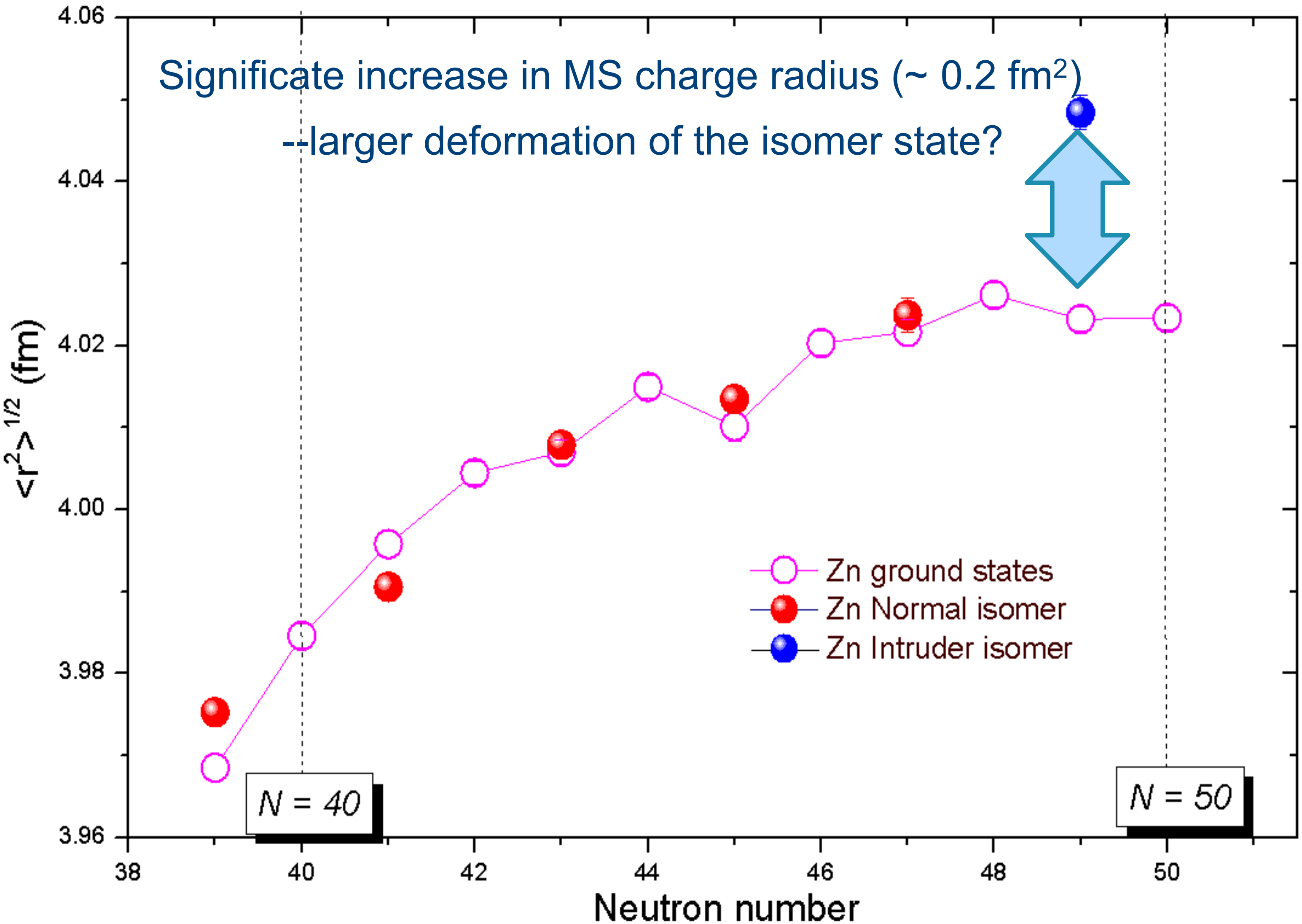


Y. Tsunoda et al.,
PRC 89, 031301(R) (2014)

F. Nowacki et al.,
http://arxiv.org/abs/1605.05103 (2016)

C. Wraith, X.F. Yang et al., to be submitted to Phys. Lett. B (2016)

Charge radii of $^{69-79}Zn$



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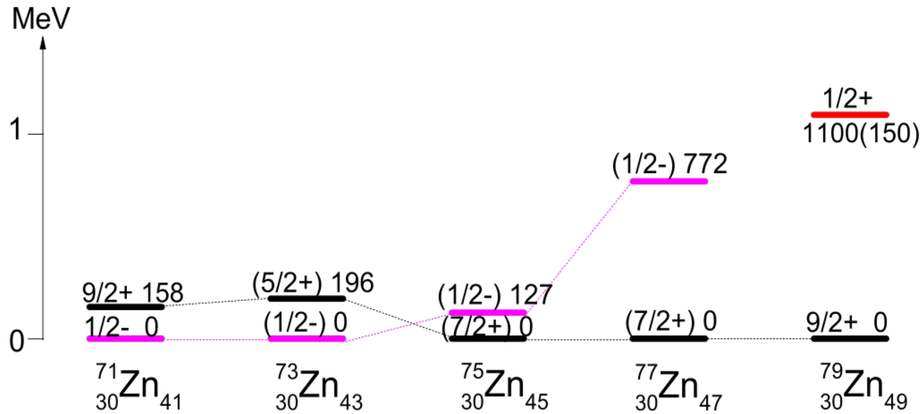
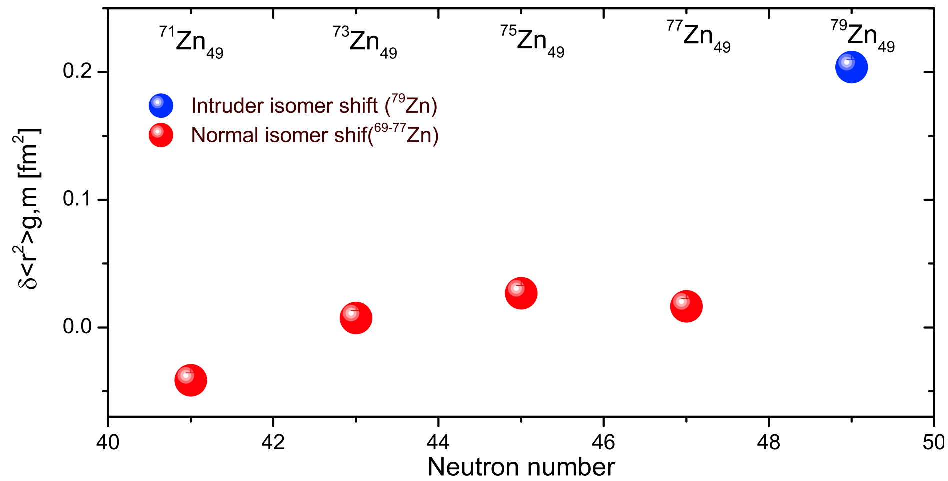
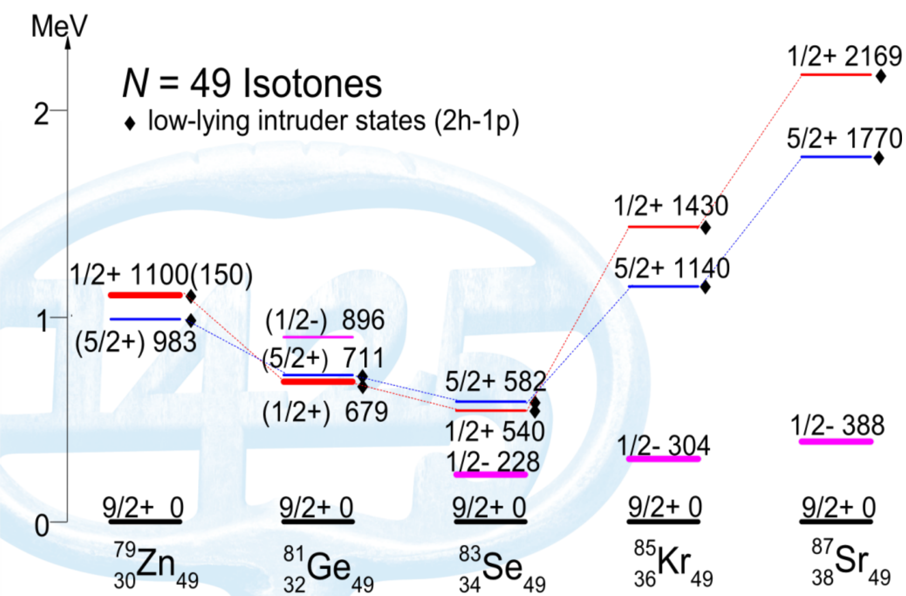
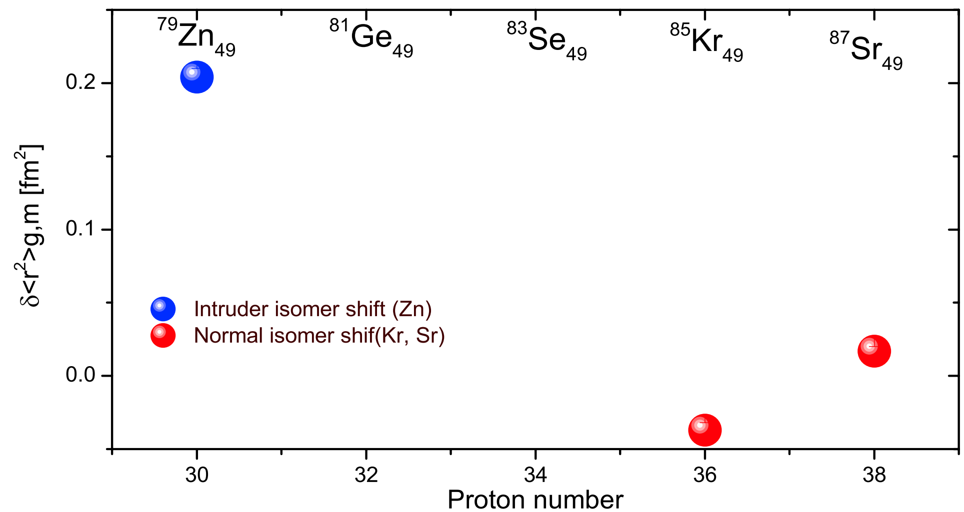
❖ Isomer shift in Zn isotopes and *N*=49 isotones









