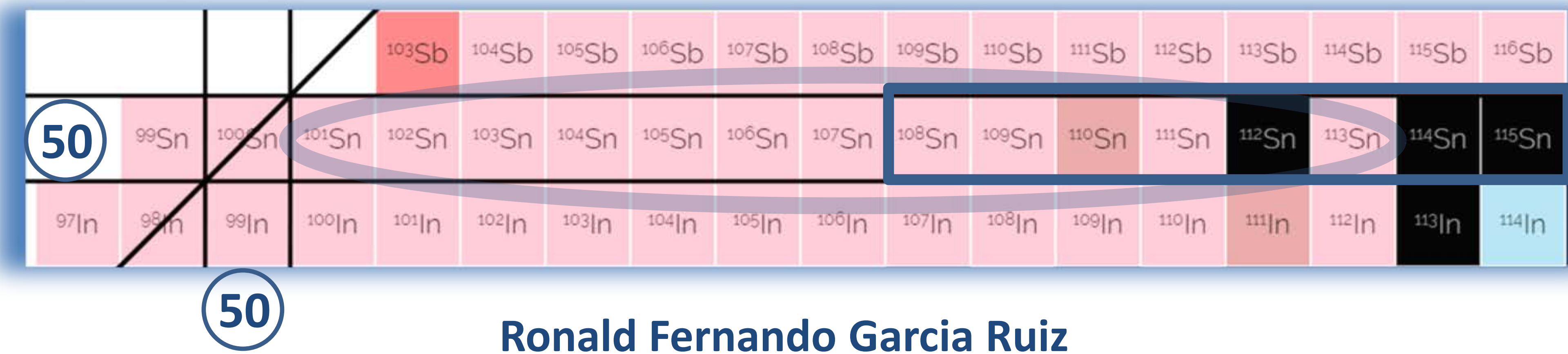
Laser spectroscopy of neutron-deficient Sn isotopes



Ronald Fernando Garcia Ruiz
The University of Manchester

52nd Meeting of the INTC
Feb 2016

D.L. Balabansk, C.L Binnersley , J. Billowes, M.L. Bissell, K. Blaum, T.E. Cocolios, R.P. de Groote, G.J. Farooq-Smith, K.T. Flanagan, S. Franchoo, G. Georgiev, A. Koszorus, M. Kowalska, K.M. Lynch, S. Malbrunot-Ettenauer, B.A. Marsh, E. Minaya Ramirez, P. Naubereit, G. Neyens, W. Nortershauser, S. Rothe, R. Sanchez, H.H. Stroke, D. Studer, A.R. Vernon, K.D.A. Wendt, S.G. Wilkins, Z. Xu, X.F. Yang, D.T. Yordanov

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Outline

- Importance of the ^{100}Sn region
- Open questions
- Results expected from these experiments
- Experimental details
- Beam time request

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Importance of the ^{100}Sn region

- **Shell evolution around N=Z=50** [Faestermann *et al.,* Prog. Part. Nucl. Phys. 69, 85 (2013)]
- **Heaviest self-conjugate doubly magic nucleus?** [Guastalla *et al.,* PRL 110, 172501 (2013)]
- **Proton-neutron correlations, pairing correlations** [Dean and Hjorth-Jensen, RMP 75, 607 (2003)]
- **Superallowed beta decay** [Hinke *et al.* Nature 486, 341 (2012)]
- **End of the rp process** [Schatz *et al*. PRL 86, 0031-9007 (2001)]

- **Particularly important for nuclear theory -> Test to nuclear structure models**

Nuclear force

- Phenomenology
- Chiral effective field theory

[PRC 91, 041301(R) (2015)]
[PRC 88, 051301(R) (2013)]
[PRL 110, 192502 (2013)]

Many-body methods

- Shell-model
- Ab-initio
- DFT

[PLB 736, 119 (2014)]
[PRC 89, 014320 (2014)]
[PRC 86, 04423 (2012)]

Electromagnetic operators

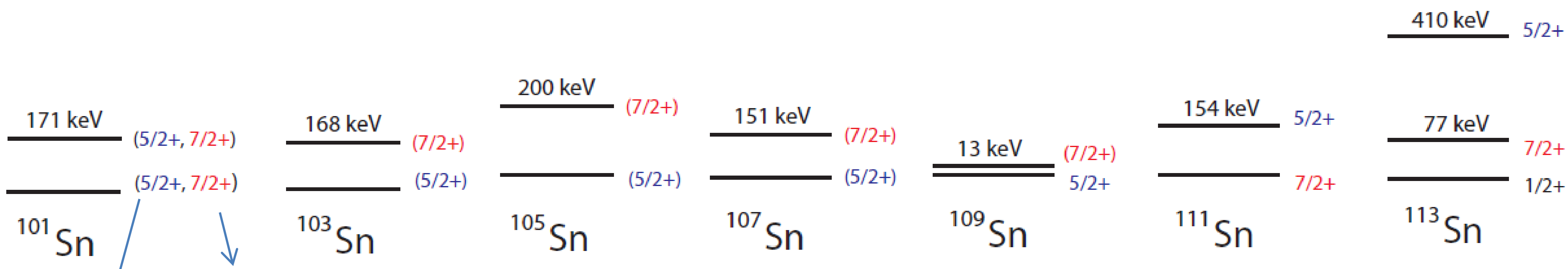
- Effective neutron/proton charges
- Microscopic description of effective operators

[PRC 91, 041301(R) (2015)]
[PRL 110, 172501 (2013)]
[PRC 87, 031306(R) (2013)]

Open questions

- Shell evolution towards N=Z=50 ?
- Ordering of shell model orbits ?

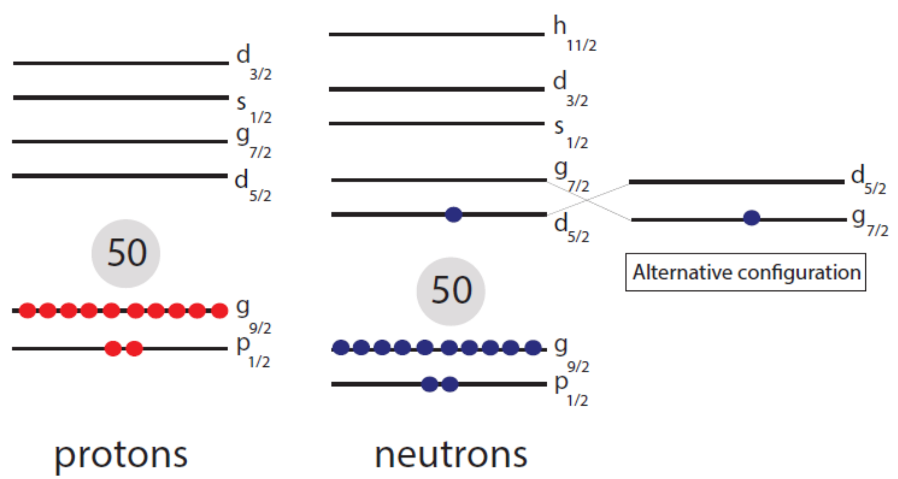
Ground state spins below ^{109}Sn?



[Darby *et al.* PRL 105, 162502 (2010)]

[Banu *et al. PRC 72, 061305(R) (2005)*]
[Seweryniak *et al*. PRL 99, 022504 (2007)]

Contradictory evidence!



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Open questions

- o **Shell evolution towards N=Z=50 ?**
- o **Ordering of shell model orbits ?**
- o **Robustness of N=Z=50 shell closures?**

N=Z=50 shell closures?

Robust ?

- **Super-allowed beta decay of ^{100}Sn**
  [Hinke *et al.* Nature 486, 341 (2012)]
- **Coulomb Excitation of ^{104}Sn**
  [Guastalla *et al.*, PRL 110, 172501 (2013)]

Sof?

