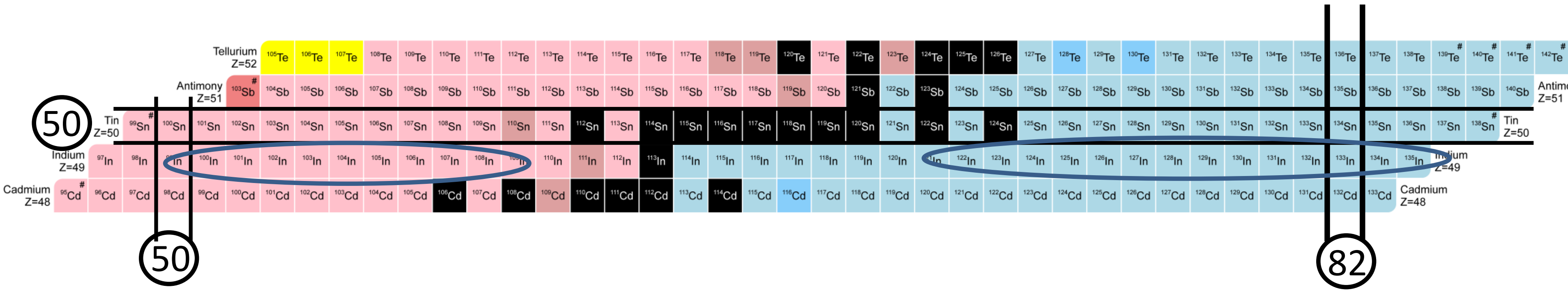
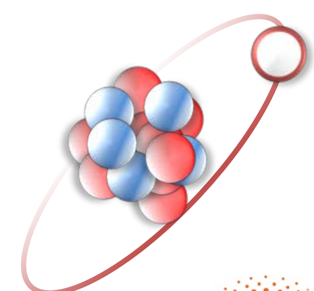
Laser Spectroscopy of exotic indium (Z = 49) isotopes: Approaching the N = 50 and N = 82 neutron numbers



Ronald Fernando Garcia Ruiz
The University of Manchester

On behalf of the CRIS collaboration

55th Meeting of the INTC
Feb 2017



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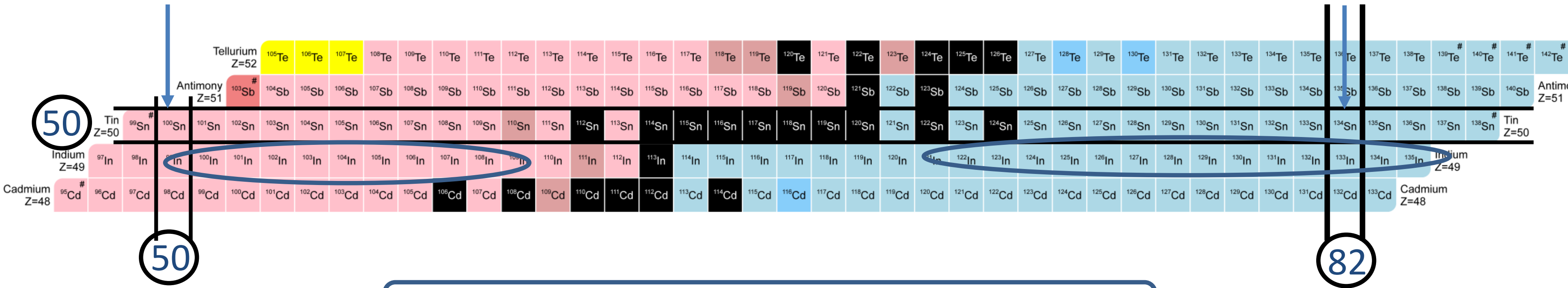
Motivation

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!

- Evolution of collectivity / single particle approaching the N=Z=50 and N=82 shell closures?
- Robustness of N=Z=50 shell closures?

Robust ? [Hinke *et al.* Nature 486, 341 (2012)]
[Guastalla *et al.*, PRL 110, 172501 (2013)]

Sof? [Vaman *et al.*, PRL 99, 162501 (2007)]
[Coraggio *et al.* PRC 91, 041301(R) (2015)]

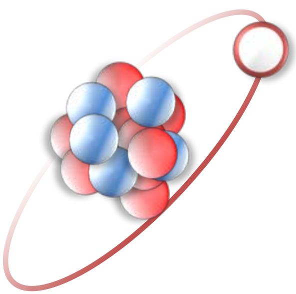
- Ordering of shell-model orbits

Contradictory evidence!

[Darby et al. PRL 105, 162502 (2010)]
[Banu et al. PRC 72, 061305(R) (2005)]
[Seweryniak et al. PRL 99, 022504 (2007)]

- Proton-neutron interaction?
- Role of electro-weak currents?

[Yuan et al. PLB 762, 237 (2016)]
[Rejmund et al. PLB 753, 86 (2016)]



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

Motivation

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

Nuclear force

- Phenomenology
- Chiral effective field theory

[Phys. Rev. Lett. 115, 122301 (2015)]
[Rev. Mod. Phys. 81, 1773 (2009)]
[Rev. Mod. Phys. 85, 197 (2013)]
…

Many-body methods

- Ab-initio
- Shell-model
- Mean-field, DFT…

[Phys. Rep. 621, 165 (2016)]
[Rev. Mod. Phys. 87, 1067 (2015]
[Rev. Mod. Phys. 77, 424 (2005)]
…

Electro-weak currents

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

[Rev. Mod. Phys. 87, 1067 (2015)]
[Phys Rev. Lett. 113, 262504 (2014)]
[Phys. Rev. C 87, 035503 (2013)]

- ***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)]

Can these studies be extended to indium isotopes?

Motivation

Laser spectroscopy ⇒ I , $\Delta\langle r^2\rangle$, μ , Q

Nuclear force
- Phenomenology
- Chiral effective field theory

Many-body methods
- Ab-initio
- Shell-model
- Mean-field, DFT…

Electro-weak currents
- Effective neutron/proton charges
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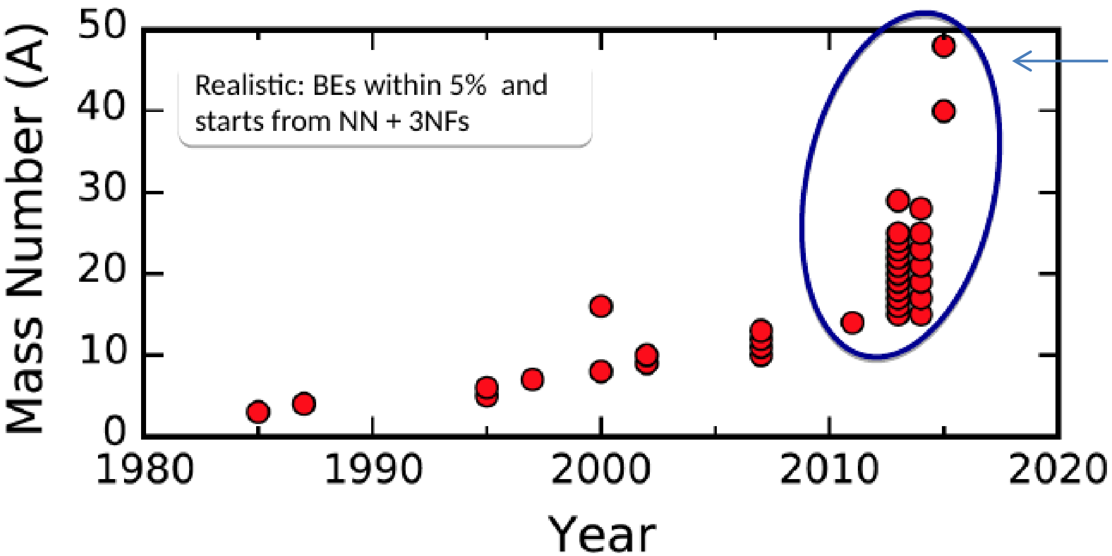


Status of ab-initio calculations (2016)

✓ **Ca region**
[Hagen et al, Nature Physics 12, 186 (2016)]
[Garcia Ruiz et al, Nature Physics 12, 594 (2016)]

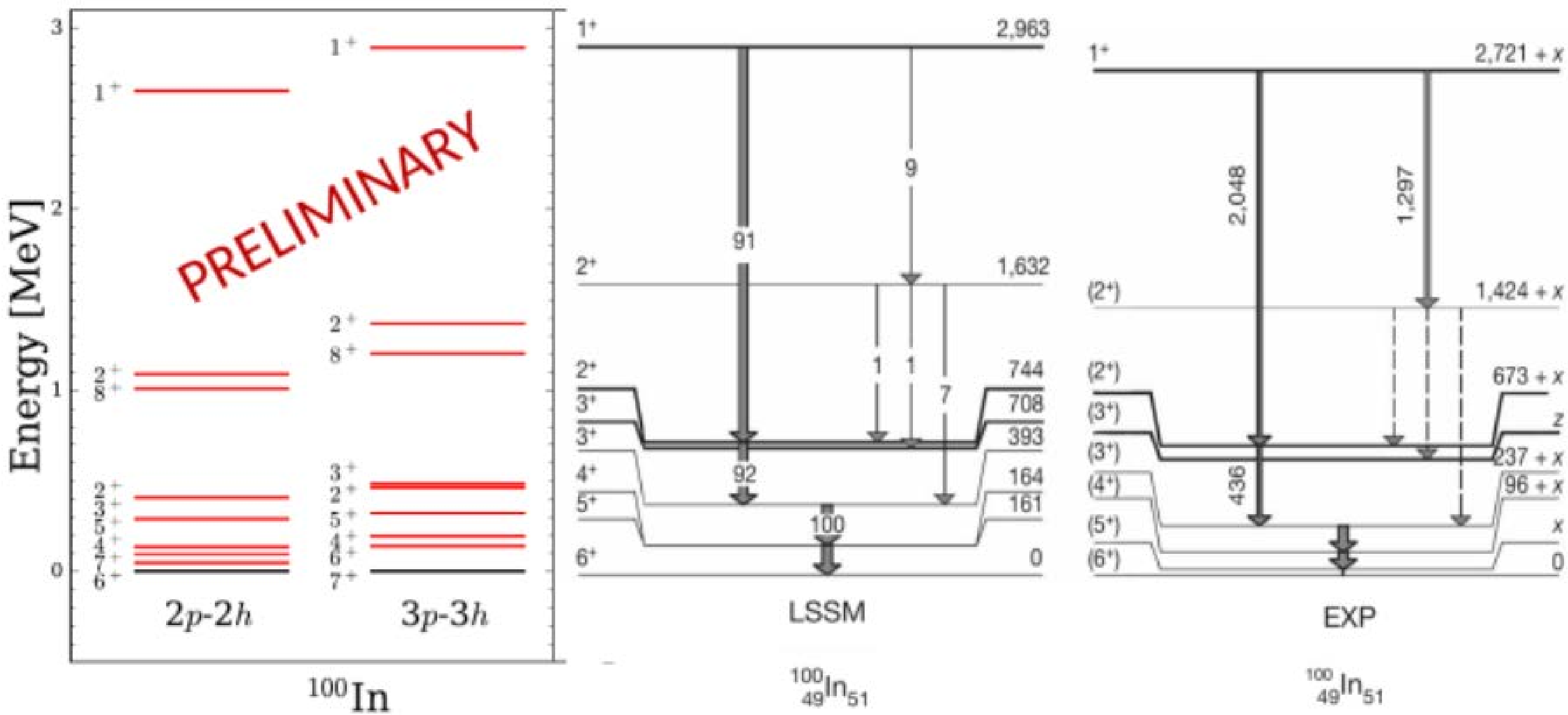
✓ **Ni region**
[Stroberg et al. Phys. Rev. Lett. 118, 032502 (2017)]
[Hagen et al , Phys. Rev. Lett 117, 172501 (2016)]

o **Sn region ?**

New developments in EFT + Normalization group + many-body methods:

Coupled clusters [Hagen et al. Phys. Rev. Lett 117, 172501 (2016)]
In-Medium SRG [Phys. Rev. Lett 118, 032502 (2017)]
Gorkov-Green Function [Phys. Rev. Lett 117, 052501 (2016)]
…

Ab-initio results around ^{100}In



Ab-initio calculations
[Hagen et al. In preparation (2017)]