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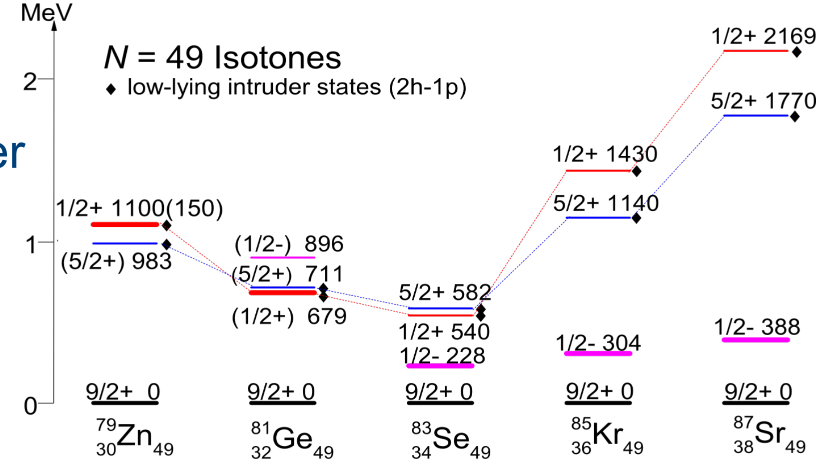
Thus, about the isomer…



1. HF spectra of ^{79g,m}Zn=> Long- lived ½+ isomer

2. Magnetic moment of ^{79g,m}Zn
   --intruder nature of isomer
   --mp-mh excitation across *N* = 50

3. Larger increase in the rms charge radii of the isomer
   --larger deformation of the isomer state

Signature of shape coexistence **near ^{78}Ni**

Need more experimental and theoretical investigation!!!