- **Coulomb Excitation of $^{106-112}$Sn**
  [Vaman *et al.*, PRL 99, 162501 (2007)]
- **Microscopic shell model studies**
  [Coraggio *et al.* PRC 91, 041301(R) (2015)]

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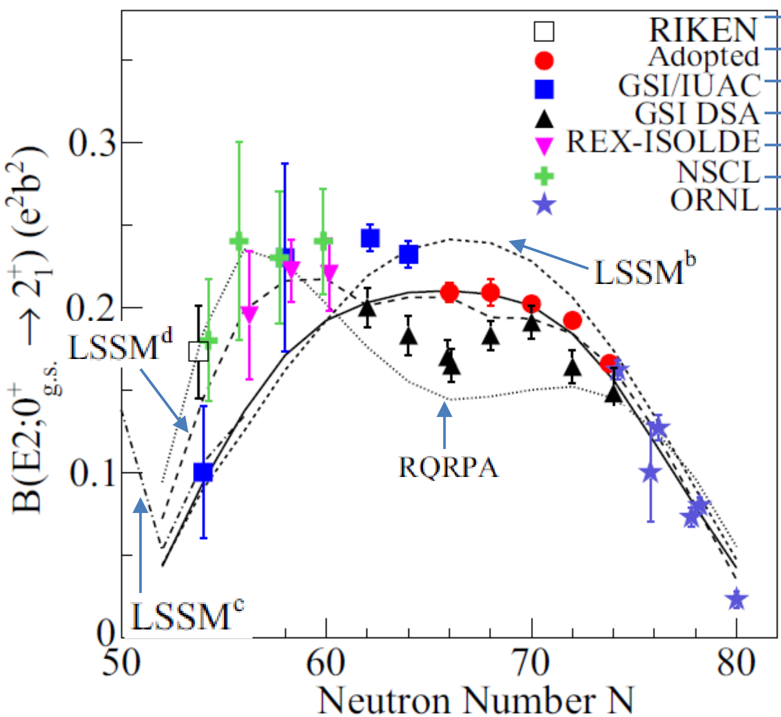
Open questions

- 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] — 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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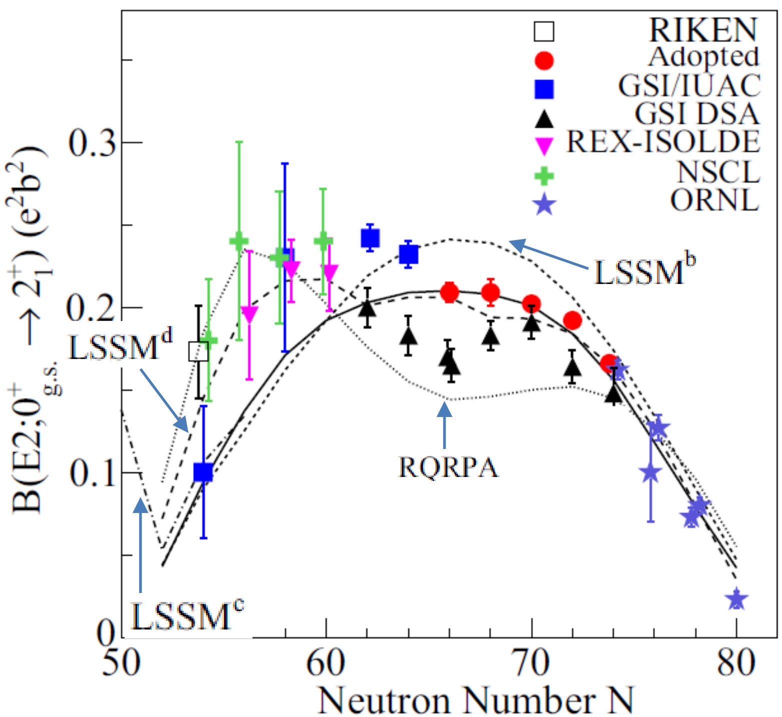
Open questions

- 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
- 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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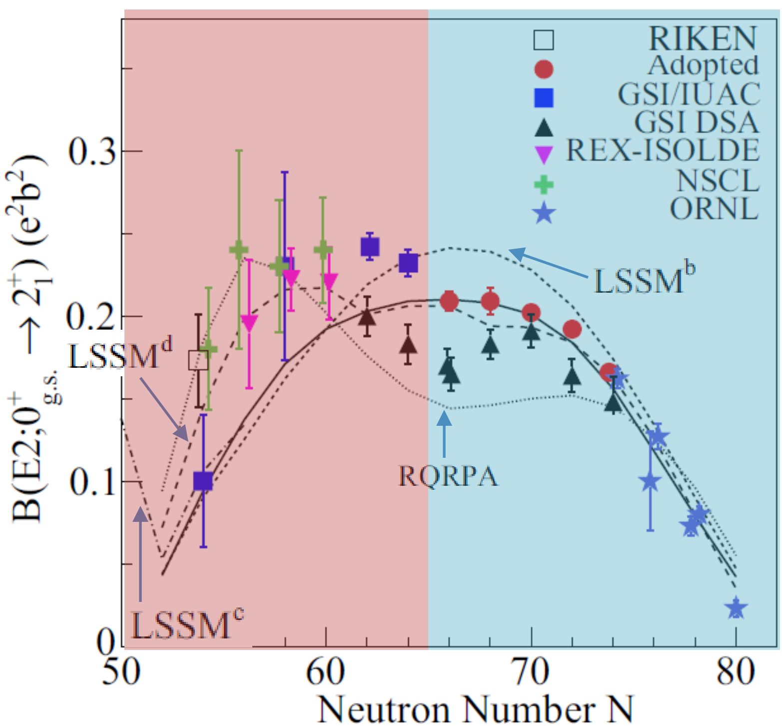
Open questions

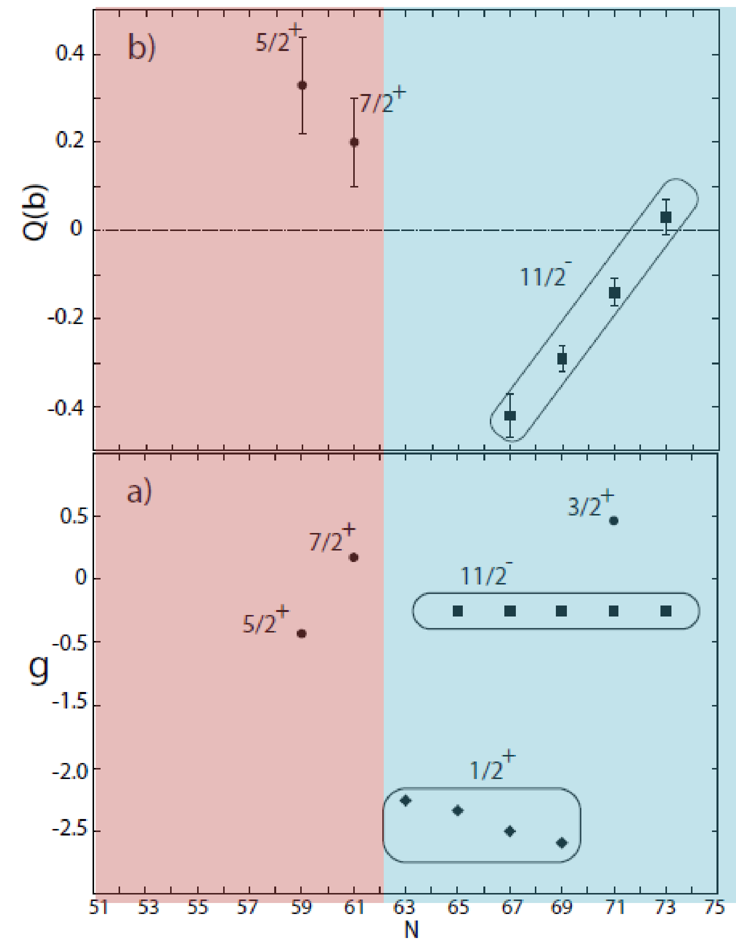
- Shell evolution towards N=Z=50 ?
- Ordering of shell model orbits ?
- Robustness of N=Z=50 shell closures?
- Proton-neutron correlations?

- Correlations across N=Z=50
- Effective operators?
  Effective charges and g-factors
- Single particle?/collective?
- Enhanced of quadrupole collectivity?



Single particle?

Collectivity?