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

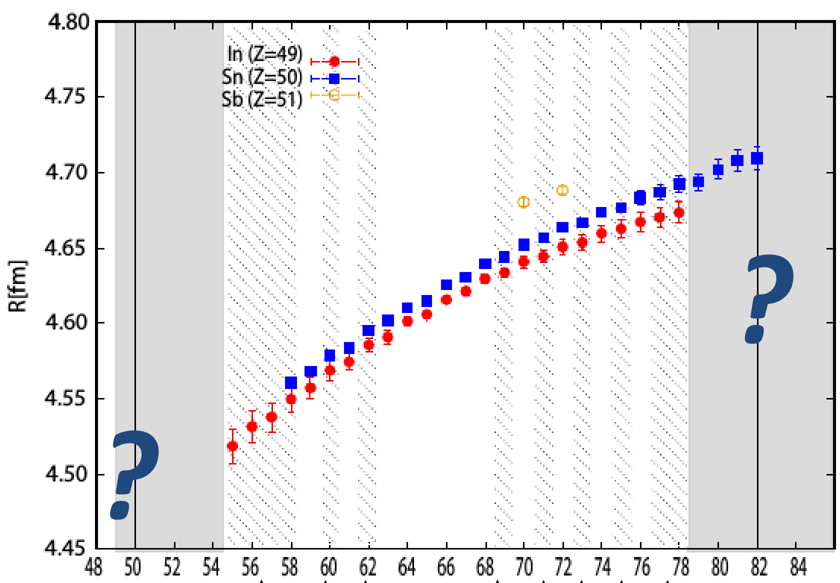
- *Ground-state spins are essential for our understanding of nuclear structure*

Charge radii and electromagnetic moments

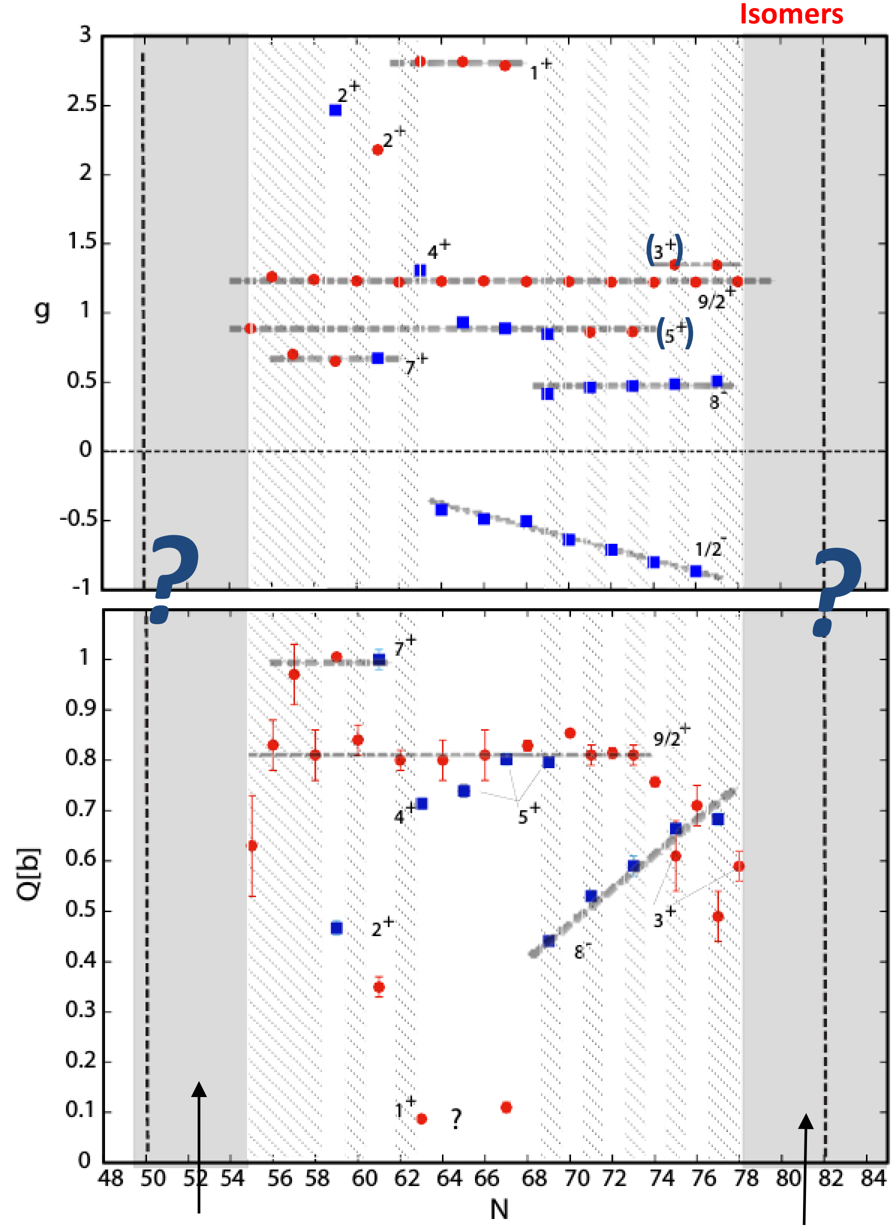
Ground states
Isomers

New experimental results expected from this proposal

Lots of unknowns!



Unknown for several isomers

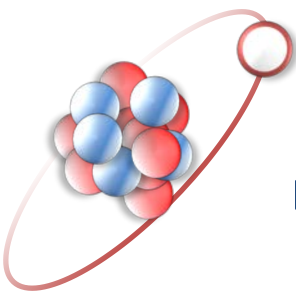


Unknown around N=50 and N=82!

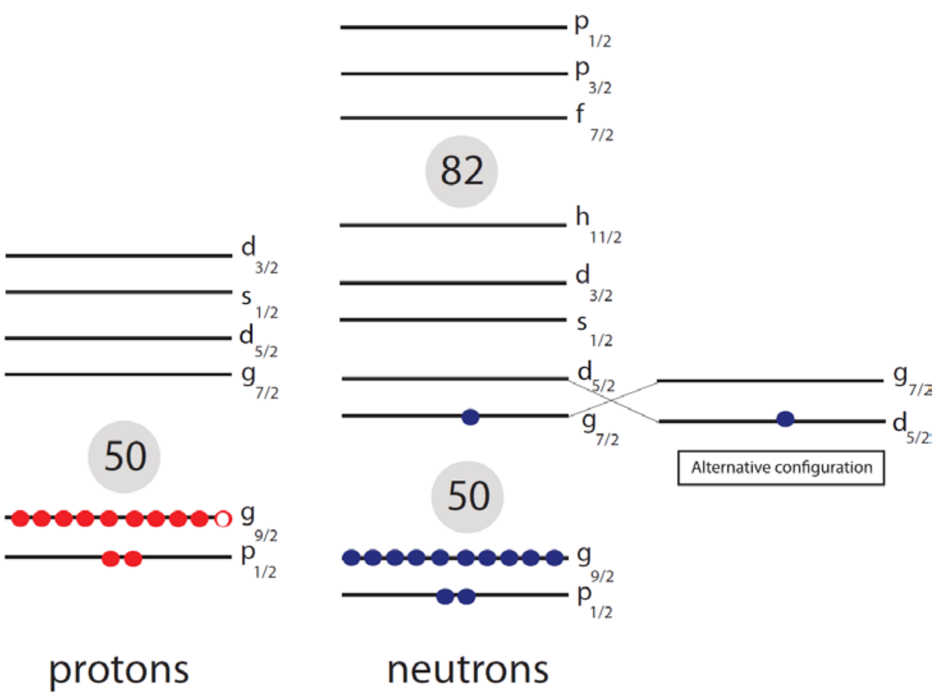
Charge radii and electromagnetic moments

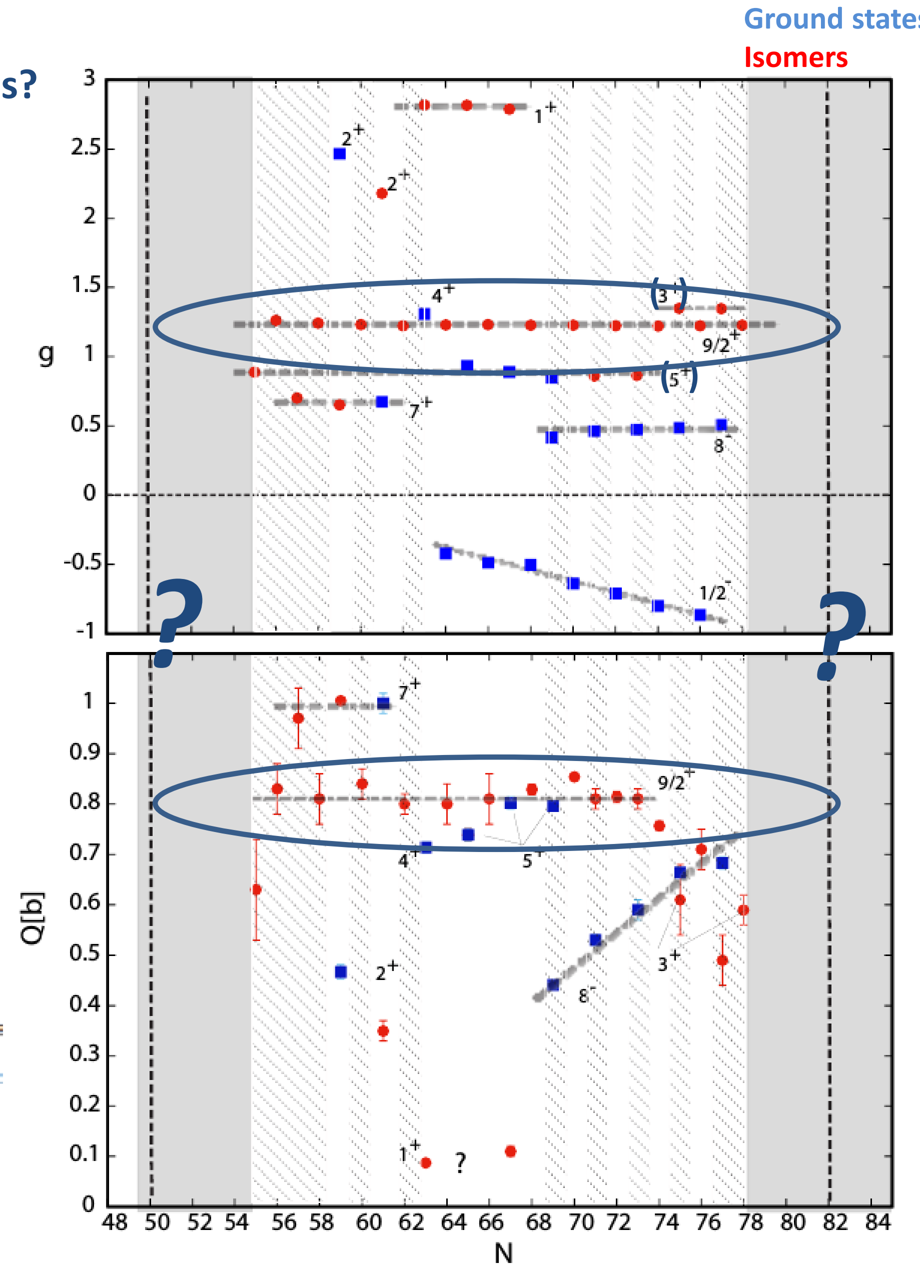
- Evolution of collectivity / single particle approaching the N=Z=50 and N=82 shell closures?
- Role of correlations across N=Z=50 and N=82?

Odd-even isotopes



Dominant single-particle?