First Evidence of Shape Coexistence in the ^{78}Ni Region: Intruder 0_2^+ State in ^{80}Ge

A. Gottardo *et al.* Phys. Rev. Lett.**116** 182501 (2016)

Shape coexistence in ^{78}Ni as the portal to the fifth island of inversion

F. Nowacki *et al.* Phys. Rev. Lett (2016)

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Outline :

- **Introduction**
  - ✓ My group
  - ✓ Regions of interest
  - ✓ Observables (using few examples from COLLAPS experiment)

- **Experimental methods**
  - ✓ COLLAPS (Collinear Laser Spectroscopy) (Ni, Zn as example)
  - ✓ CRIS (Collinear resonance ionization spectroscopy) (Cu as example)

- **COLLAPS results for $^{62\text{-}80}Zn$ isotopes** ← **Main focus**
  - ✓ Spins, moments and charge radii

- **Further plans in Ni and Ca regions**
  - ✓ Ge experiment approved at COLALPS
  - ✓ K Sc experiments approved at CRIS

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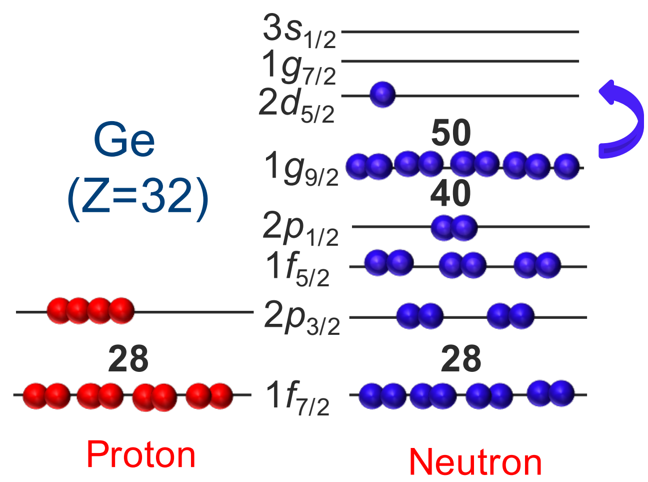
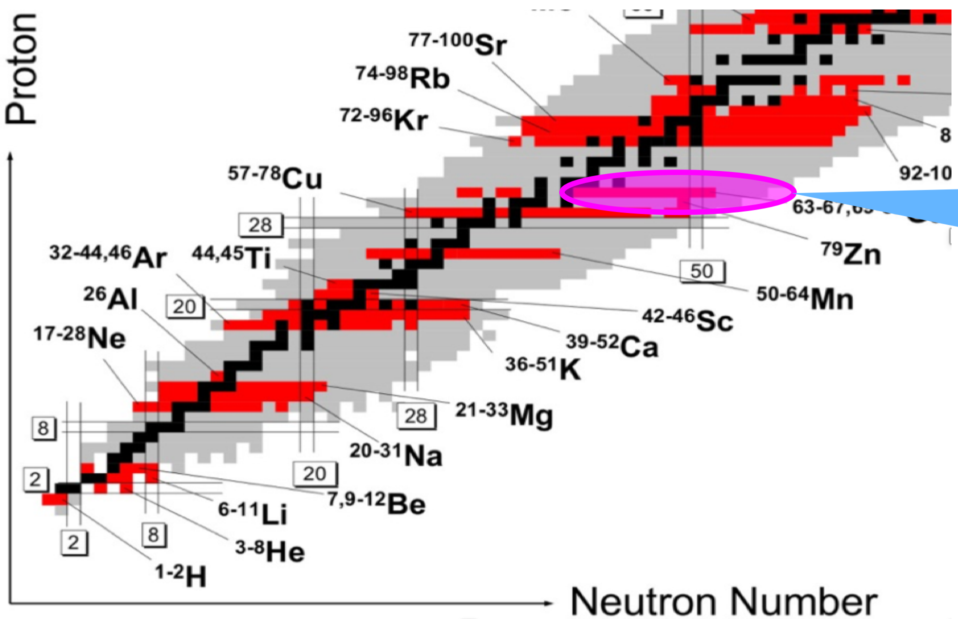
$^{65-83}$Ge experiment

Spins, moments, charge radii





Ni Regions

- Role of tensor force
- Sub/shell closure *N* = 40， 50
- New region of shape coexistence?