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Open questions

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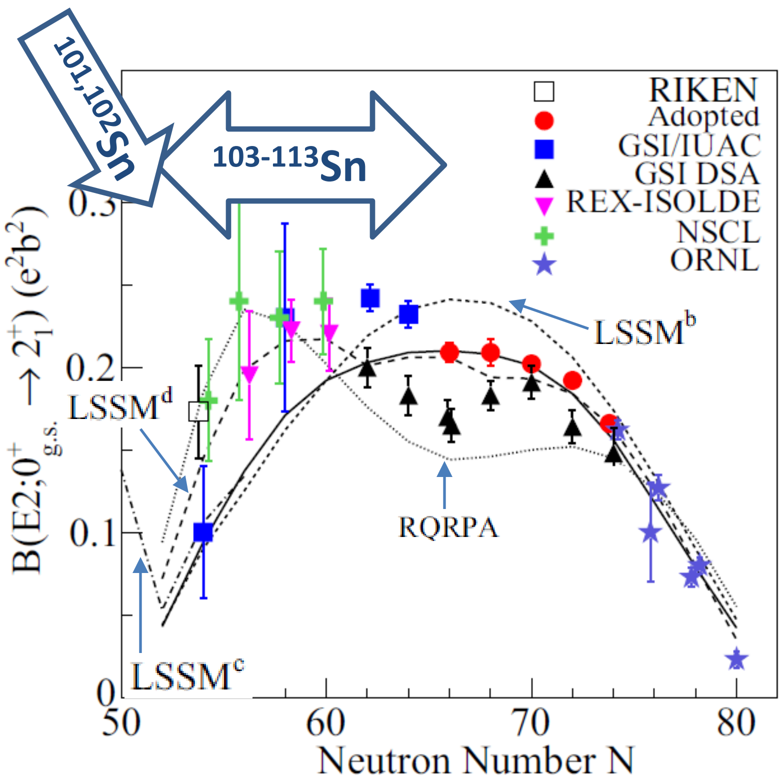

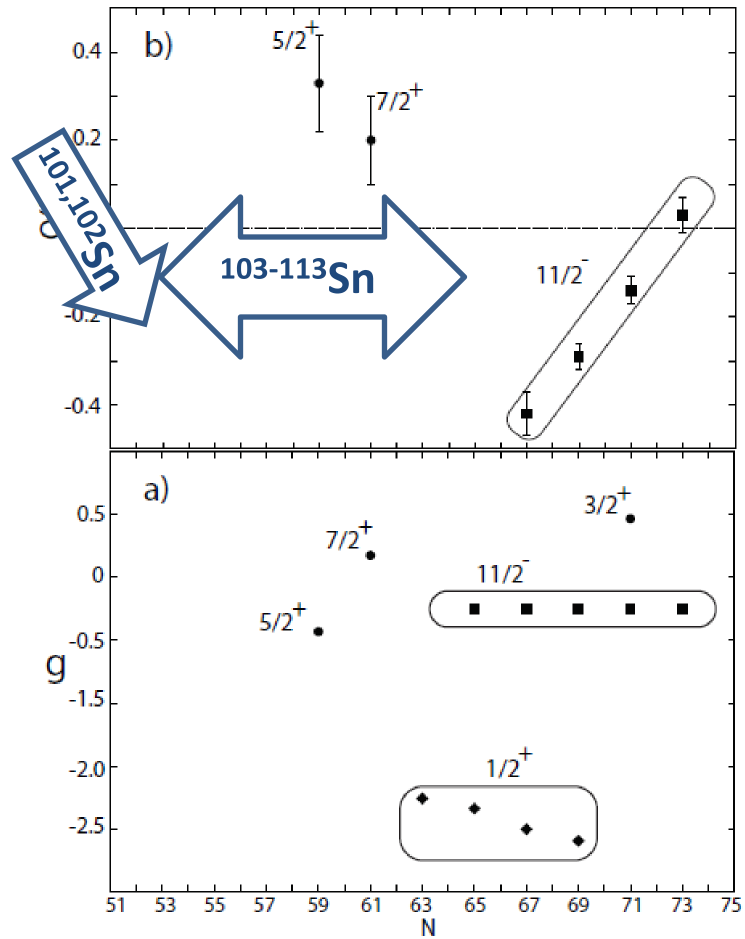

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Results expected from these experiments

101-107, ^{113m}Sn

✓ **Ground-state spins:**

- o Shell evolution towards N=Z=50 ?
- o Ordering of shell-model orbits towards N=Z=50

✓ **Ground state magnetic and quadrupole moments:**

- o Importance of cross-shell correlations across N=Z=50
- o single particle/collective?
- o Proton-neutron correlations
- o Understanding effective operators: effective charges and and quenching of g-factors

✓ **Changes in the root-mean-squared charge radii:**

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101-107, ^{113m}Sn

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✓ **Changes in the root-mean-squared charge radii:**

Test to nuclear theory

Nuclear force	Many-body methods	Electromagnetic operators
➢ Phenomenology ➢ Chiral effective field theory	➢ Shell-model ➢ Ab-initio ➢ DFT	➢ Effective neutron/proton charges ➢ Microscopic description of effective operators

Sn isotopes constitute a test laboratory for many concepts of Nuclear structure!

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Results expected from this proposal

$^{101-107,\ 113m}$Sn

✓ **Ground-state spins:**

- Shell evolution towards N=Z=50 ?
- Ordering of shell-model orbits towards N=Z=50

✓ **Ground state magnetic and quadrupole moments:**

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- single particle/collective?
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- Understanding effective operators: effective charges and and quenching of g-factors

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Test to nuclear theory

Nuclear force	Many-body methods	Electromagnetic operators
➢ Phenomenology ➢ Chiral effective field theory	➢ Shell-model ➢ Ab-initio ➢ DFT	➢ Effective neutron/proton charges ➢ Microscopic description of effective operators

Sn isotopes -> frontier for *ab-initio* calculations

[Hergert et al. Phys. Rep. (Online) (2016)]
[*Binder et al.* PLB 736, 119 (2014)]

"Currently ab-initio is able to provide charge radii". Work is in progress to calculate electromagnetic moments" (IM-SRG + No-Core SM)
[Robert Roth, *Private communication* (2016)]
[http://arxiv.org/abs/1601.07209 (2016)]

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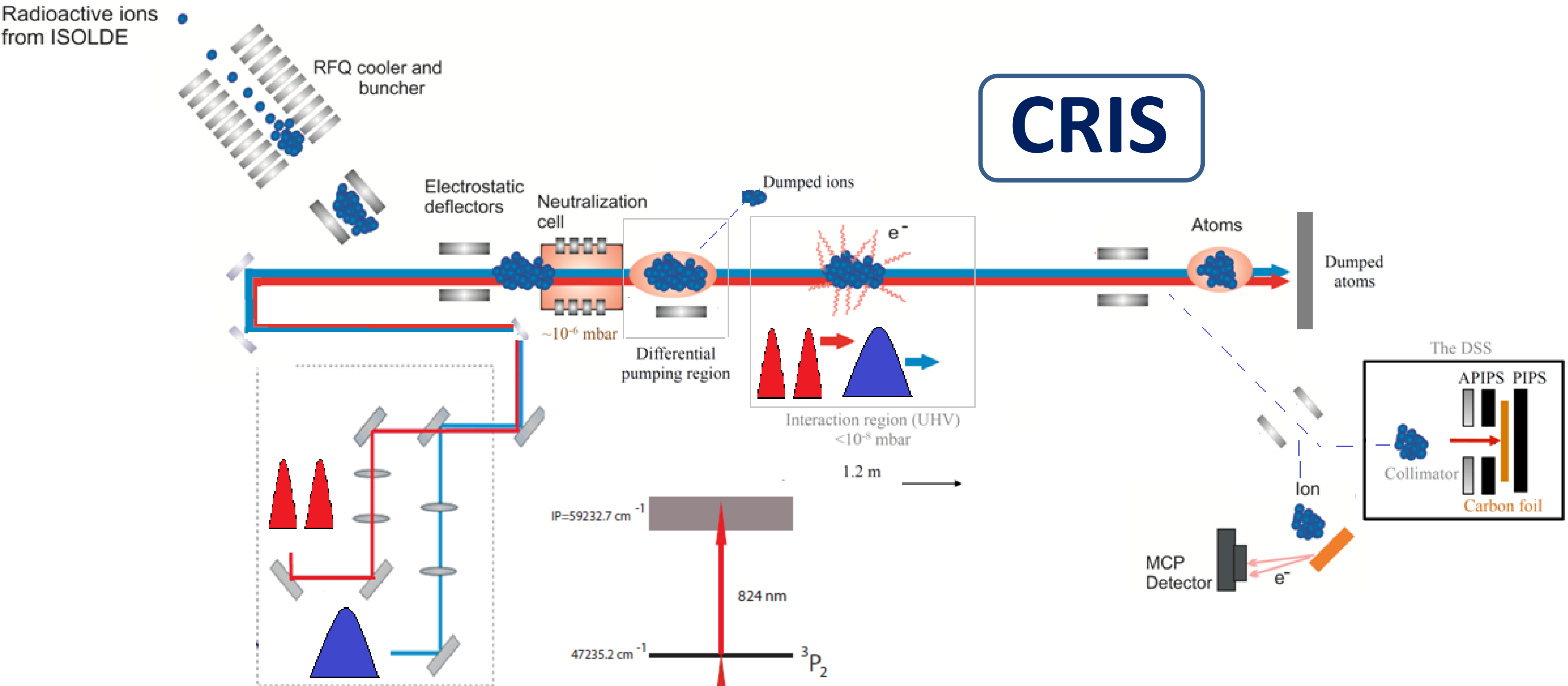
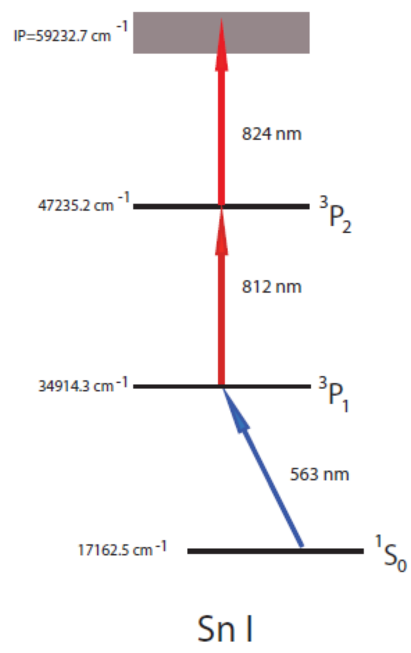
Experimental details