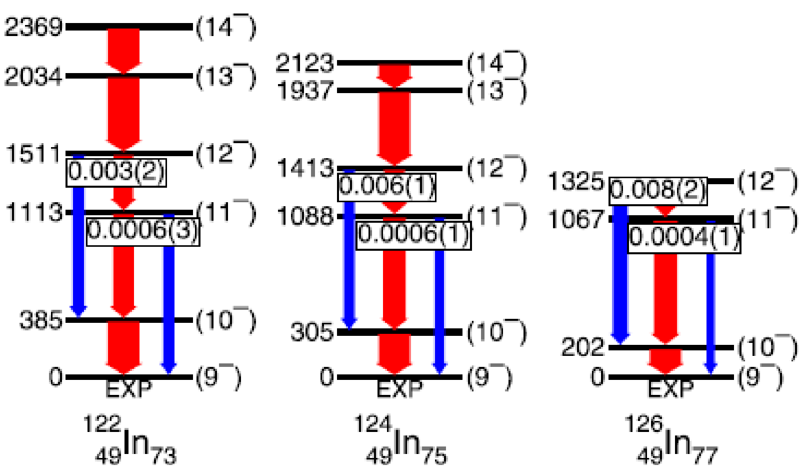
Charge radii and electromagnetic moments

- 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?
- Proton-neutron interaction?
- High-spin isomers / exotic decays

Odd-odd isotopes

- New isomers predicted
- Role of proton-neutron interaction
- High-spin isomers/neutron emission

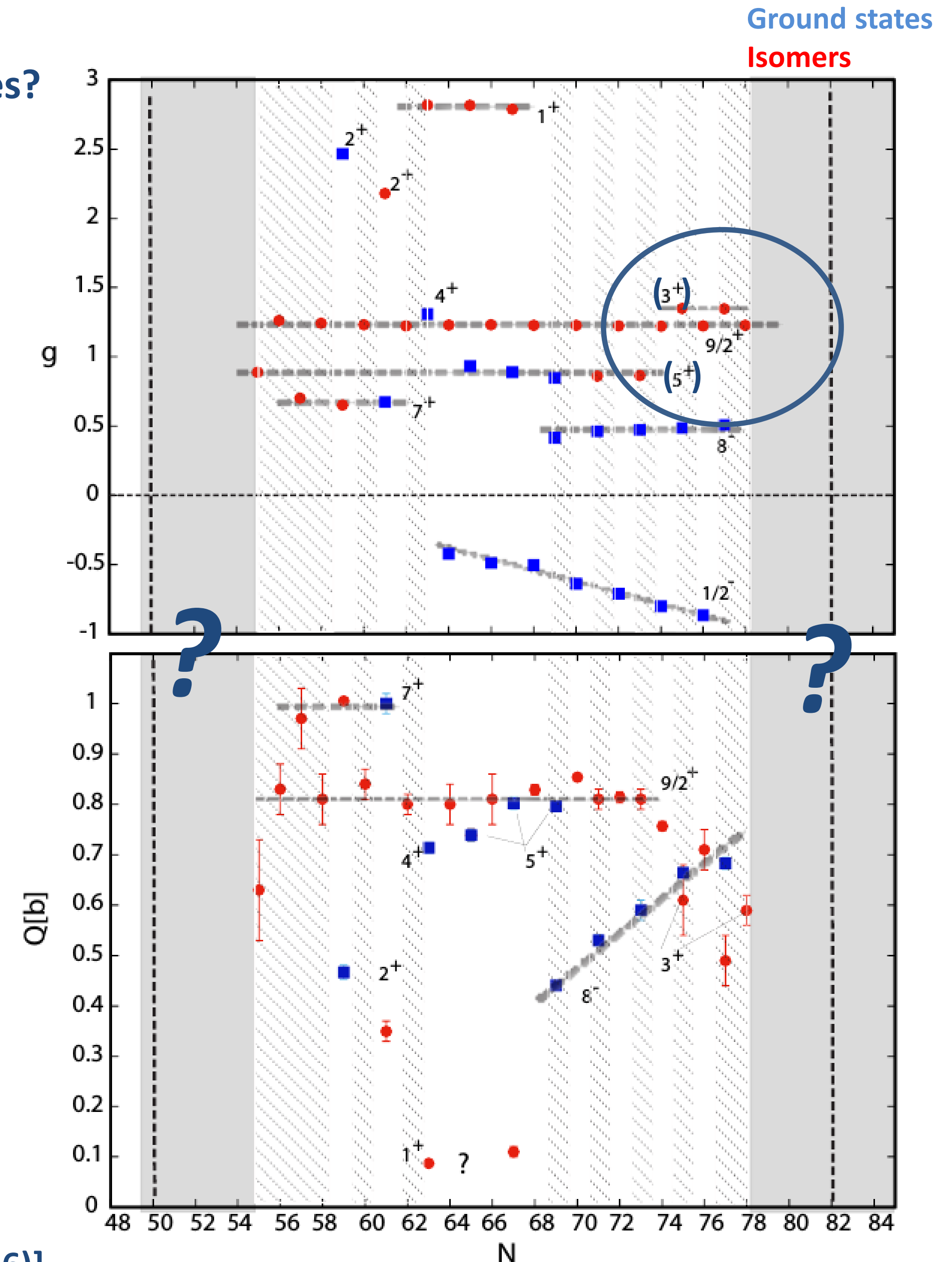
[Yuan et al. Phys. Lett. B 762, 237 (2016)]



(Based on large scale shell-model calculations)

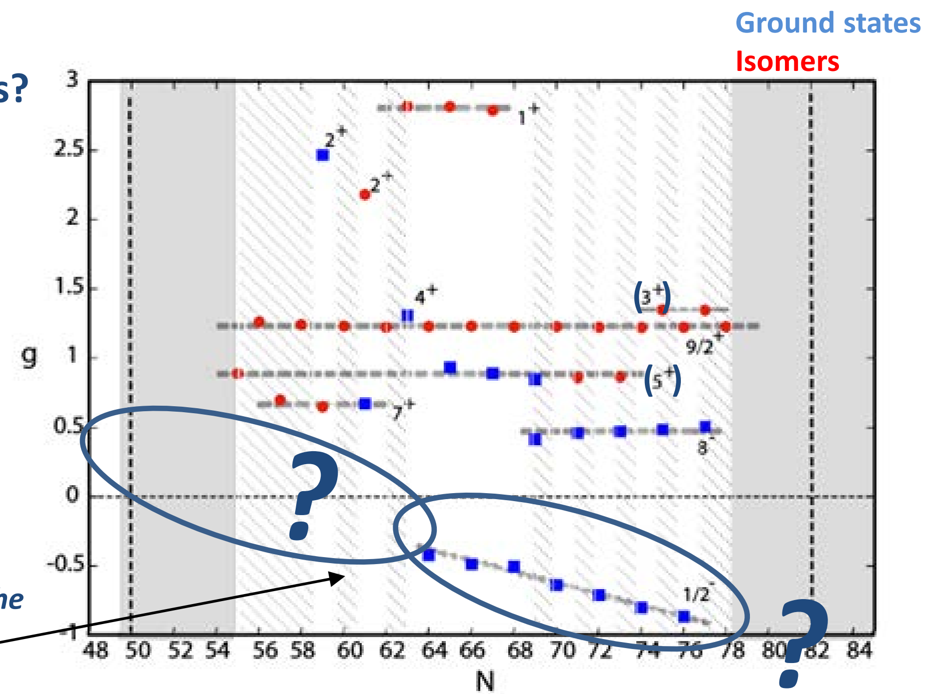
Indium isotopes can *"reveal novel aspects of the competition between the proton-neutron interaction and the like-nucleon pairing interaction"*

[Rejmund et al. Phys. Lett. B 753, 86 (2016)]



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?
- Proton-neutron interaction?
- High-spin isomers / exotic decays
- Role of electro-weak currents?
- Microscopic origin of effective operators? Effective charges and g-factors



"..Still, the unusual magnetic moments of the I=1/2 isomeric states represent an unresolved puzzle and may require a reconsideration of the overall nuclear structure of these isotopes"
[J. Eberz Nucl. Phys A 464 (1987) Q-28]

$$\mu \equiv \langle I, m = I \mid \mathbf{M_1} \mid I, m = I \rangle$$

→ $p_{1/2}$ moments insensitive to first-order core polarisation

odd proton	$l+1/2$	$-\frac{(l+2)\,l_1}{(2l+3)\,(2l_1+1)} \times \{ \cdots$
	$l-1/2$	$\frac{(l-1)\,l_1}{(2l+1)\,(2l_1+1)} \times \{ \cdots$

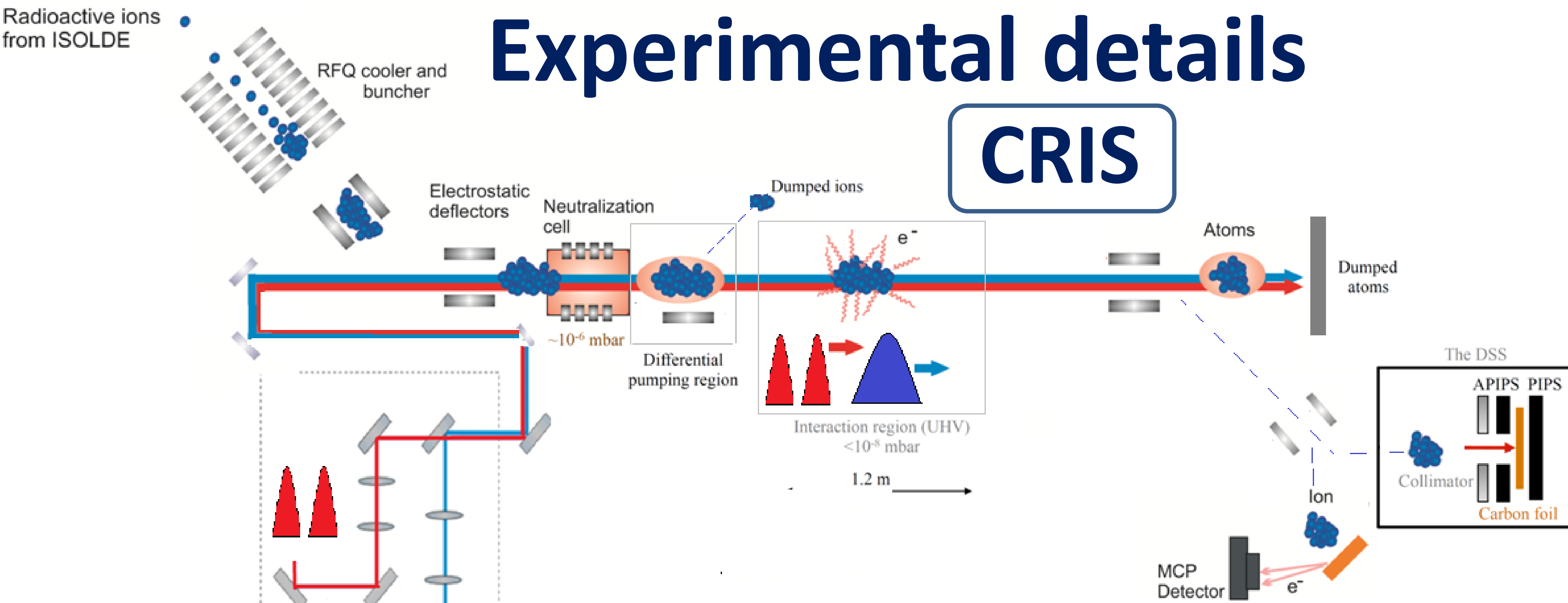
[Arima and H. Horie, Prog. Theor. Phys. 12, 623 (1954)]

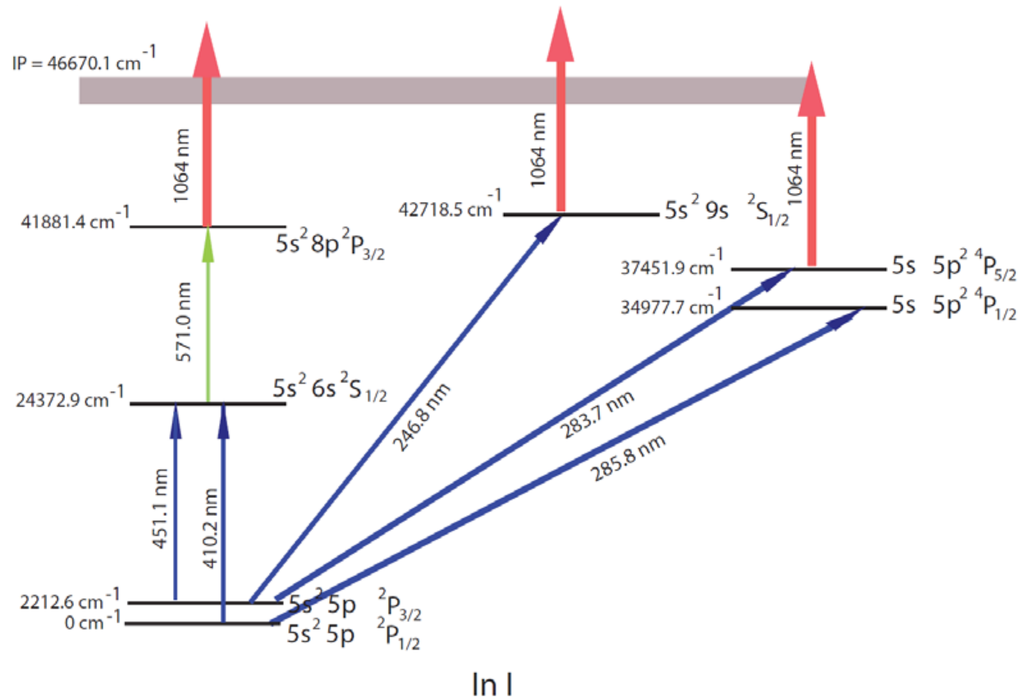
→ Sensitive to many-body currents (?)