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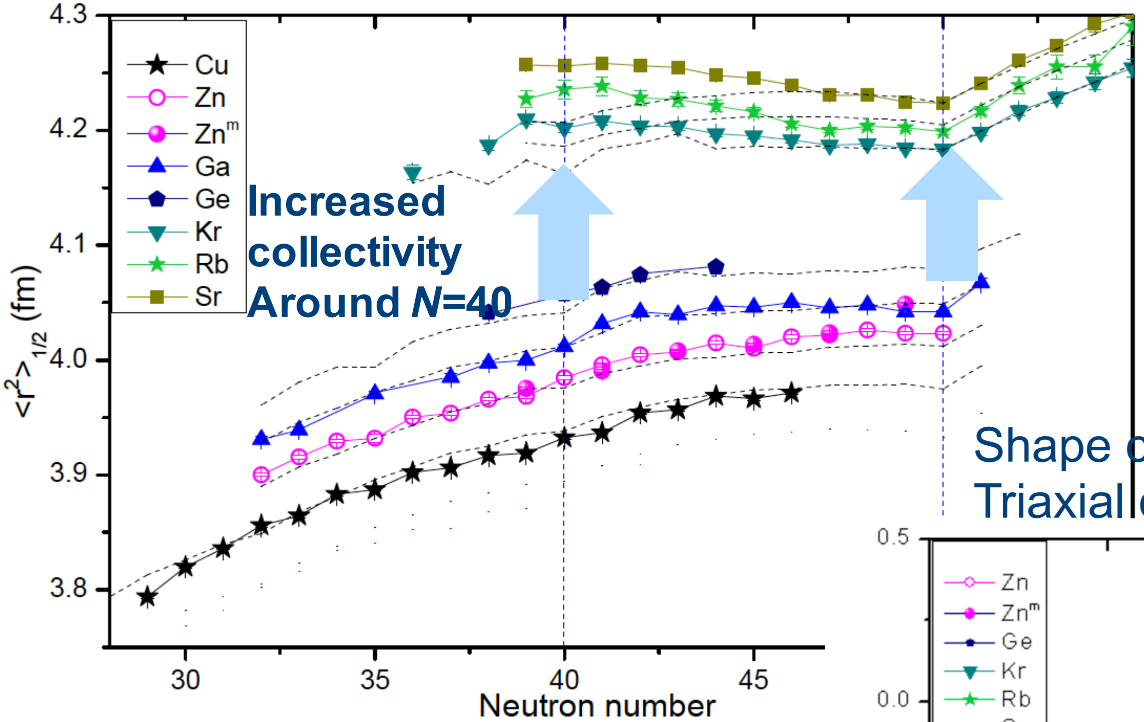
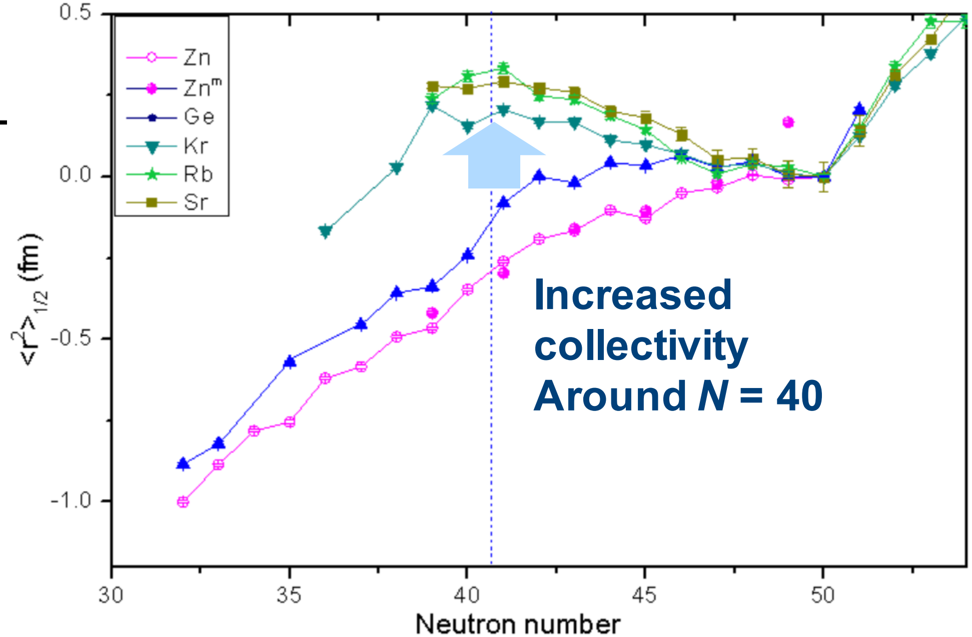
The Landscape in Ni region



Shape coexistence around N=40?
Triaxial deformation above N= 40?



A new region of shape coexistence? (Near N=50)

PRL **116,** 182501 (2016) PHYSICAL REVIEW LETTERS week ending 6 MAY 2016

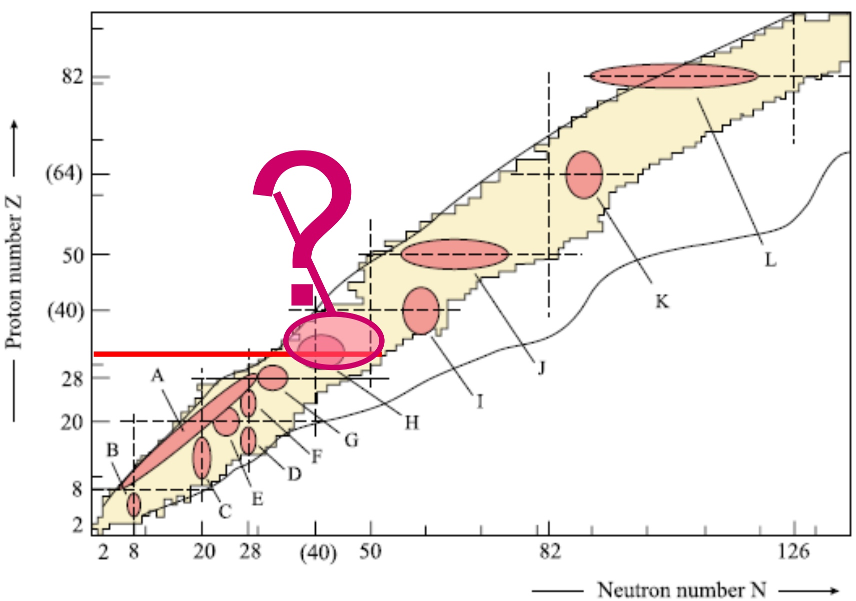
First Evidence of Shape Coexistence in the ^{78}Ni Region: Intruder 0_2^+ State in ^{80}Ge