563 nm resonant step
-> Narrow band (~ MHz)
812 nm + 823 nm non-resonant (auto-ionizing) steps
-> Broad band (~ GHz)

Alternative resonant step -> 452 nm

[Eberz, J. et al. Z. Phys. A326, 121 (1987)]

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New laser lab

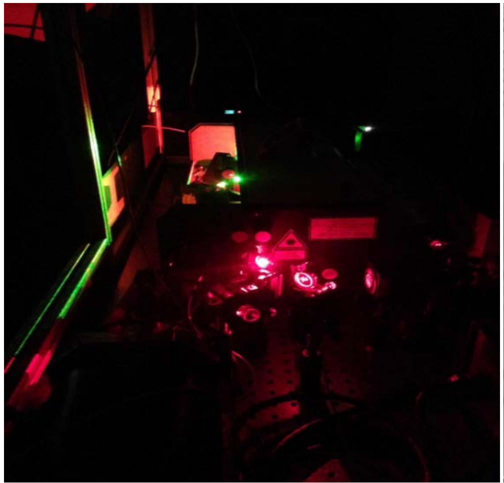
- ✓ M2 Ti:Sa laser and frequency-doubling cavity (735 – 975 nm, 368 – 487 nm)
- ✓ Matisse dye laser and frequency-doubling cavity (550 – 750 nm, 275 – 375 nm)
- ✓ Injection seeded TiSa laser system

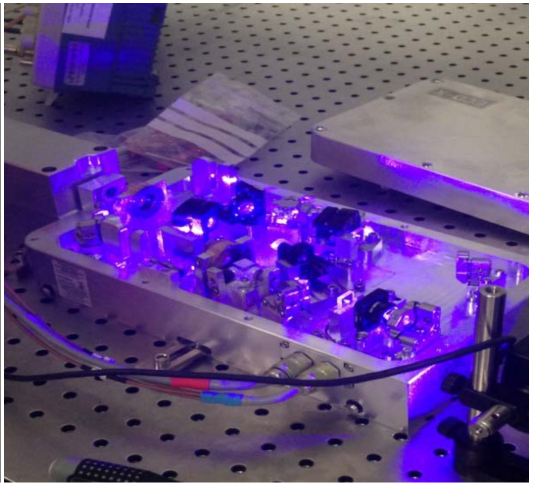
Narrow band

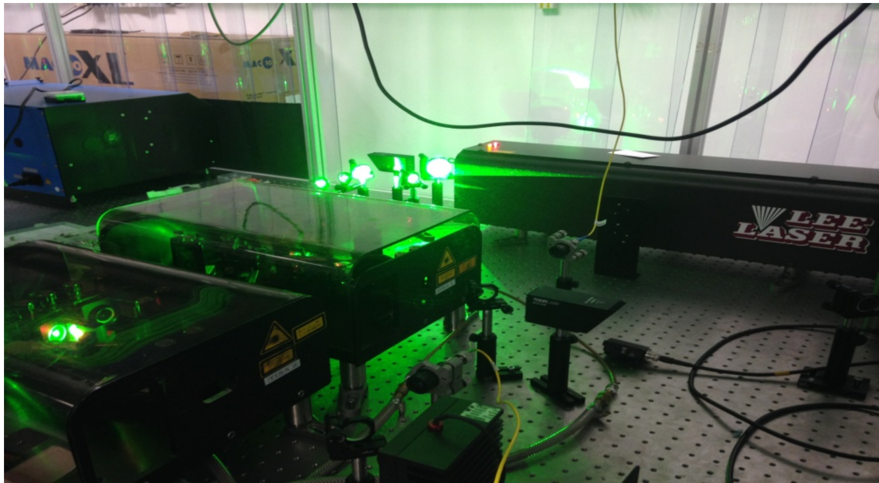
- ✓ Industrial Nd:YAG laser (13 W, 1 kHz, 120 ns)
- ✓ Two Ti:Sa cavities (6.8 W, 5 kHz)
- ✓ 200 Hz Nd:YAG laser
- ✓ Pulsed-dye laser

Broad band

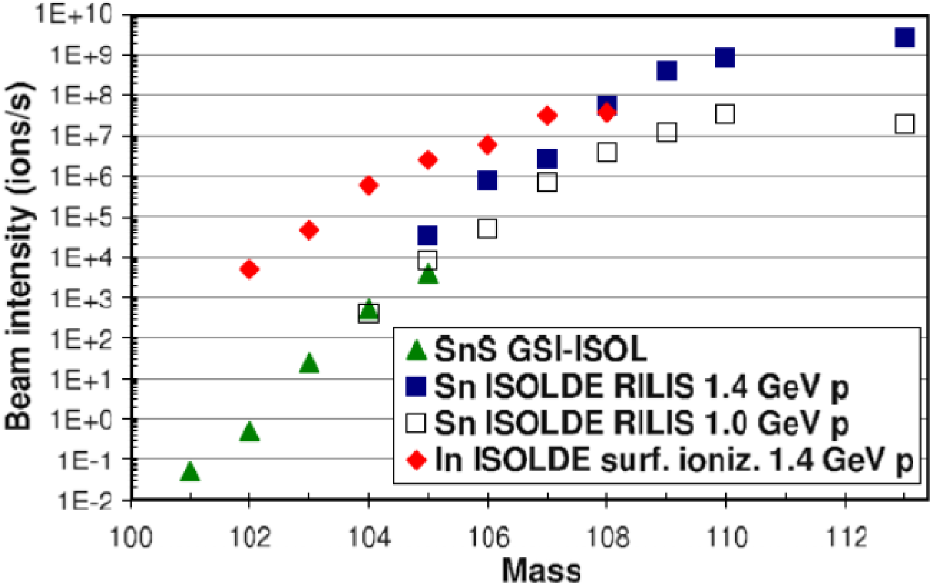
Photos courtesy of Kara Lynch







Beam time request



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

Isotope	Half life	Estimated Yield (ions/s)	Target+RILIS	Shifts
^{101}Sn	0.86 s	~ 1	LaC_x	
^{102}Sn	3.8 s	$\sim 10^1$	LaC_x	(Total: 15 shifts)
^{103}Sn	7.0 s	$\sim 10^2$	LaC_x	
$^{104-113,113m}$Sn	> 20 s	$\geq 10^3$ (Ref. [32])	LaC_x	
^{117m,119m,121m}Sn	> 40 min	$\geq 10^7$	LaC_x	(Total: 15 shifts)
$^{114-124}$Sn	stable	$\geq 10^7$	LaC_x	5

Summary of requested shifts: 35 shifts are required, distributed in two runs of 18 and 17 shifts, respectively.

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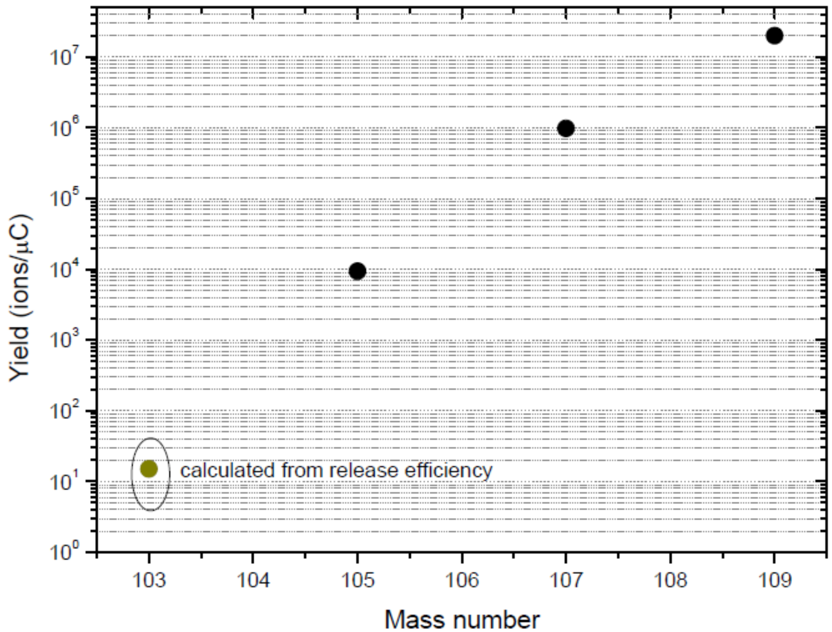
Beam time request