- ***Electromagnetic moments are sensitive probes to the role of electro-weak currents***

Experimental details

CRIS





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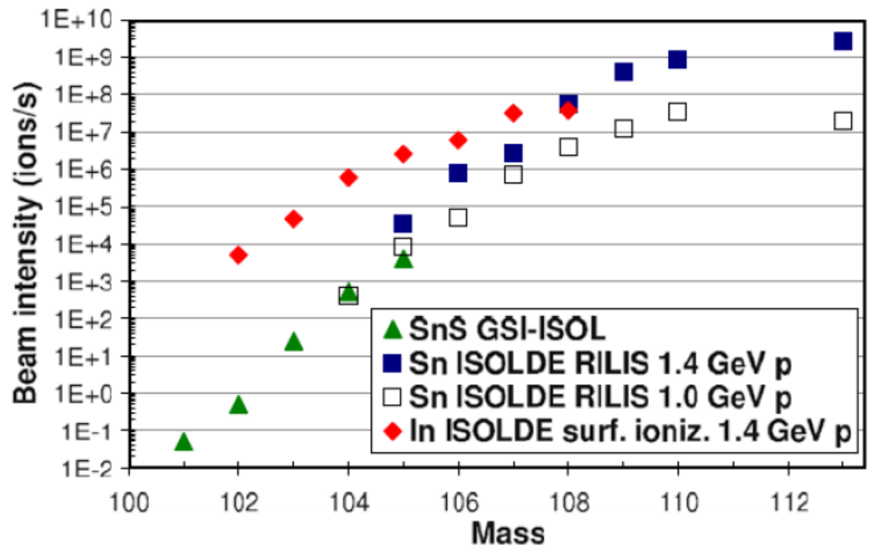
Beam time request

18.5 + 18.5 shifts

Isotope	I (Tentative)	Half life	Yield (ions/s)	Target+RILIS	Shifts
^{100}In	$(6^+, 7^+)$	7.0 s	16	LaC_x	6
^{101}In	$(9/2^+)$	15 s	380	LaC_x	2
^{102}In	(6^+)	22 s	8.6×10^3	LaC_x	0.5
^{103}In	$(9/2^+)$	65 s	8.0×10^4	LaC_x	0.5
^{103m}In	$(1/2^-)$	34 s	$>10^2$	LaC_x	1
^{104m}In	(3^+)	15.7 s	$>10^2$	LaC_x	1
^{105m}In	$(1/2^-)$	48 s	$>10^4$	LaC_x	0.3
^{106m}In	(2^+)	5.2 m	$>10^4$	LaC_x	0.3
^{107m}In	$1/2^-$	50.4 s	$>10^5$	LaC_x	0.3
^{109m_1}In	$1/2^-$	1.34 m	$>10^3$	LaC_x	0.3
^{109m_2}In	$(19/2^-)$	0.21 s	$>10^3$	LaC_x	0.3
^{111m}In	$(1/2^-)$	7.7 m	$>10^3$	LaC_x	0.3
^{118m}In	(1^+)	5.0 s	$>10^5$	LaC_x	0.3
^{120m}In	(1^+)	3.1 s	$>10^4$	LaC_x	0.3
^{122m}In	(1^+)	1.5 s	$>10^2$	LaC_x	1
$^{112-122}$In	–	>1 s	$\geq 10^4$	LaC_x	4
$^{112-122}$In	–	>1 s	$\geq 10^4$	UC_x	2^i
^{124m}In	(1^+)	3.1 s	$>10^2$	UC_x	0.5
^{127m_1}In	$(1/2^-)$	3.7 s	$>10^2$	UC_x	0.5
^{127m_2}In	(21^+)	1.0 s	$>10^2$	UC_x	0.5
^{128}In	(3^+)	0.84 s	$>10^4$	UC_x	0.5
^{128m}In	(8^-)	0.72 s	$>10^2$	UC_x	1
^{129}In	$(9/2^+)$	0.61 s	$>10^4$	UC_x	0.5^{ii}
^{129m_1}In	$(1/2^-)$	1.23 s	$>10^2$	UC_x	1
^{129m_2}In	$(23/2^-)$	0.67 s	$>10^2$	UC_x	1
^{130}In	(1^-)	0.29 s	$>10^3$	UC_x	0.5
^{130m_1}In	(10^-)	0.54 s	$>10^2$	UC_x	1
^{130m_2}In	(5^+)	0.54 s	$>10^2$	UC_x	1
^{131}In	$(9/2^+)$	0.28 s	$>10^3$	UC_x	0.5
^{131m_1}In	$(1/2^-)$	0.35 s	$>10^2$	UC_x	1
^{131m_2}In	$(21/2^+)$	0.32 s	$>10^2$	UC_x	1
^{132}In	(7^-)	0.20 s	1.6×10^4	UC_x	0.5
^{133,133m}In	$(9/2^+, 1/2^-)$	165 ms	1.8×10^3	UC_x	1.5
^{134}In	$(4^-$ to $7^-)$	138 ms	190	UC_x	4

Lots of unknowns!



[Koster et al. NIMB 266, 4229 (2008)]

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^{105m}In	$(1/2^-)$	48 s	$>10^4$	LaC_x	0.3
^{106m}In	(2^+)	5.2 m	$>10^4$	LaC_x	0.3
^{107m}In	$1/2^-$	50.4 s	$>10^5$	LaC_x	0.3
^{109m_1}In	$1/2^-$	1.34 m	$>10^3$	LaC_x	0.3
^{109m_2}In	$(19/2^-)$	0.21 s	$>10^3$	LaC_x	0.3
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^{128m}In	(8^-)	0.72 s	$>10^2$	UC_x	1
^{129}In	$(9/2^+)$	0.61 s	$>10^4$	UC_x	0.5^{ii}
^{129m_1}In	$(1/2^-)$	1.23 s	$>10^2$	UC_x	1
^{129m_2}In	$(23/2^-)$	0.67 s	$>10^2$	UC_x	1
^{130}In	(1^-)	0.29 s	$>10^3$	UC_x	0.5
^{130m_1}In	(10^-)	0.54 s	$>10^2$	UC_x	1
^{130m_2}In	(5^+)	0.54 s	$>10^2$	UC_x	1
^{131}In	$(9/2^+)$	0.28 s	$>10^3$	UC_x	0.5
^{131m_1}In	$(1/2^-)$	0.35 s	$>10^2$	UC_x	1
^{131m_2}In	$(21/2^+)$	0.32 s	$>10^2$	UC_x	1
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TAC summary:

- ^{100}In 16/s :ok
  -> ☺
- NanoLaCx (not currently possible)
  -> Not needed
- Impurities claimed Cs:
  -> Important for neutron-rich
- Level of Cs impurity needs to be assessed during beamtime…
  -> Expected: ^{132}Cs/^{132}In ~ 10^2
  ^{133}Cs/^{133}In ~ 10^3
  ^{134}Cs/^{134}In ~ 10^4
- LaC: fluctuations in yield possible.
  ->We quoted lowest reported yields
- RILIS optimization for isomers could be needed for odd isotopes.
  -> Isotope shift corrections should be assessed at the start of the run. Knowledge acquired during previous IDS run.

Summary

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^{106m}In	(2^+)	5.2 m
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^{120m}In	(1^+)	3.1 s
^{122m}In	(1^+)	1.5 s
$^{112-122}$In	–	>1 s
$^{112-122}$In	–	>1 s
^{124m}In	(1^+)	3.1 s
^{127m_1}In	$(1/2^-)$	3.7 s
^{127m_2}In	(21^+)	1.0 s
^{128}In	(3^+)	0.84 s
^{128m}In	(8^-)	0.72 s
^{129}In	$(9/2^+)$	0.61 s
^{129m_1}In	$(1/2^-)$	1.23 s
^{129m_2}In	$(23/2^-)$	0.67 s
^{130}In	(1^-)	0.29 s
^{130m_1}In	(10^-)	0.54 s
^{130m_2}In	(5^+)	0.54 s
^{131}In	$(9/2^+)$	0.28 s
^{131m_1}In	$(1/2^-)$	0.35 s
^{131m_2}In	$(21/2^+)$	0.32 s
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Indium isotopes offer a unique insight to understand the structure around N=Z=50 and N=82

✓ **^{100}In: key physics case for our understanding of nuclear structure around N=Z=50 and the development of inter-nucleon interactions and many-body methods**

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^{128m}In	(8^-)	0.72 s
^{129}In	$(9/2^+)$	0.61 s
^{129m_1}In	$(1/2^-)$	1.23 s
^{129m_2}In	$(23/2^-)$	0.67 s
^{130}In	(1^-)	0.29 s
^{130m_1}In	(10^-)	0.54 s
^{130m_2}In	(5^+)	0.54 s
^{131}In	$(9/2^+)$	0.28 s
^{131m_1}In	$(1/2^-)$	0.35 s
^{131m_2}In	$(21/2^+)$	0.32 s
^{132}In	(7^-)	0.20 s
^{133,133m}In	$(9/2^+, 1/2^-)$	165 ms
^{134}In	$(4^-$ to $7^-)$	138 ms

Laser spectroscopy ⇨ I , $\Delta\langle r^2\rangle$, μ , Q

Nuclear force
- Phenomenology
- Chiral effective field theory

Many-body methods
- Ab-initio
- Shell-model
- Mean-field, DFT…

Electro-weak currents
- Effective neutron/proton charges
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Indium isotopes offer a unique insight to understand the structure around N=Z=50 and N=82

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^{103m}In	$(1/2^-)$	34 s
^{104m}In	(3^+)	15.7 s
^{105m}In	$(1/2^-)$	48 s
^{106m}In	(2^+)	5.2 m
^{107m}In	$1/2^-$	50.4 s
^{109m_1}In	$1/2^-$	1.34 m
^{109m_2}In	$(19/2^-)$	0.21 s
^{111m}In	$(1/2^-)$	7.7 m
^{118m}In	(1^+)	5.0 s
^{120m}In	(1^+)	3.1 s
^{122m}In	(1^+)	1.5 s
$^{112-122}$In	–	>1 s
$^{112-122}$In	–	>1 s
^{124m}In	(1^+)	3.1 s
^{127m_1}In	$(1/2^-)$	3.7 s
^{127m_2}In	(21^+)	1.0 s
^{128}In	(3^+)	0.84 s
^{128m}In	(8^-)	0.72 s
^{129}In	$(9/2^+)$	0.61 s
^{129m_1}In	$(1/2^-)$	1.23 s
^{129m_2}In	$(23/2^-)$	0.67 s
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“Simple” two-photon ionization

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"Simple" two-photon ionization

Why we have not measured it?

Thank you for your attention!

Acknowledgements

Experiment:

-> CRIS group

Theory:

-> G. Hagen (ORNL)

-> J. Holt (TRIUMF)