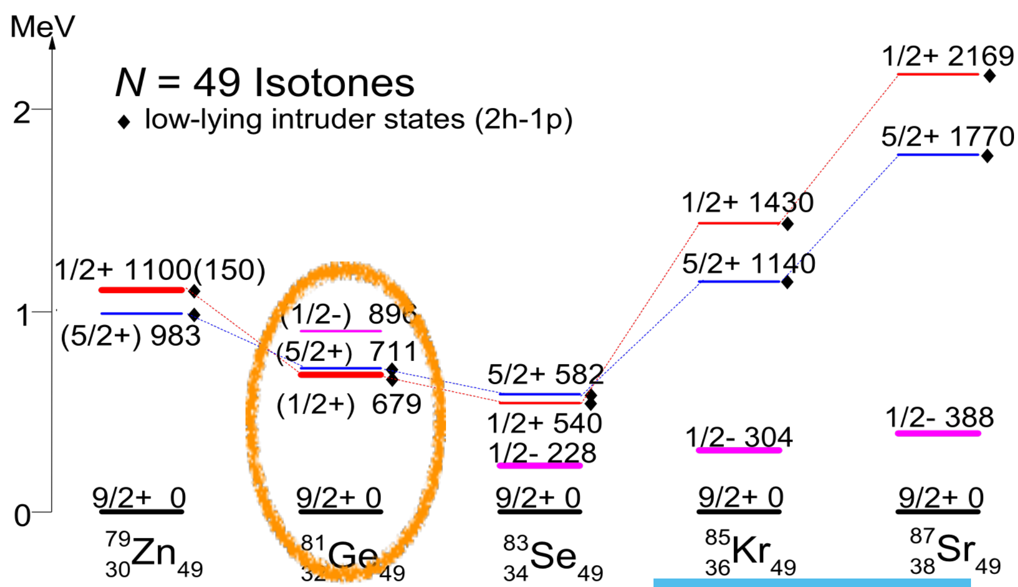
A. Gottardo,[1,*] D. Verney,[1] C. Delafosse,[1] F. Ibrahim,[1] B. Roussière,[1] C. Sotty,[2] S. Roccia,[3] C. Andreoiu,[4] C. Costache,[2] M.-C. Delattre,[1] I. Deloncle,[3] A. Etilé,[5] S. Franchoo,[1] C. Gaulard,[3] J. Guillot,[1] M. Lebois,[1] M. MacCormick,[1] N. Marginean,
L. Qi,[1] L. S

PRL **116,** 182502 (2016) PHYSICAL REVIEW LETTERS week ending 6 MAY 2016

Isomer Shift and Magnetic Moment of the Long-Lived 1/2$^+$ Isomer in $^{79}_{30}$Zn$_{49}$: Signature of Shape Coexistence near ^{78}Ni

X. F. Yang,[1,*] C. Wraith,[2] L. Xie,[3] C. Babcock,[2,4] J. Billowes,[3] M. L. Bissell,[3,1] K. Blaum,[5] B. Cheal,[2] K. T. Flanagan,[3] R. F. Garcia Ruiz,[1] W. Gins,[1] C. Gorges,[6] L. K. Grob,[7,6] H. Heylen,[1] S. Kaufmann,[6,8] M. Kowalska,[7] J. Kraemer,[6] S. Malbrunot-Ettenauer,[7] R. Neugart,[5,8] G. Neyens,[1] W. Nörtershäuser,[6] J. Papuga,[1] R. Sánchez,[9] and D. T. Yordanov[10]





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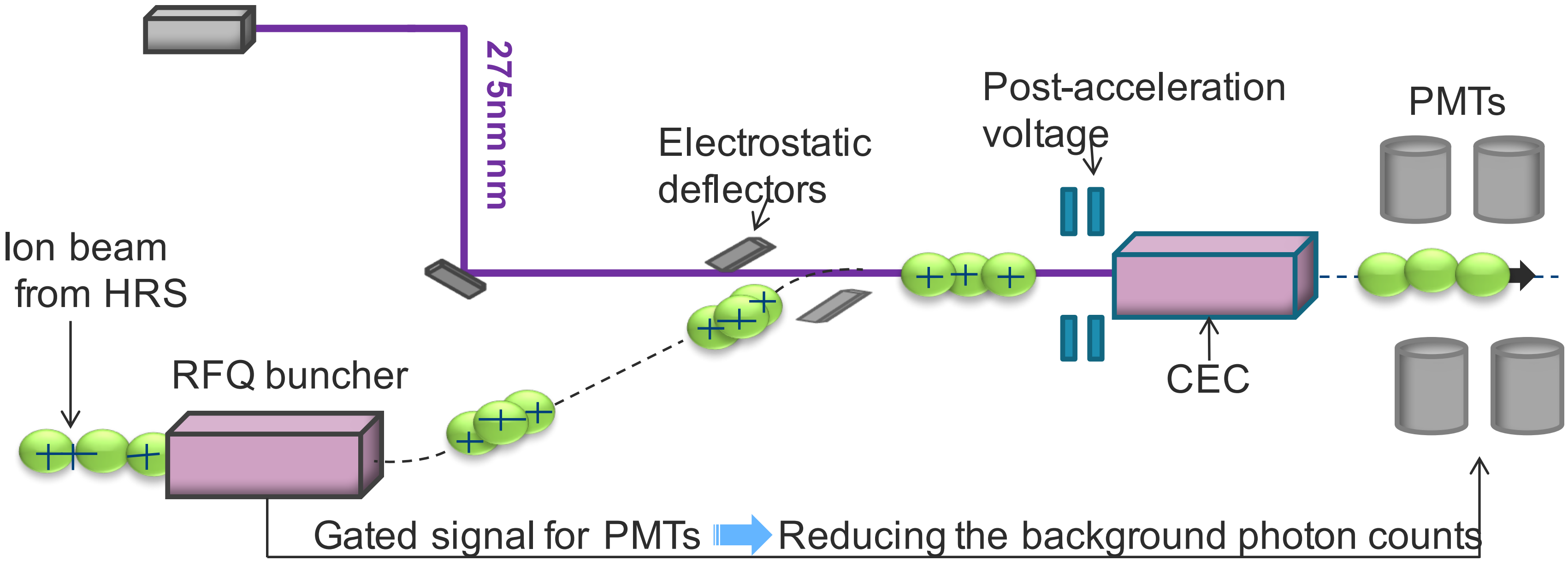
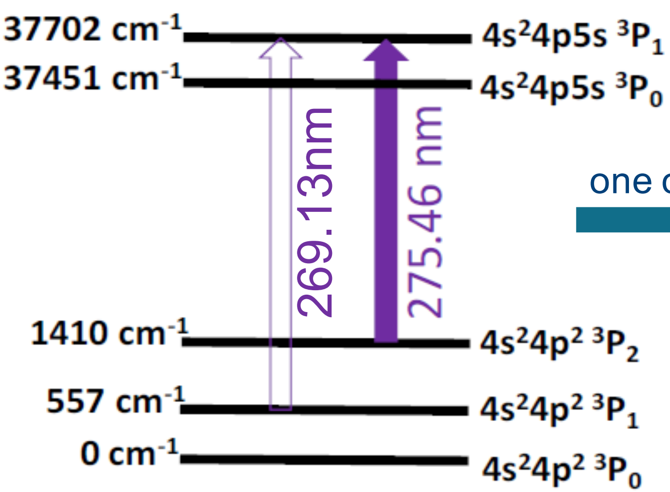
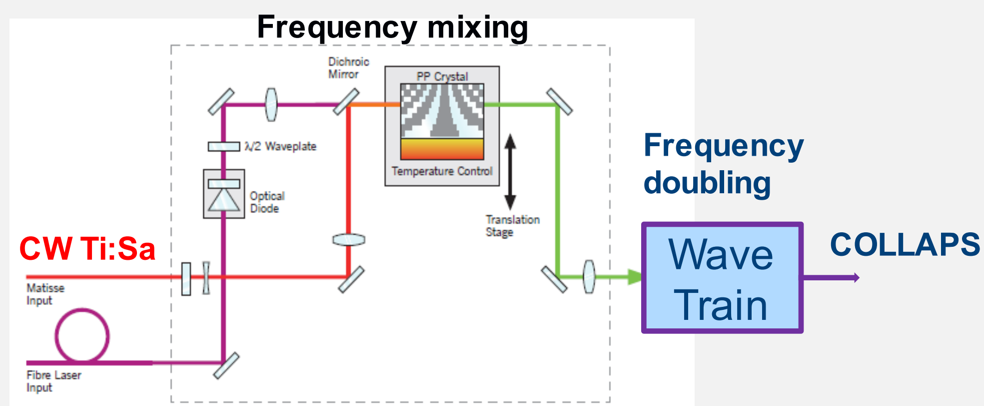
Ge: COLLPAS@ISOLDE-CERN