● Measured yields target LaC #411

[T. De Melo Mendoca, *Private communication* (2016)]

New estimates (Target group) (Feb 2016)

Isotope	Half life	Estimated Yield (ions/s)	New estimates (Target group)	Target+RILIS	Shifts
^{101}Sn	0.86 s	~ 1	~ 0.01 /uC	LaC_x	10
^{102}Sn	3.8 s	$\sim 10^1$	~ 0.5 /uC	LaC_x	5
^{103}Sn	7.0 s	$\sim 10^2$	~ 10 /uC	LaC_x	3
$^{104-113,113m}$Sn	$>$ 20 s	$\geq 10^3$ (Ref. [32])	~ 600 /uC	LaC_x	10
^{115m,117m,119m,121m}Sn	$>$ 40 min	$\geq 10^7$		LaC_x	2
$^{114-124}$Sn	stable	$\geq 10^7$		LaC_x	5

Summary of requested shifts: 35 shifts are required, distributed in two runs of 18 and 17 shifts, respectively.

With protons on target -> required as reference isotopes for high-precision calibration

Suppression factor of contaminants -> 1:10^5

[Flanagan *et al.* PRL 111, 212501 (2013)]

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Thank you for your attention!

Laser Spectroscopy of neutron-deficient Sn isotopes

D.L. Balabansk, C.L Binnersley , J. Billowes, M.L. Bissell, K. Blaum, T.E. Cocolios, R.P. de Groote, G.J. Farooq-Smith, K.T. Flanagan, S. Franchoo, G. Georgiev, A. Koszorus, M. Kowalska, K.M. Lynch, S. Malbrunot-Ettenauer, B.A. Marsh, E. Minaya Ramirez, P. Naubereit, G. Neyens, W. Nortershauser, S. Rothe, R. Sanchez, H.H. Stroke, D. Studer, A.R. Vernon, K.D.A. Wendt, S.G. Wilkins, Z. Xu, X.F. Yang, D.T. Yordanov

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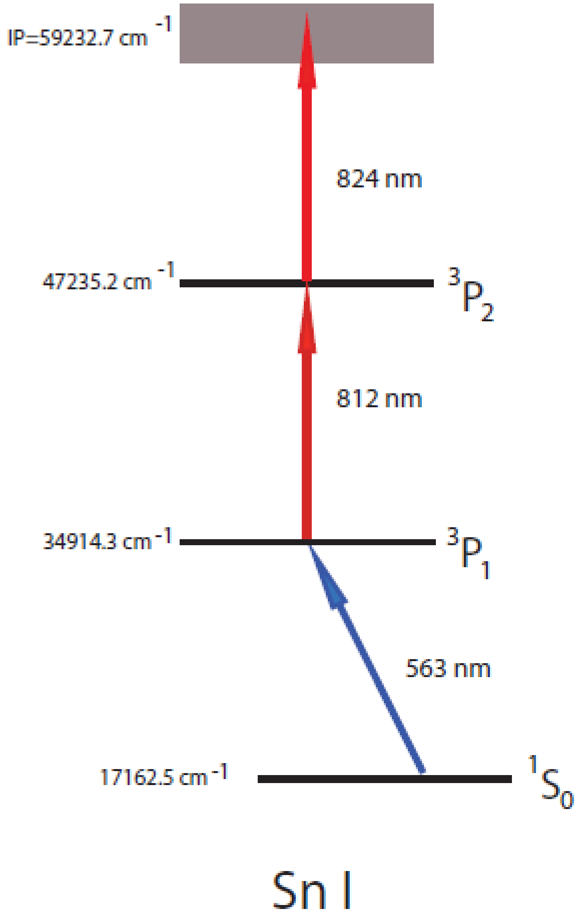
Experimental details

-> Atomic transition studied previously
[Eberz, J. et al. Z. Phys. A326, 121 (1987).]



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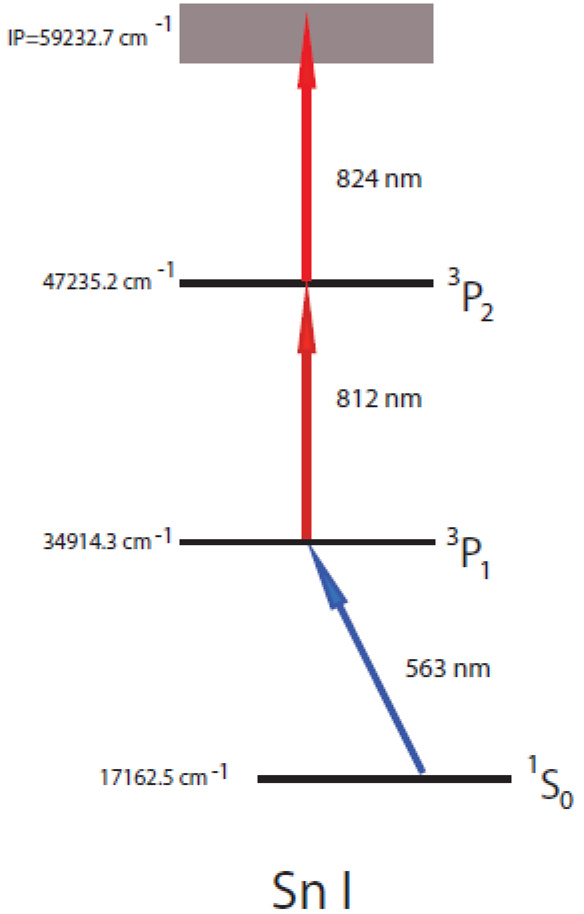
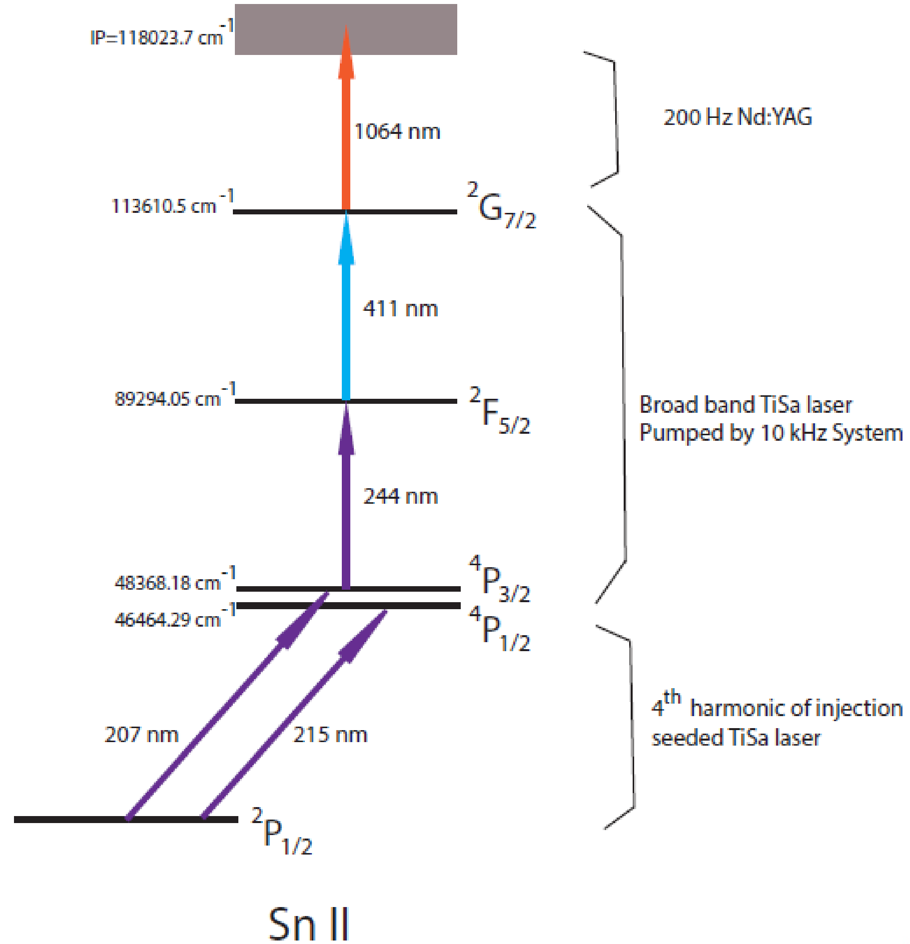


-> Ionic transition -> Potentially more sensitive



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Some questions on the effective operators….