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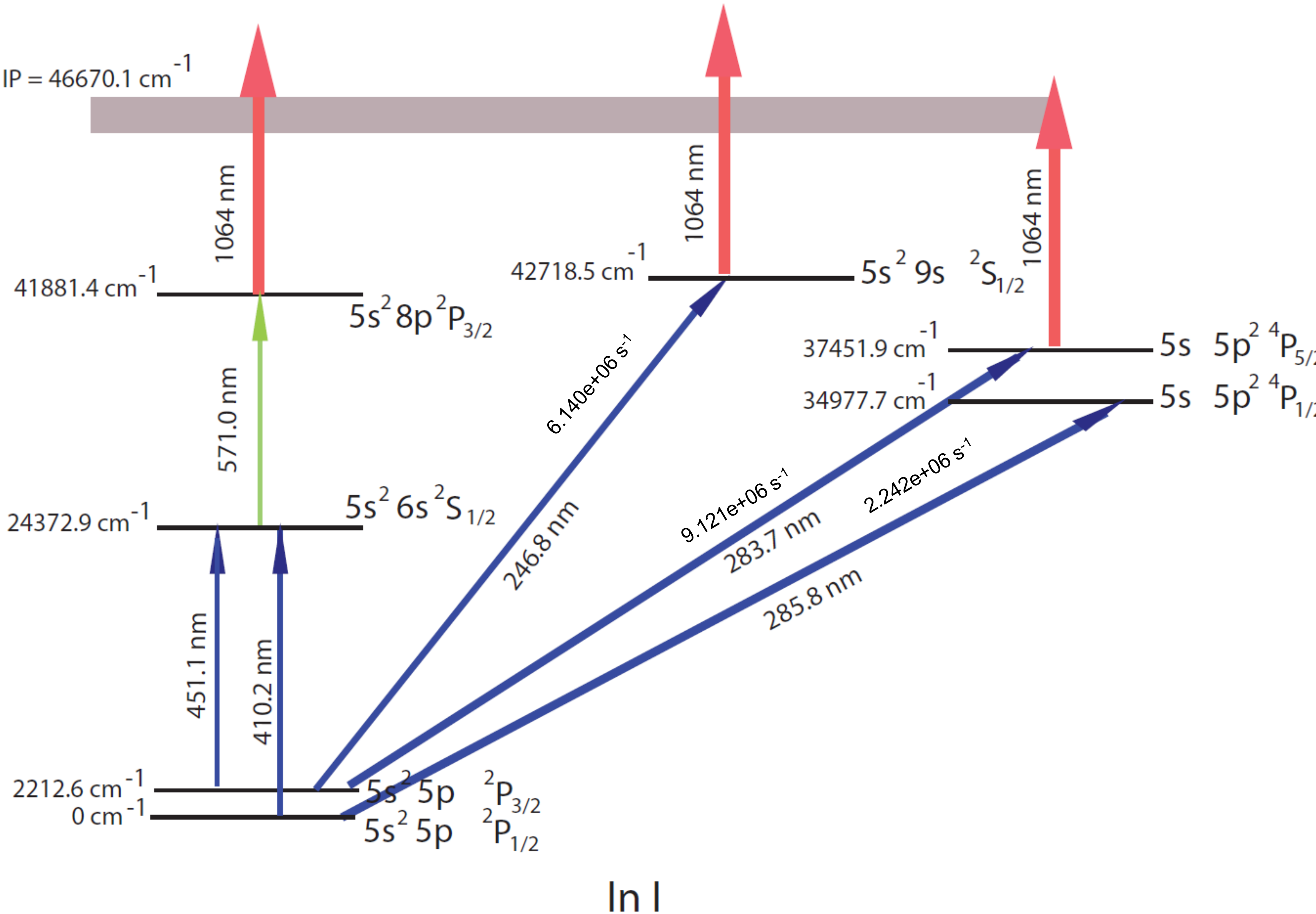
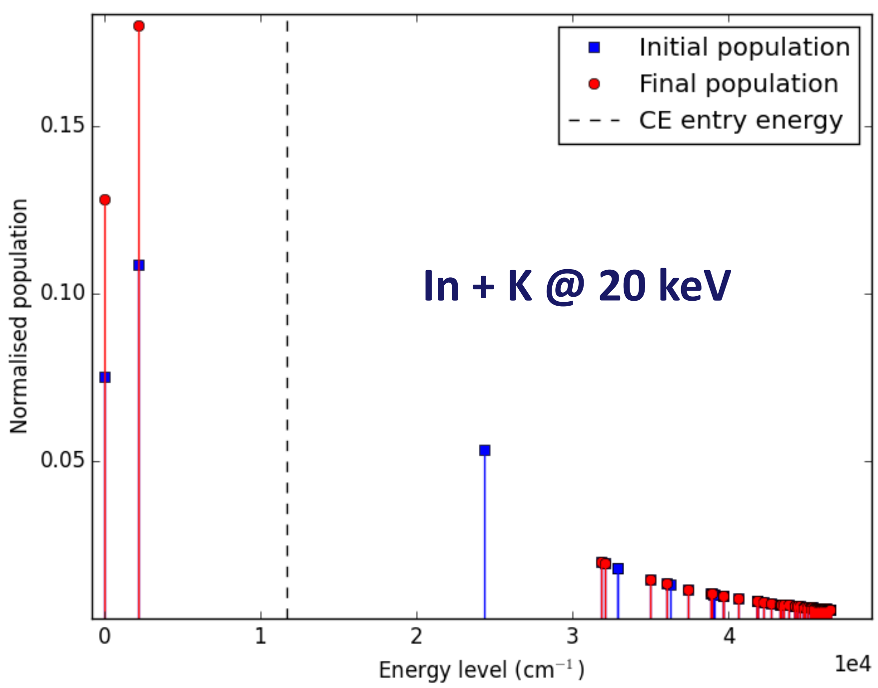
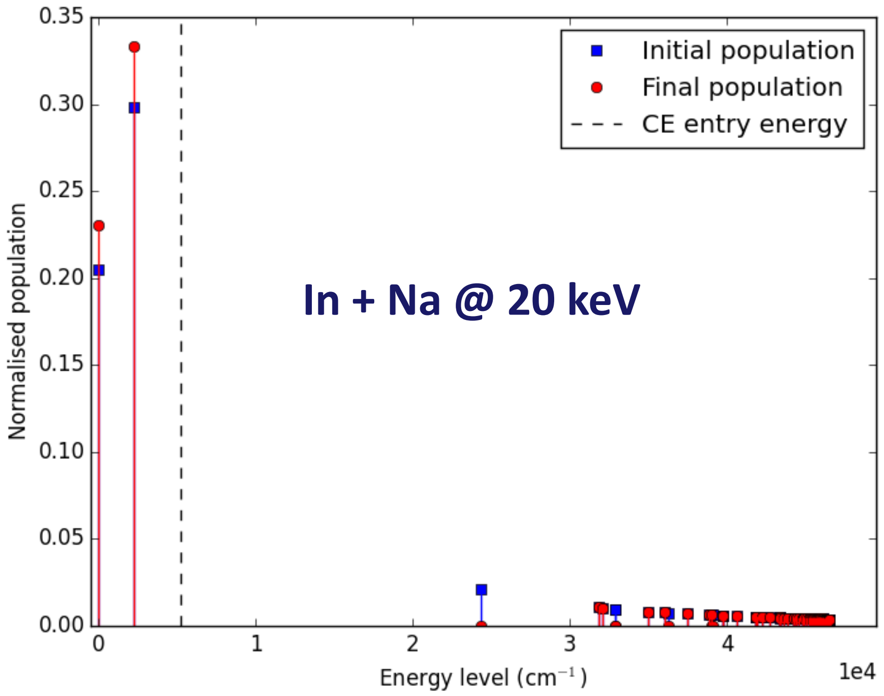
Ionization schemes