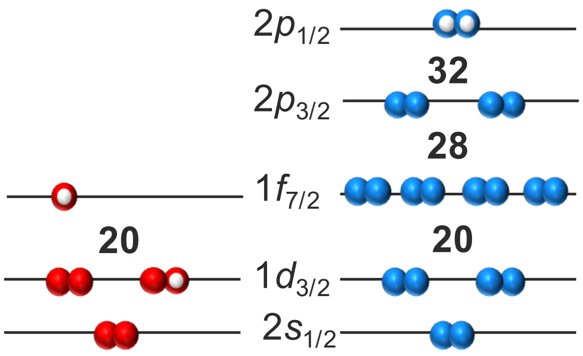


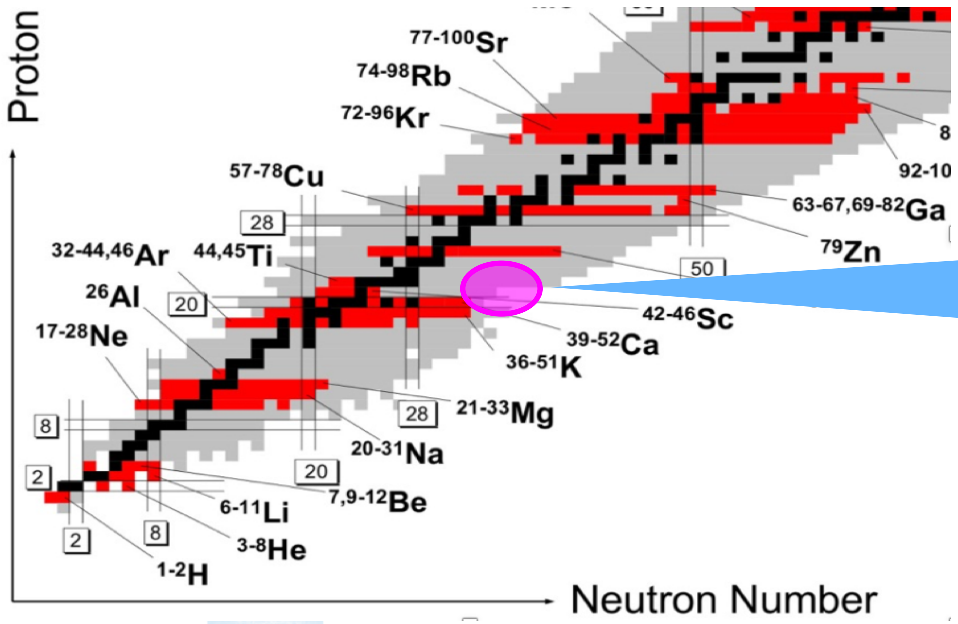
one option



$^{32-33}$K experiment @CRIS
$^{47-54}$Sc experiment @COLLAPS+CRIS

Spins, moments, charge radii





Around ^{52}Ca, ^{54}Ca beyond *N*=32
- **3-N forces**
- **Test *ab initio* theory**
- **New magic numbers *N* = 32， 34**