- Unusually <u>large</u> effective charges (e_n>2 e) on neutron-deficient around ^{100}Sn [Lipoglavsek et al. PLB 440, 246 (1998)]
- Unusually <u>small</u> effective charges (e_p<1 e) on neutron-deficient around ^{100}Cd [Górska et al. PRL 79, 2415 (1997)]
- Effective g factors?

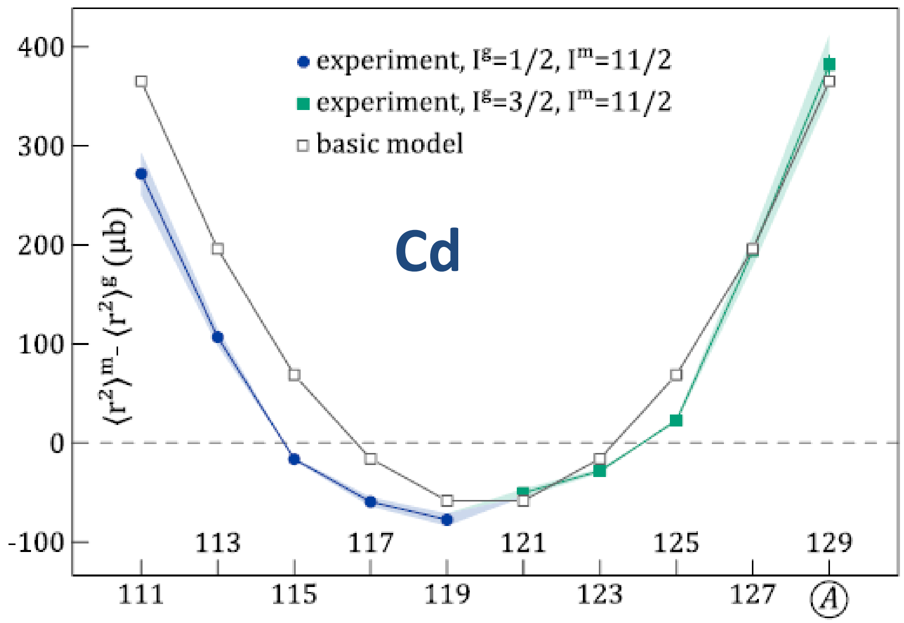
  -> Efforts to derive microscopically [Brown et al, PRC 71, 044317 (2005)]

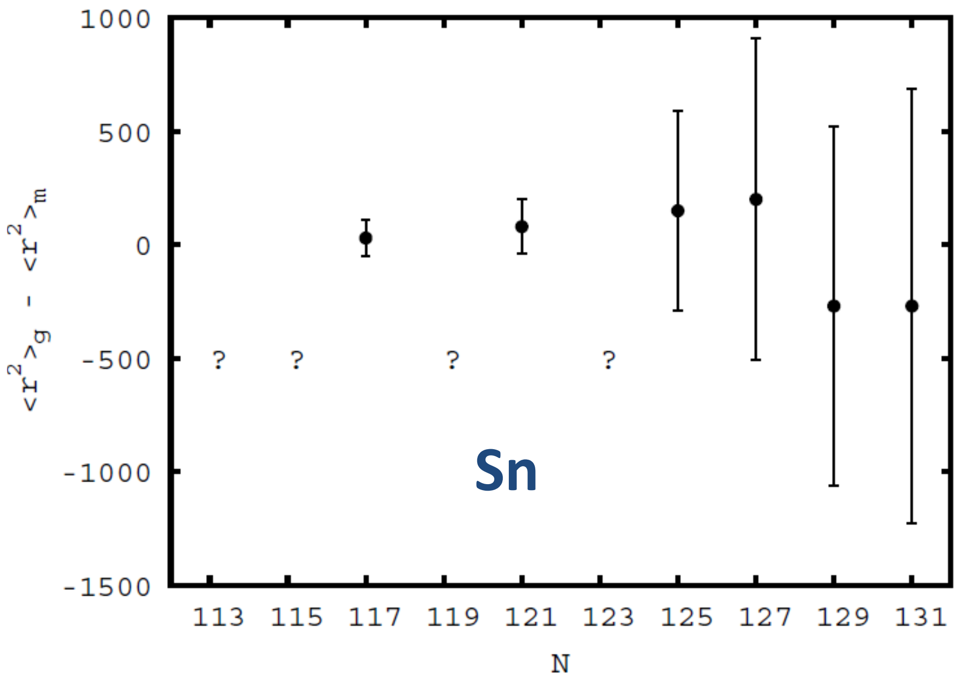
  Role of core polarization and meson exchange currents?