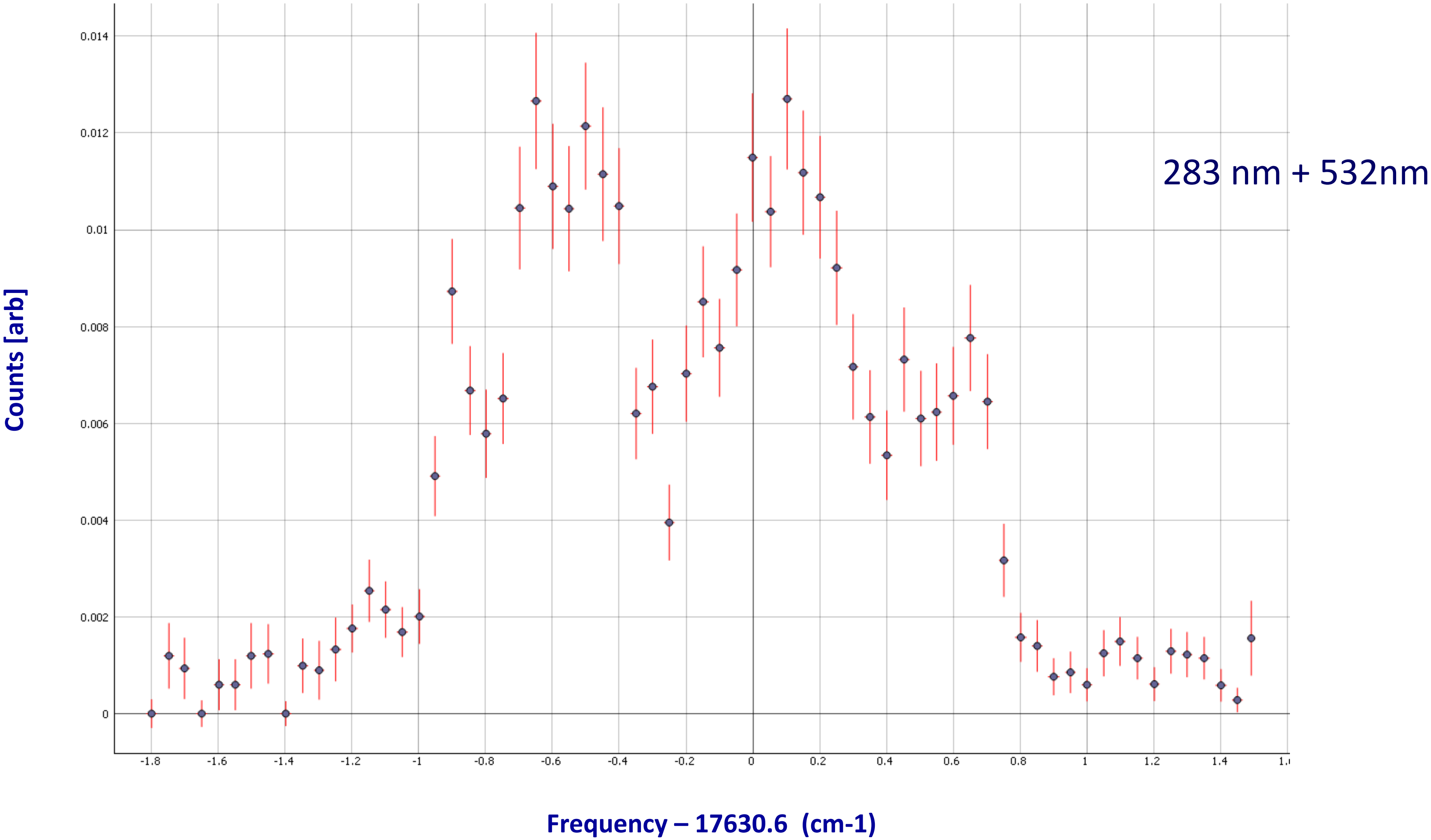
Population of states after CEC



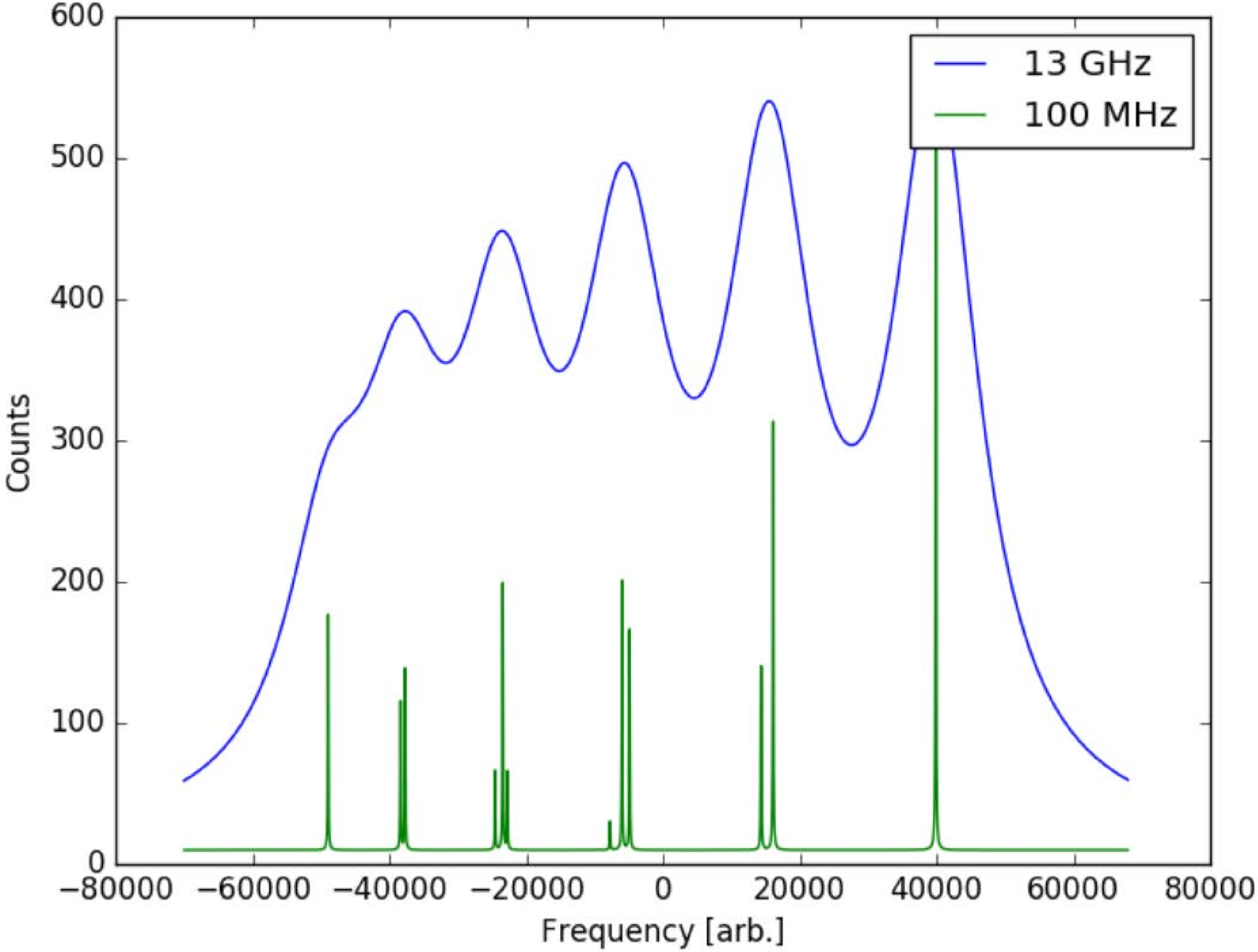


First off-line CRIS with In

- Ablation source and low resolution
- Up to ~50% neutralization

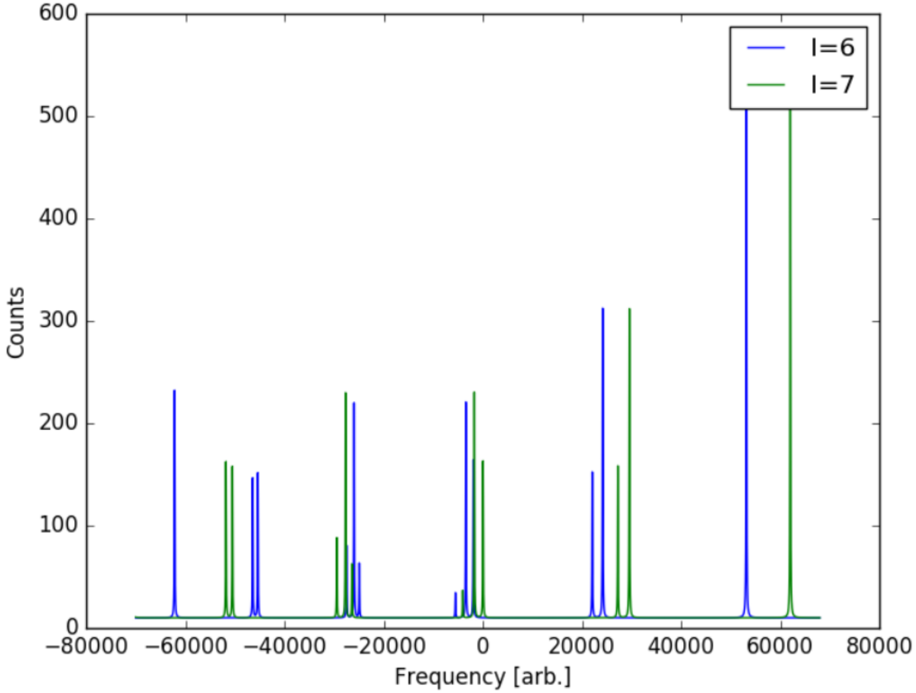


Simulations ^{115}In

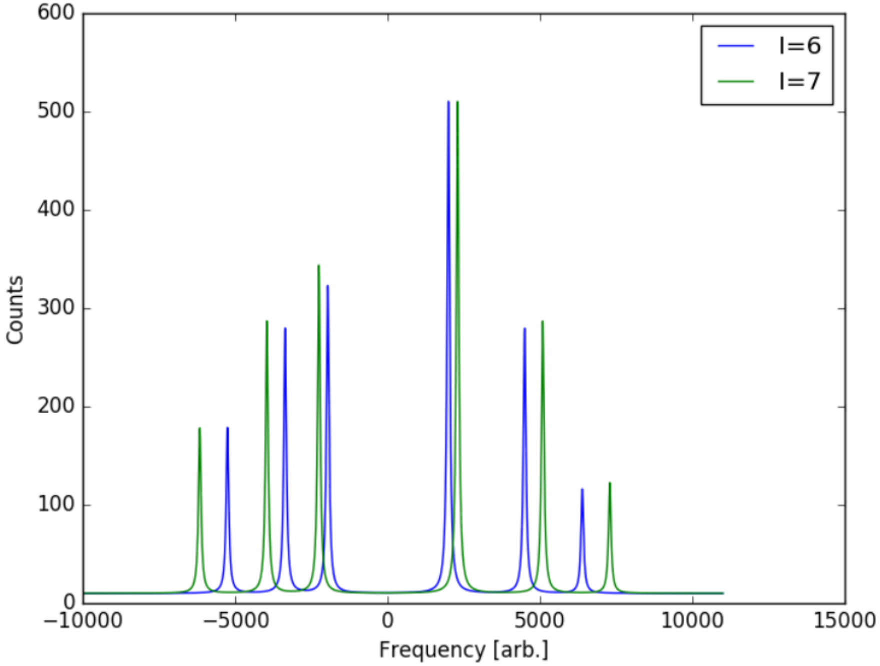


Simulations In

283.7 nm

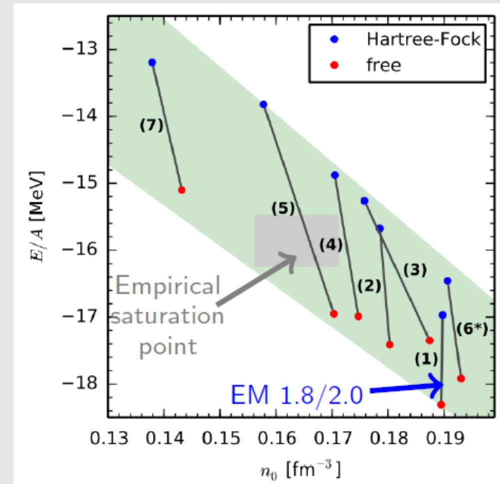


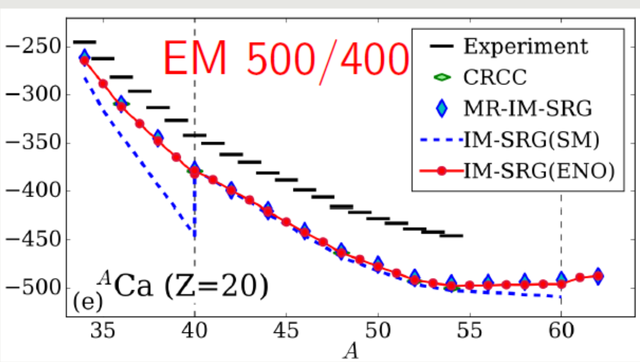
246.8 nm

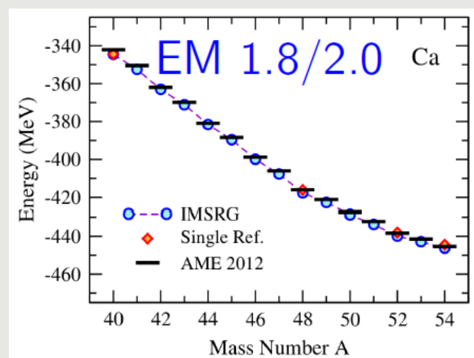


VS-IMSRG

	EM 500/400	EM 1.8/2.0
NN	N^3LO	same
	$\Lambda_{2N} = 500$ MeV	same
	non-local regulator	same
	fit to NN scattering, ^{2}H	same
	$\lambda_{SRG} = 1.88$ fm^{-1}	$\approx$ same
3N	N^2LO	same
	$\Lambda_{3N} = 400$ MeV	$\approx$ same
	local regulator	non-local regulator
	fit to ^{3}H BE, $t_{1/2}$	fit to ^{3}H BE, ^{4}He r_{ch}
	consistently SRG evolved	no SRG for 3N







- Neither interaction is fully consistent

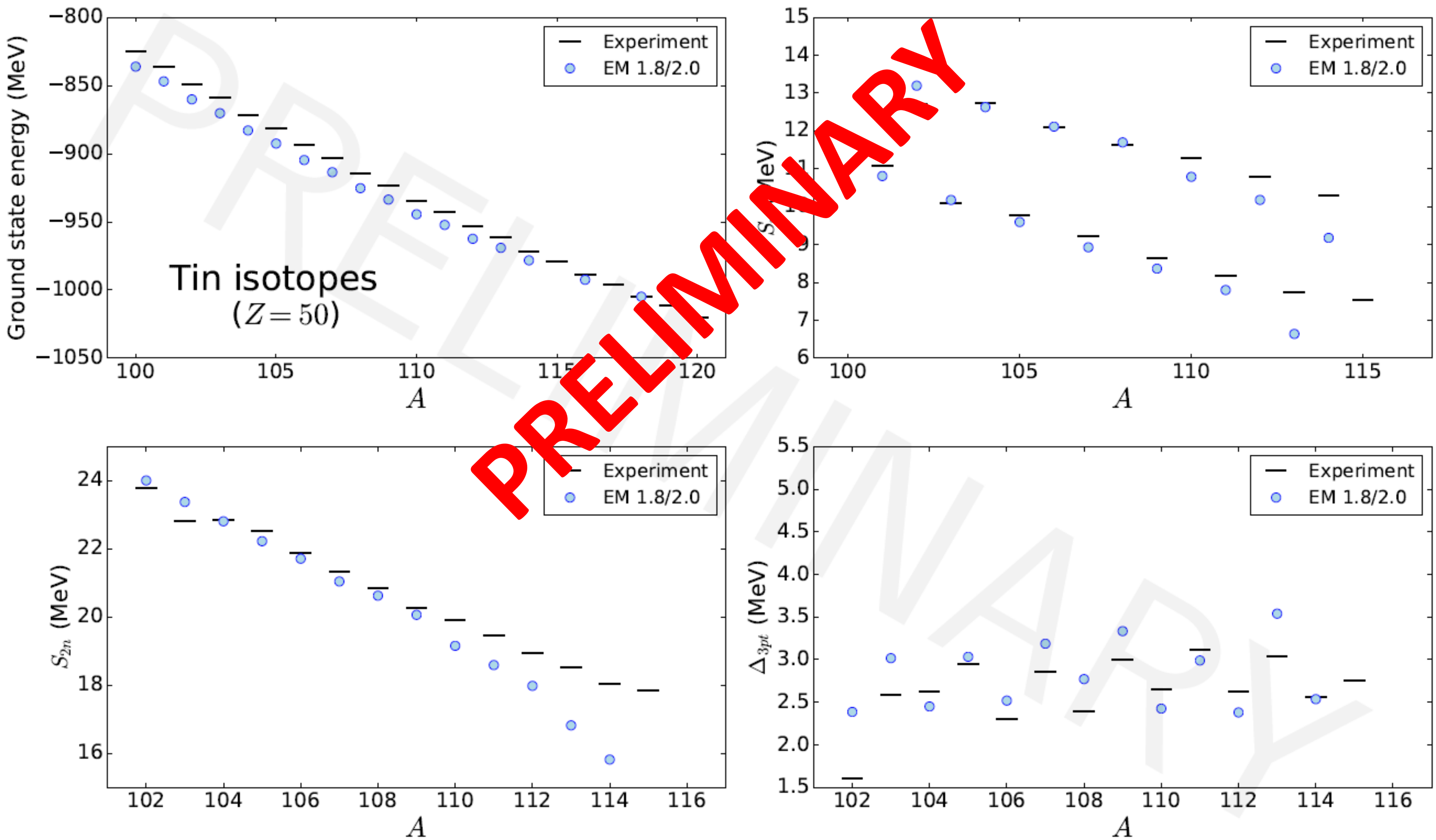
  however. . .