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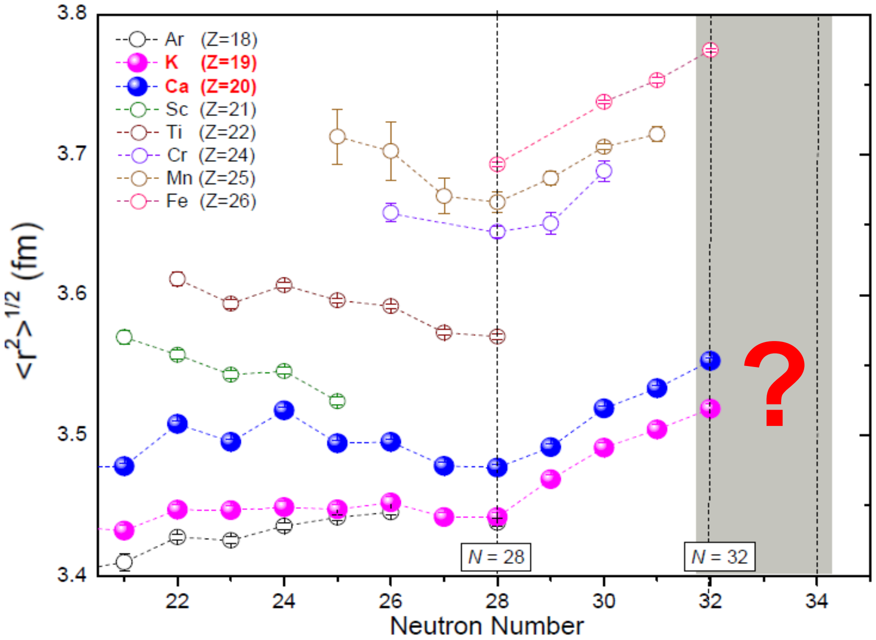
Physics motivation (charge radii of k, Sc across N = 32)



Garcia Ruiz *et al*, Nature Physics 2016,
Kreim *et al*, PLB **731** 97 (2014)

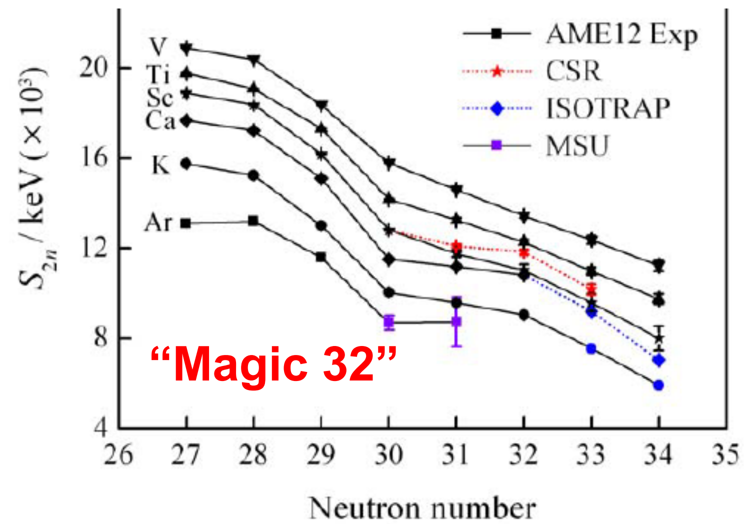
- **large charge radii of ^{52}Ca**
  --no signature of shell closure at N = 32 ?
- **same trend as Fe**
  --no shell closure is expected

Charge radii of ^{52,53}K and ^{54}Sc across N = 32
--the key information to test the N = 32

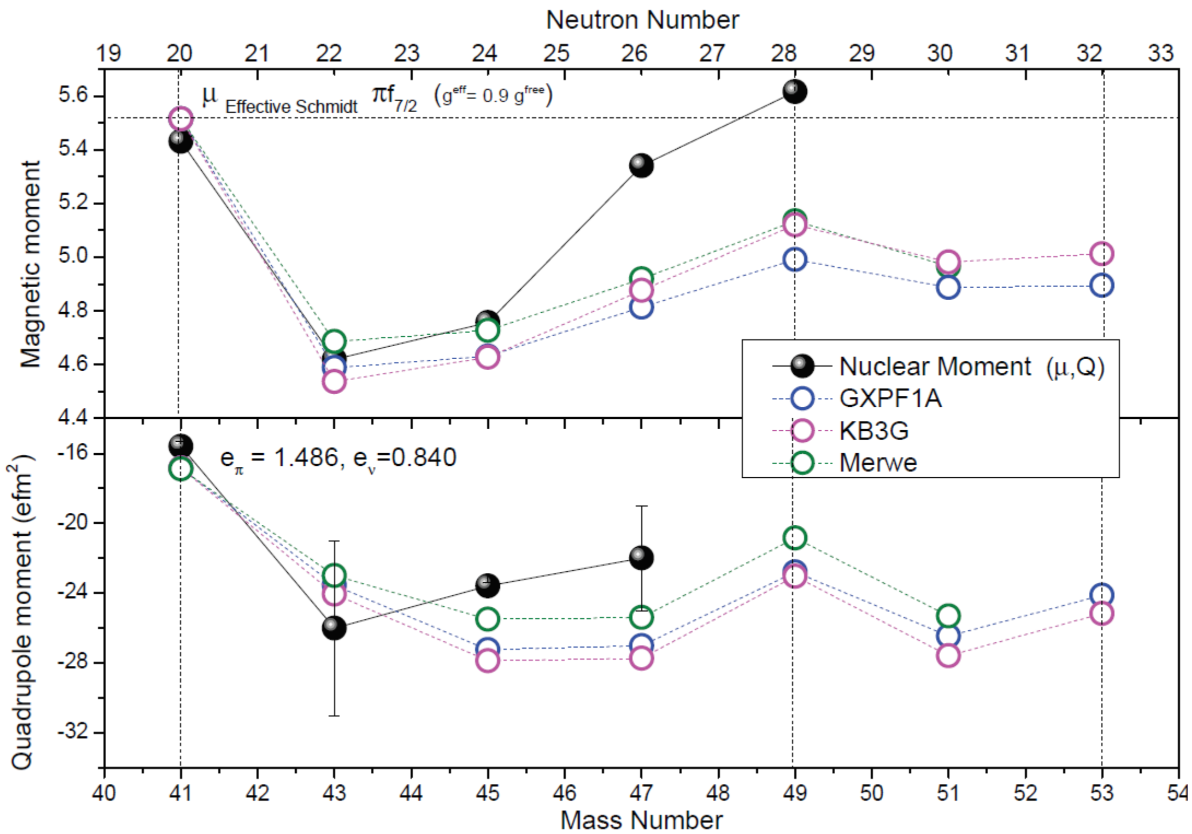
Test newly developed theoretical calculation