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

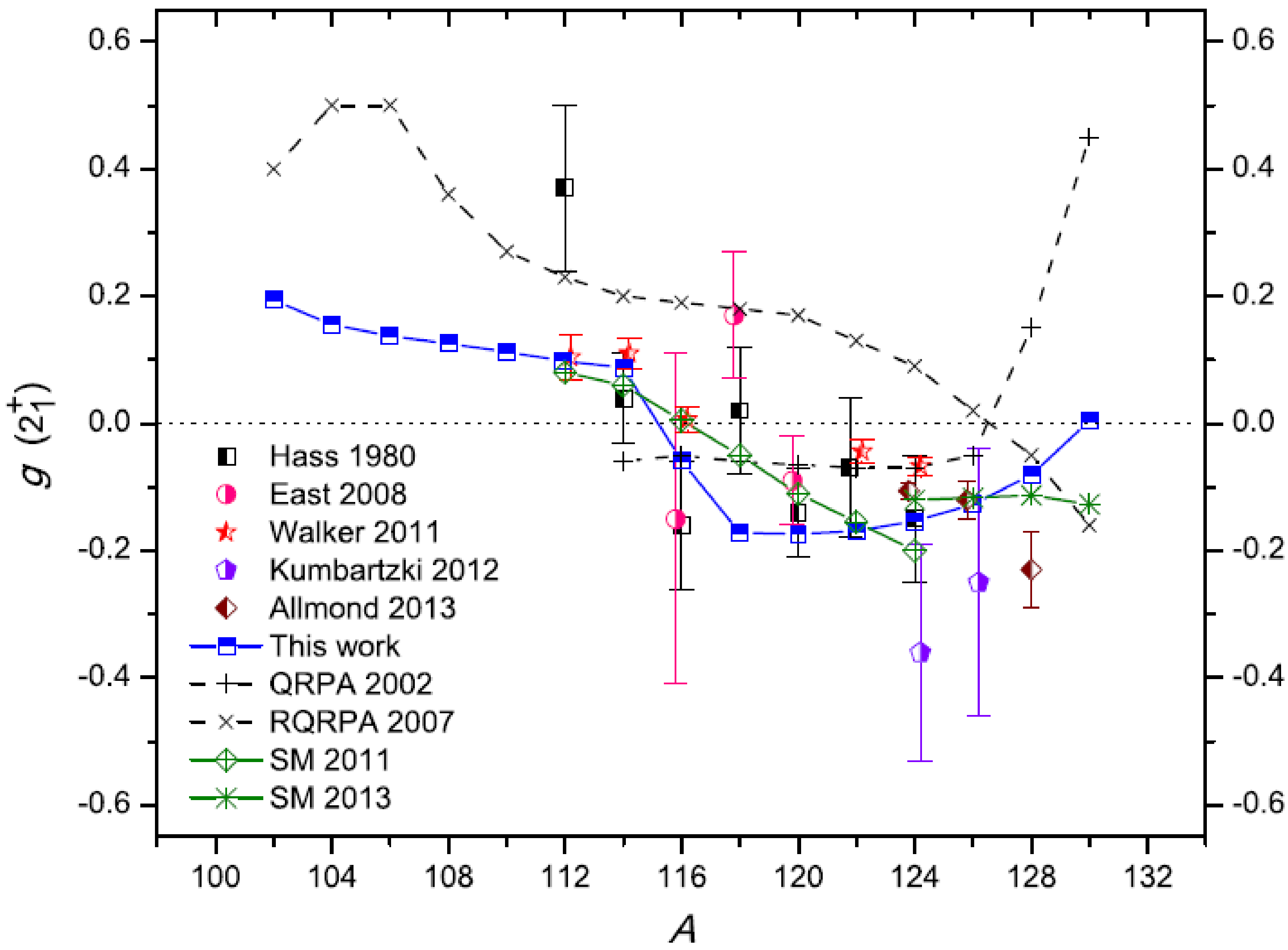


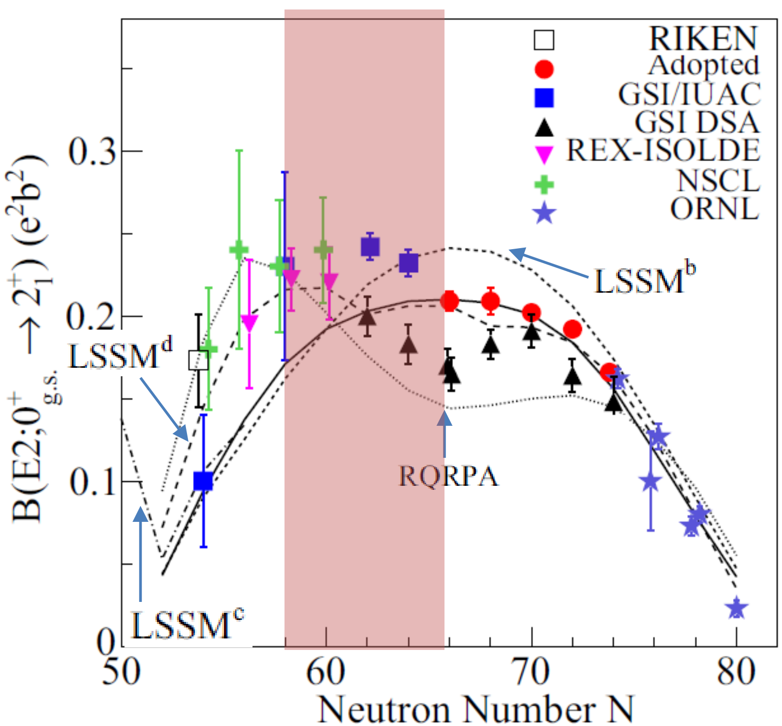
Figure taken from Jiang *et al*, PRC 89, 014320 (2014)

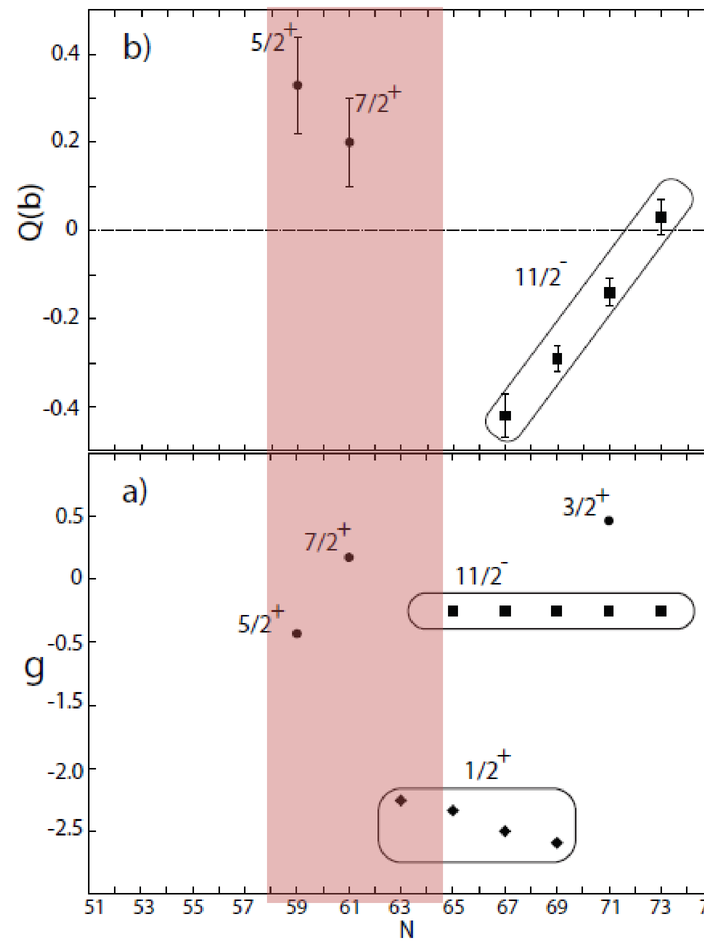
Open questions

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

- o Correlations across N=Z=50
- o Effective operators?
  Effective charges and g-factors
- o Single particle?/collective?
- o Enhanced of quadrupole collectivity?

Dominant neutron collectivity (max. around ^{110}Sn)
[Corsi et al. PLB 743, 451 (2015)]





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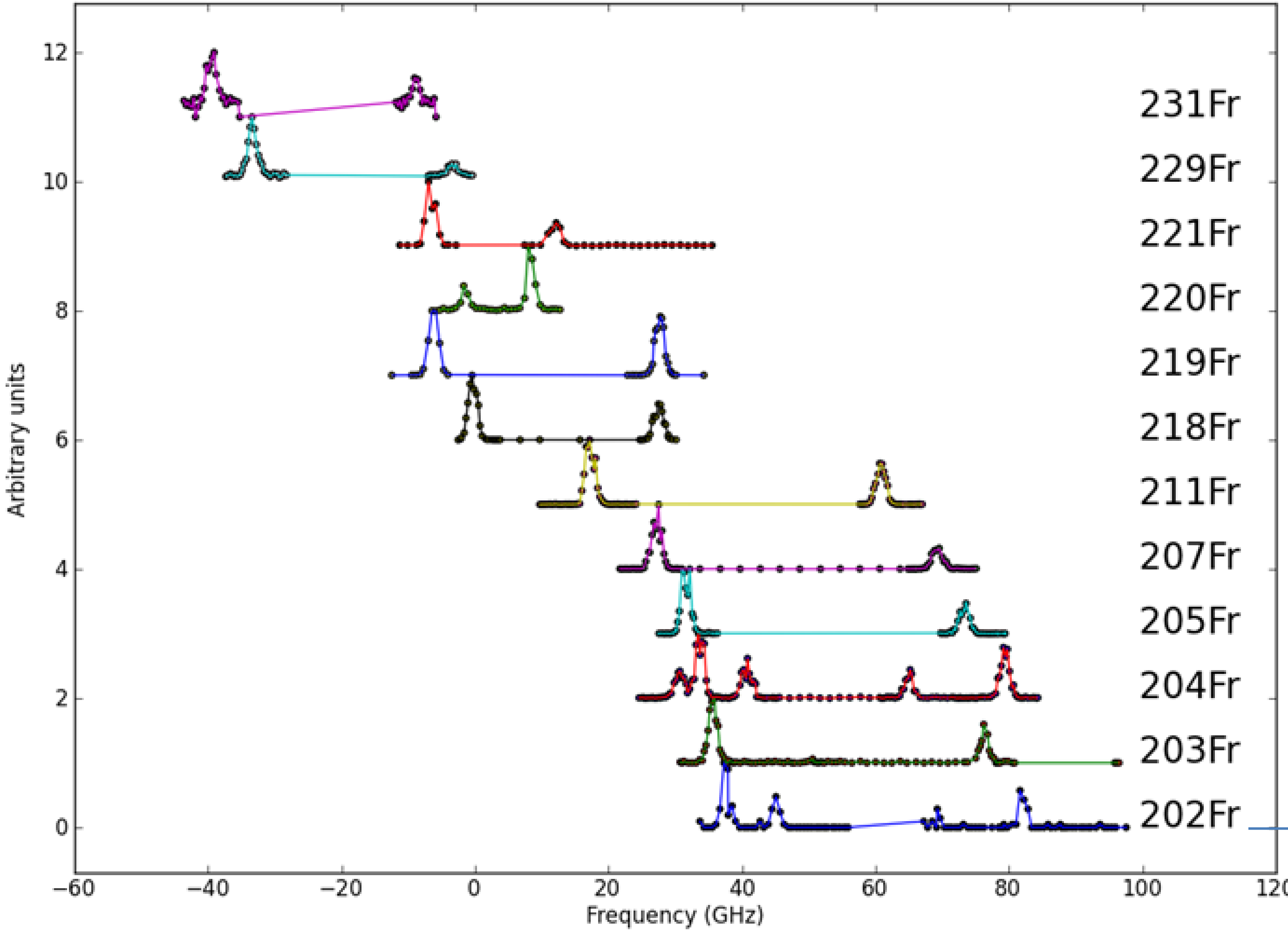
CRIS results 2012: Fr isotopes



Very low background!

~0.002 counts/s ^{202}Fr (cf 3-5 counts/s for fluorescence detection).