- Saturation properties appear important for finite nuclei

[J. Holt, R. Stroberg. Private communication (2017)]

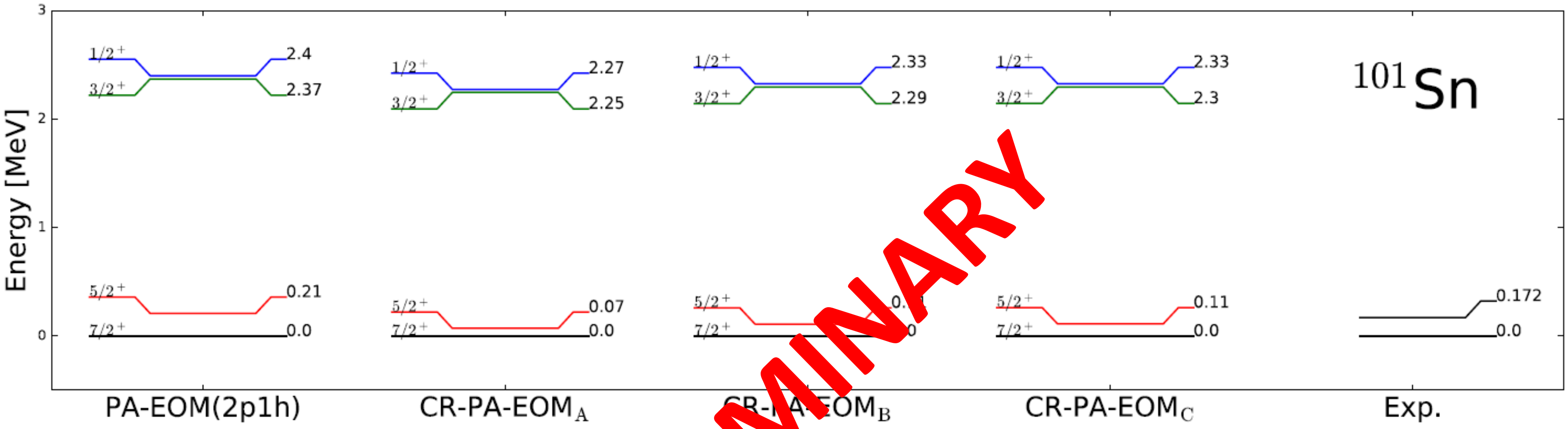
VS-IMSRG

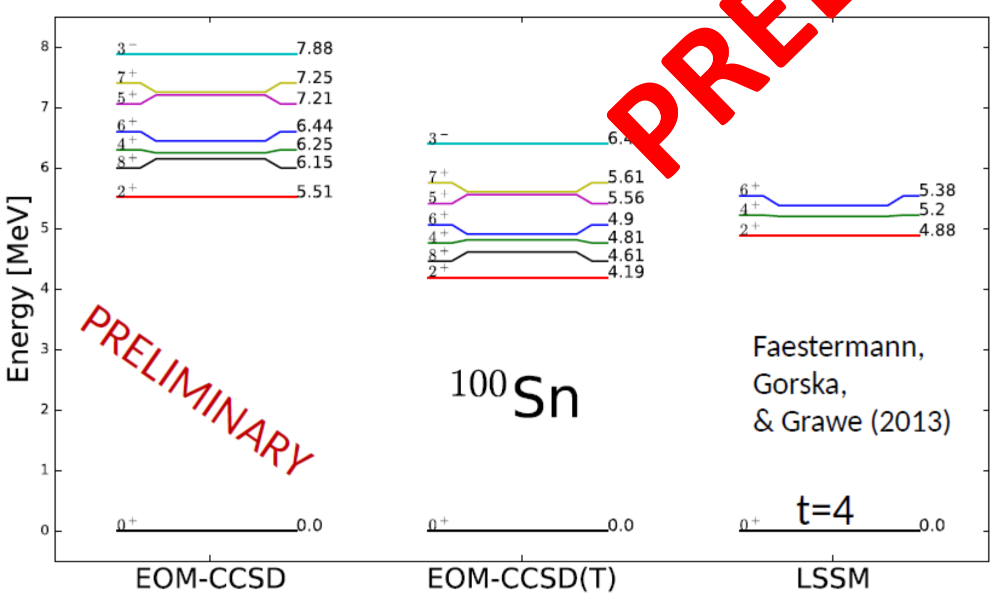
Isotopic chain with $\hbar\omega = 16$, $e_{max} = 14$, $E3_{max} = 16$



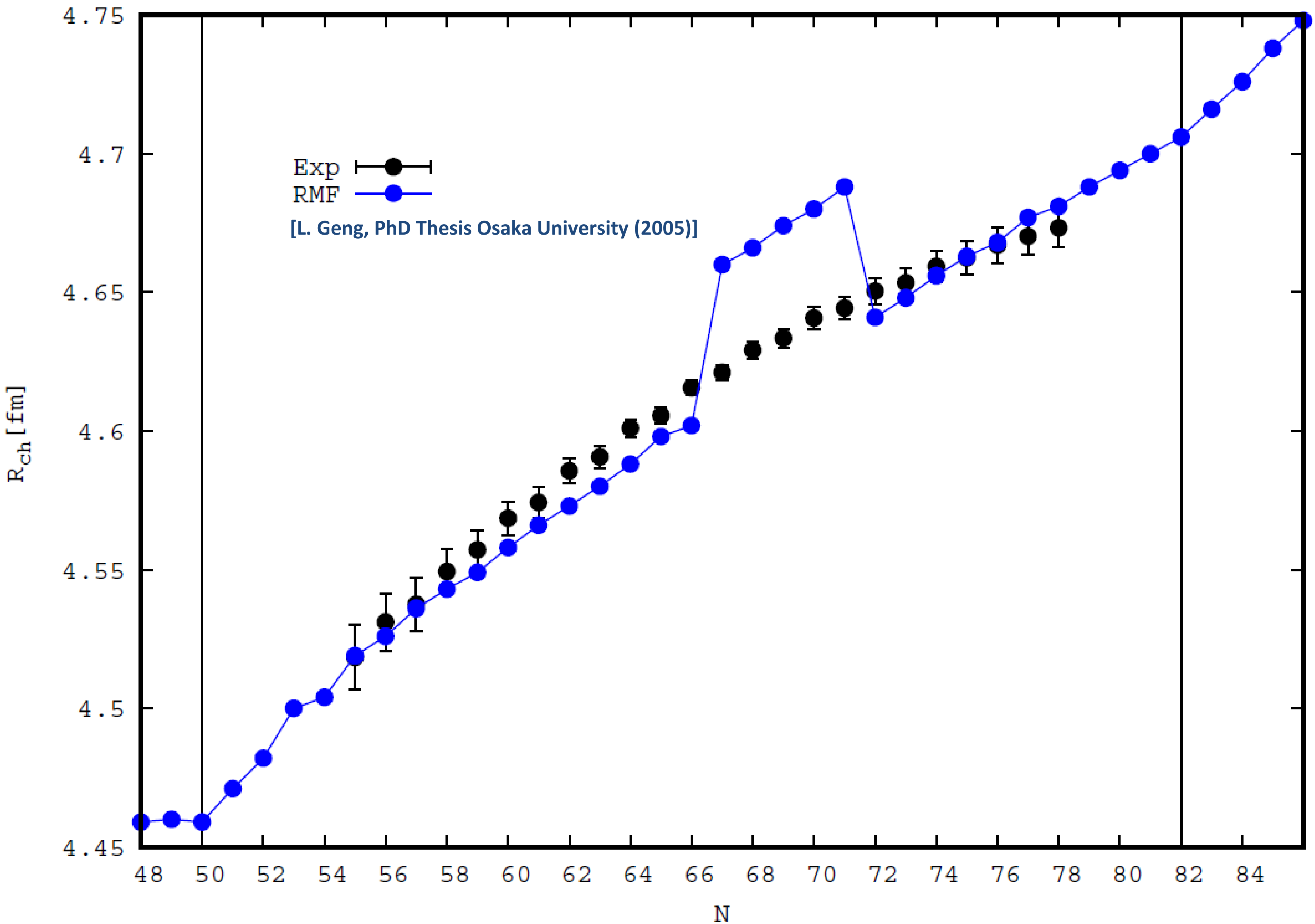
[J. Holt, R. Stroberg. Private communication (2017)]

Structure of the ligthest tin isotopes





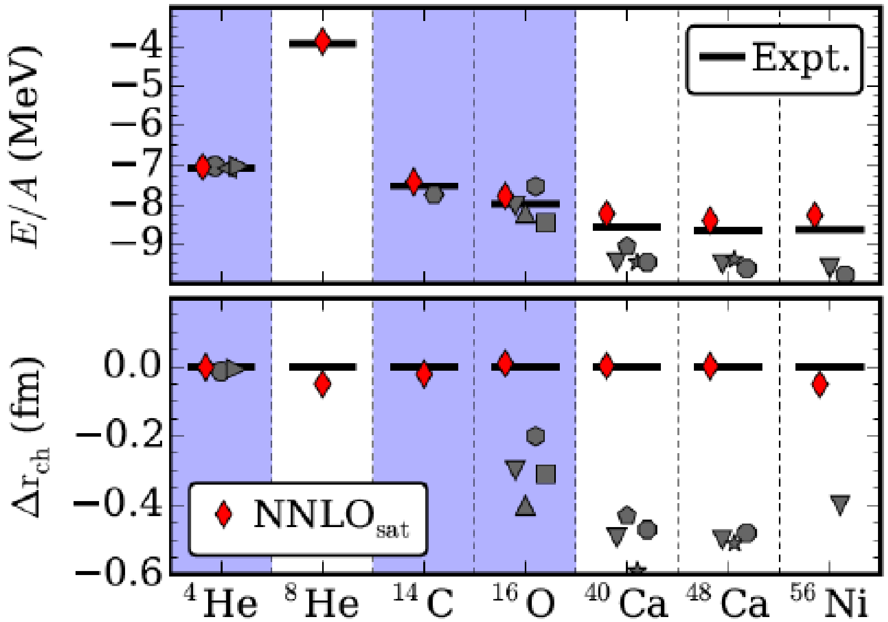
[Hagen et al. In preparation (2017)]


Exp
RMF
[L. Geng, PhD Thesis Osaka University (2005)]
4.75
4.7
4.65
4.6
4.55
4.5
4.45
48
50
52
54
56
58
60
62
64
66
68
70
72
74
76
78
80
82
84
R_ch [fm]
N

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)

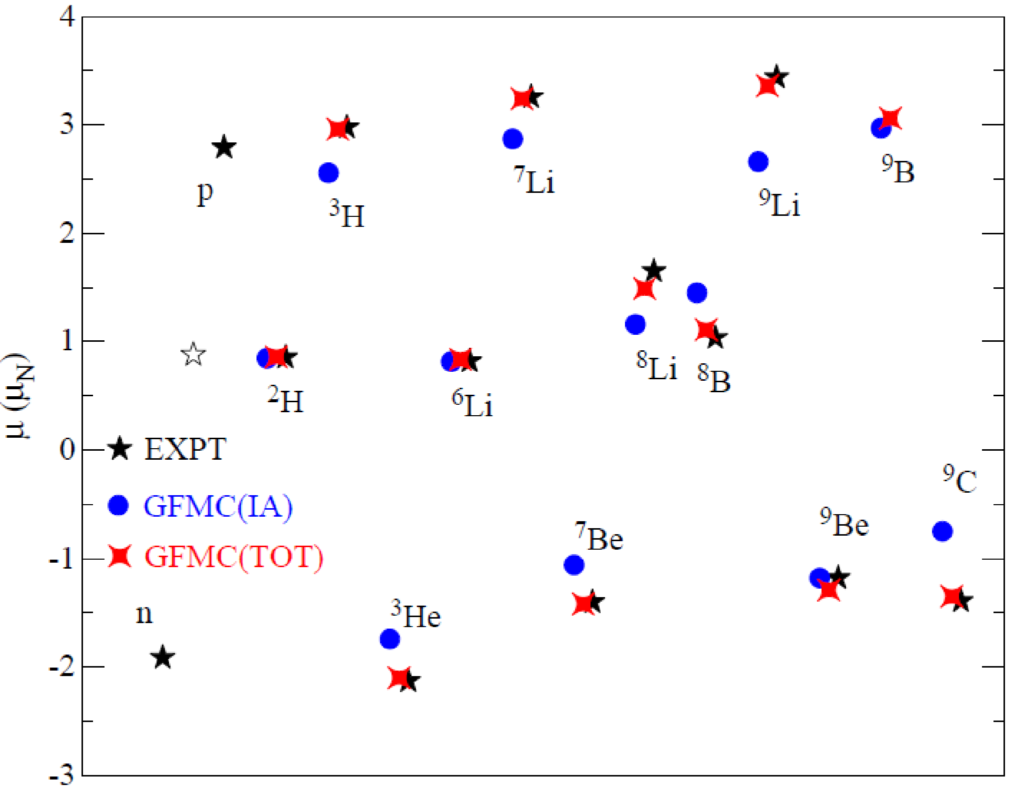
Extension to the Sn region is underway! [Hagen et *al.* In preparation (2017)] [J. Holt. Private commun. (2017)]

- ❑ *Ground-state spin are essential observables for our understanding of nuclear structure*
- ❑ *Charge radii provides a test to inter-nucleon interactions and many-body methods*

Electromagnetic moments

Laser spectroscopy ⇒ I , $<r^2>$, μ , Q

Ab-initio calculations (QMC)