--Charge radii from ab-initio in Ca region

K, Ca, Sc (Z = 19,20,21): S_{2n}



Physics motivation (Moments of ^{49}Sc and ^{53}Sc)



^{49}Sc (^{48}Ca + p)
^{53}Sc (^{52}Ca + p)

^{41}Sc(^{40}Ca + p)

Magnetic moment and quadrupole moments of ^{53}Sc (52Ca+p)
----Test magicity of sub/shell closure

---- the calculation in this region from microscopic interactions (e.g NN+3N?)

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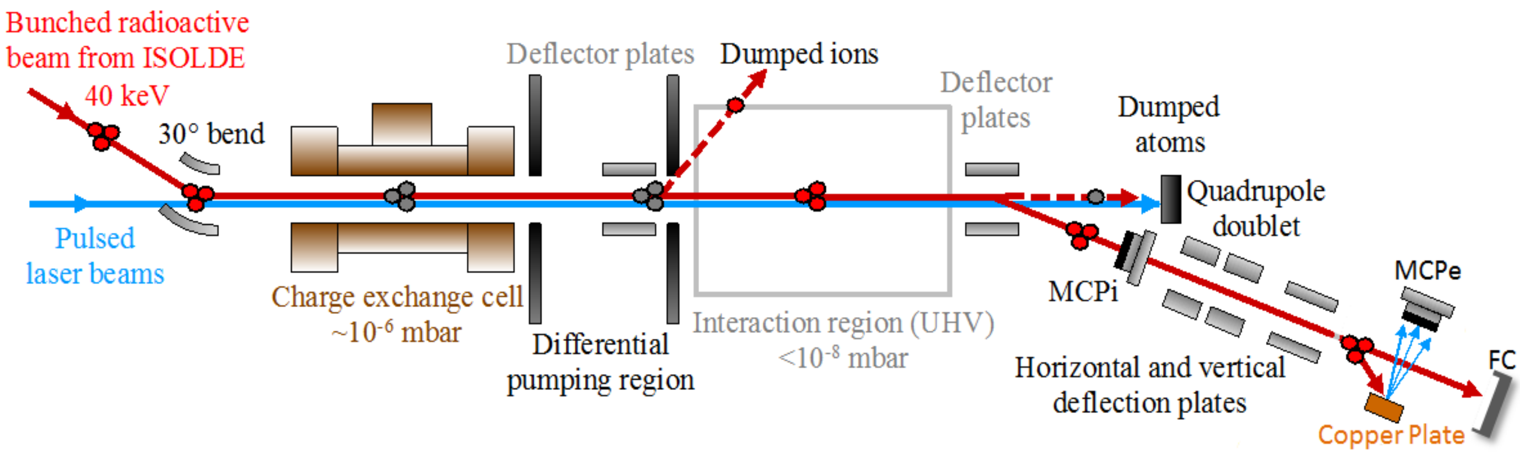
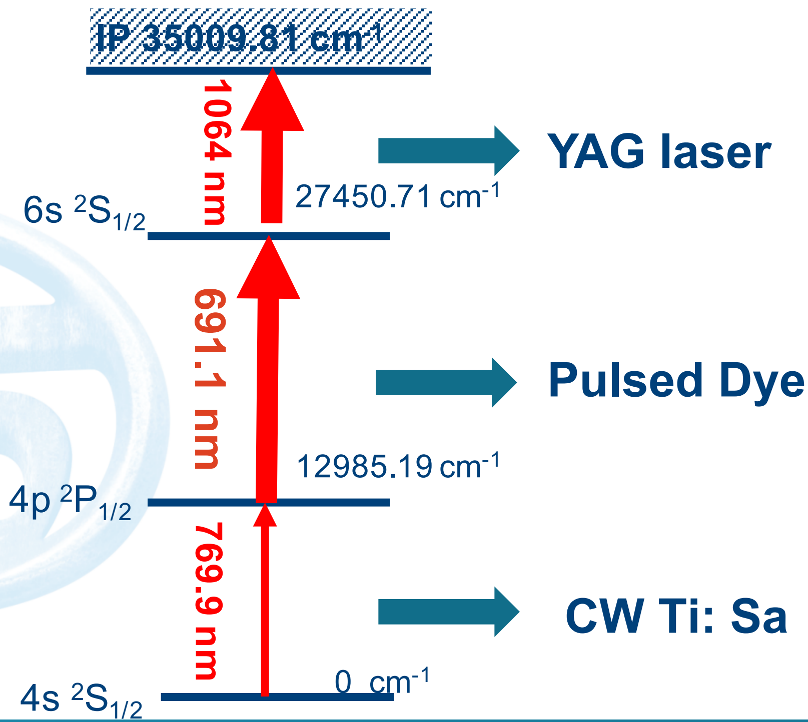
K: CRIS@ISOLDE-CERN



All fundamental steps



=> Experiment of Sc was pended due to the target development

Summary…

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

COLLAPS and CRIS technique are well demonstrated to do the high-resolution laser spectroscopy measurement of exotic nuclei (Ni, Zn)

Experiment has been performed on Zn isotopes and produced many important result in Ni region.

Measurement of neutron-rich K and Ge isotopes are on going
Measurement of neutron rich Sc isotopes are planned also

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Thanks for your attention!