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

[Pastore et al. PRC 87, 035503 (2013)]

Work in progress to include MEC in medium mass and heavy-nuclei

[J. Holt. *Private communication* (2017)]

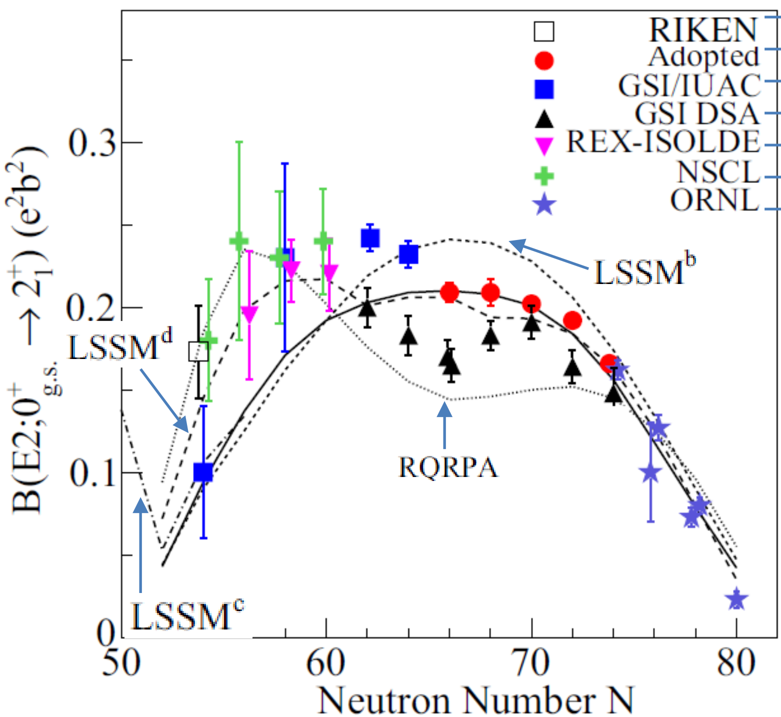
[A. Calci and R. Roth.PRC 94, 014322 (2016)]

[A. Ekstrom et al. PRL 113, 262504 (2014)]

- ❑ *Ground-state spin are essential observables for our understanding of nuclear structure*
- ❑ *Charge radii provides a test to inter-nucleon interactions and many-body methods*
- ❑ *Electromagnetic moments are sensitive probes to the role of electro-weak currents*

Open questions

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



→ [Doornenbal *et al.* PRC 90, 061302(R) (2014)]
→ [Raman *et al.* ADNDT 78, 1 (2001)]
→ [Guastalla *et al.* PRL 110, 172501 (2013)]
→ [Jungclaus *et al.* PLB 695, 110 (2011)]
→ [Ekstrom *et al.* PRL 101, 012502 (2008), Cederkall *et al.* PRL 98, 172501 (2007)]
→ [Vaman *et al.* PRL 99, 162501 (2007), Bader *et al.* PRC 88, 021301(R) (2013)]
→ [Allmond *et al.* PRC 84, 061303 (2011)]

^{100}Sn core { — LSSM^a

^{90}Zr core { ---- LSSM^b, -·-· LSSM^c, - - - LSSM^d

LSSM^b, LSSM^c: Different truncations

LSSM^d: Only neutron across N=50.

^{88}Sr core { Mainly protons across Z=50.

[Coraggio *et al.* PRC 91, 041301(R) (2015)]

Figure adapted from Doornenbal *et al.* PRC 90, 061302(R) (2014).

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- Shell evolution towards N=Z=50 ?
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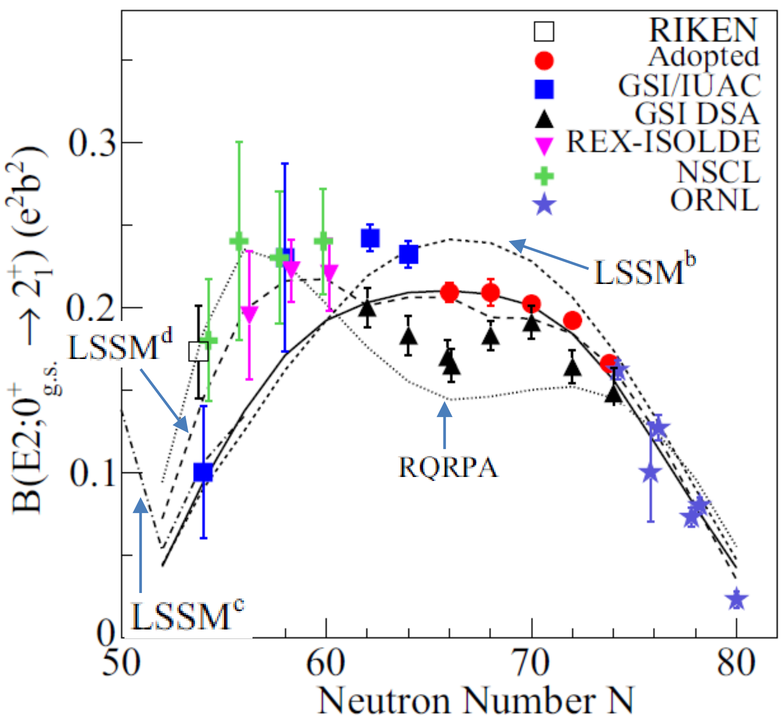
- Correlations across N=Z=50
- Effective operators?
  Effective charges and g-factors

Inconsistent use of effective charges!



Different conclusions on the robustness of N=Z=50

^{100}Sn core { — LSSM[a] e_n= 1.0 e

^{90}Zr core {
- ---- LSSM[b] e_n= 0.5 e, e_p= 1.5 e
- -.-.- LSSM[c] e_n= 0.5 e, e_p= 1.5 e
- - - - LSSM[d] Only neutron across N=50. Isospin-dependent effective charges e_n>1.0 (e_n<1.0) e below (above) ^{110}Sn

^{88}Sr core { Mainly protons across Z=50. Theoretical effective charges. e_n>0.8, e_p>1.6

[Coraggio *et al.* PRC 91, 041301(R) (2015)]

[Doornenbal et al. PRC 90, 061302(R) (2014)]

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Some questions on the effective operators….

- Unusually large effective charges (e_n>2 e) on neutron-deficient around ^{100}Sn [Lipoglavsek et al. PLB 440, 246 (1998)]

- Unusually small effective charges (e_p<1 e) on neutron-deficient around ^{100}Cd [Górska et al. PRL 79, 2415 (1997)]

- Effective g factors?

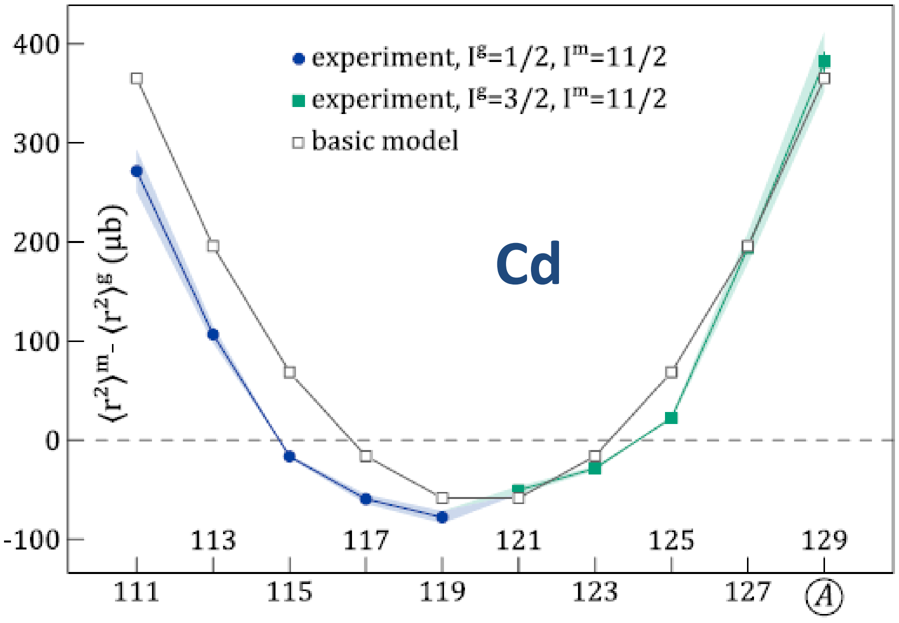
  -> Efforts to derive microscopically [Brown et al, PRC 71, 044317 (2005)]

  Role of core polarization and meson exchange currents?

Isomer shifts

[Yordanov *et al.* PRL 116, 032501 (2016)]

-> “Rms charge-radii changes from ground states to isomers of Cd isotopes follow a distinct parabolic dependence as a function of the atomic mass number”



Magnetic properties

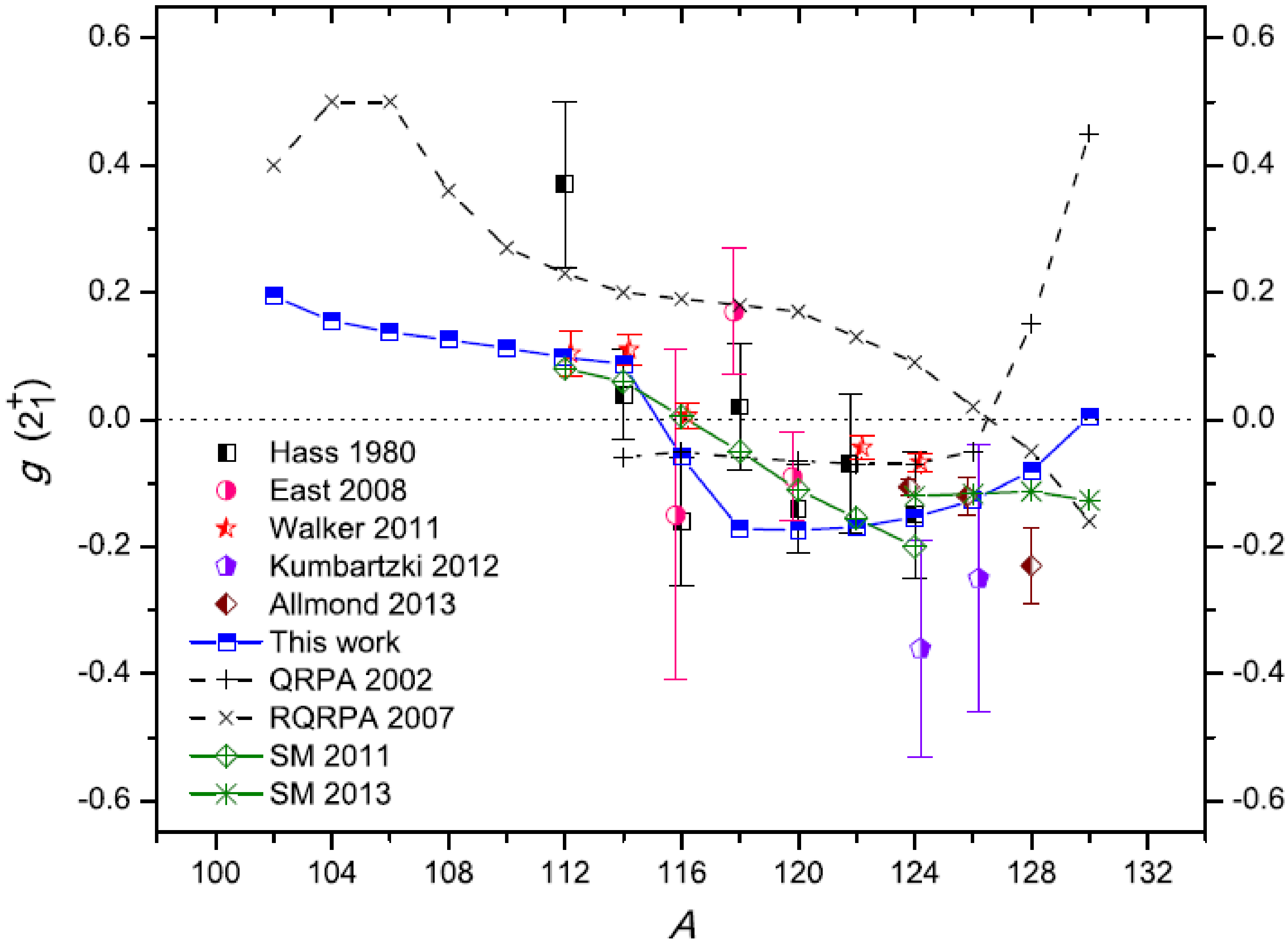


Figure taken from Jiang *et al*, PRC 89, 014320 (2014)