~ 100 ions/s ($\tau_{1/2}$ ~300 ms)

- **<u>High sensitivity:</u>~ 100 ions/s**

  <u>Non-resonant ionization -> 1:10^5</u>

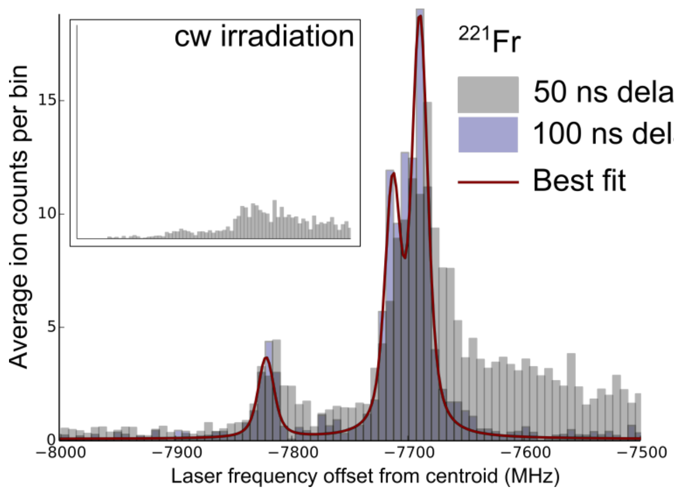
Flanagan *et al.* PRL 111, 212501 (2013)
Budinčević, *et al.* PRC 90 (1), 014317 (2014)
Lynch *et al.* PRX 4 (1), 011055 (2014)

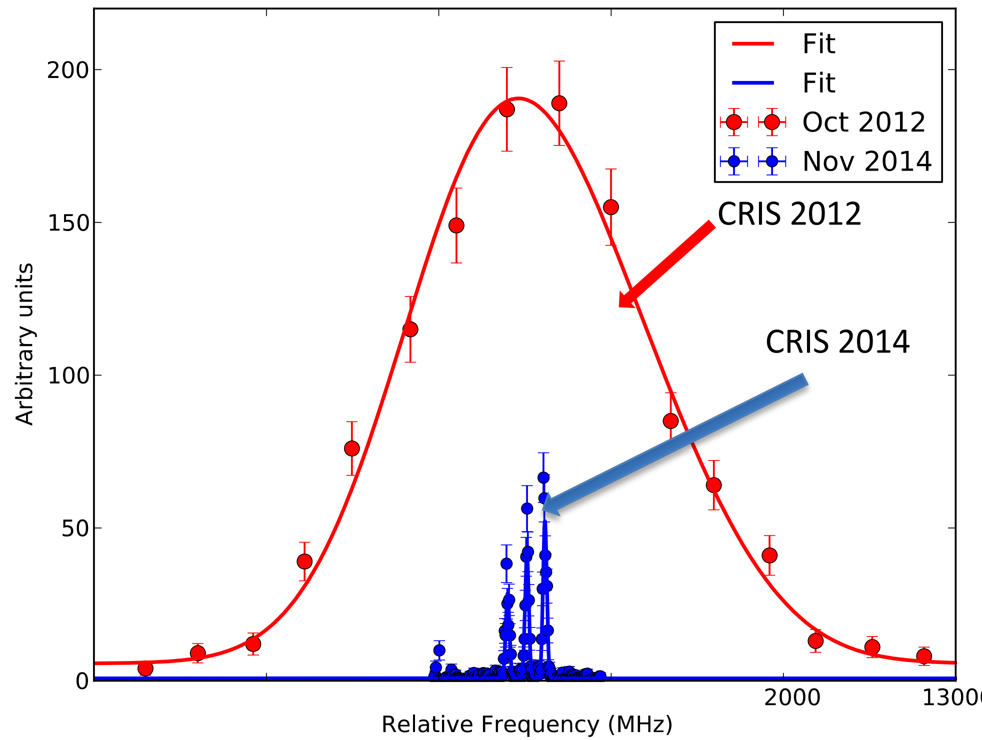
CRIS (2014): High sensitivity and high resolution

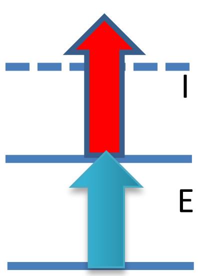
-> High resolution preserving high sensitivity

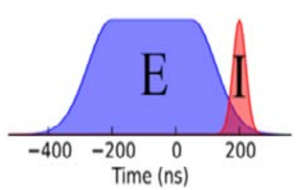
[De Groote *et al.* in preparation (2015)]

FWHM: 20(1) MHz



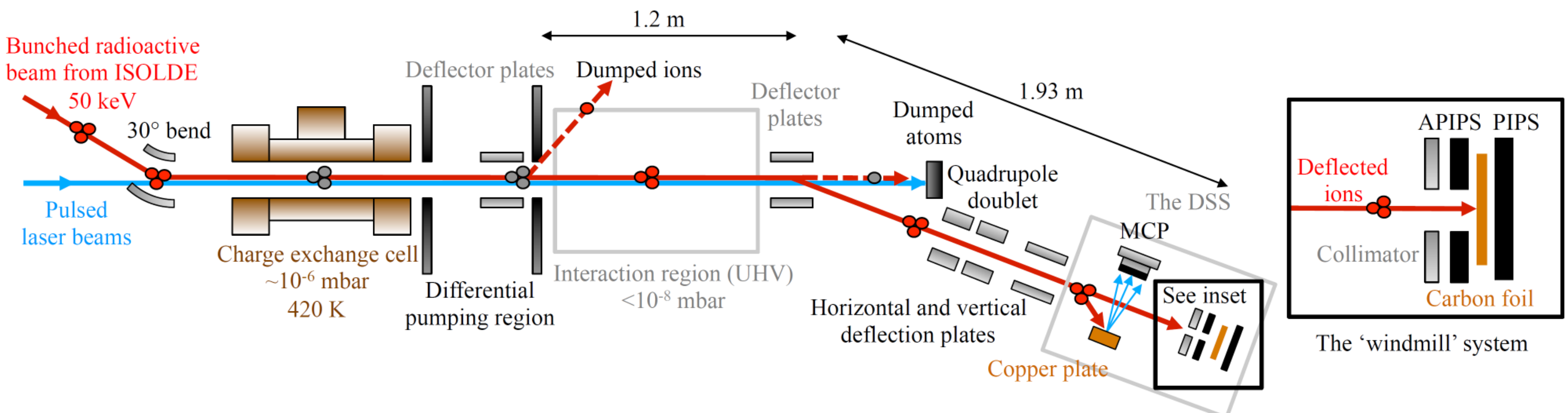




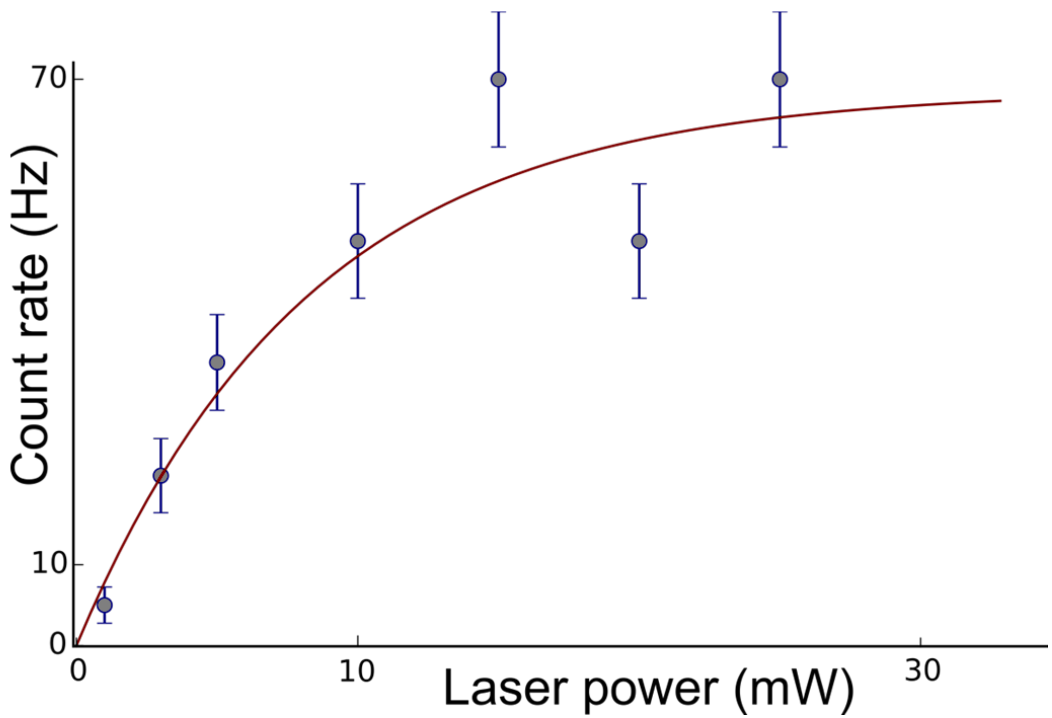


- Pulses: reduce the optical pumping
- Delayed ionization: “clean” peaks!

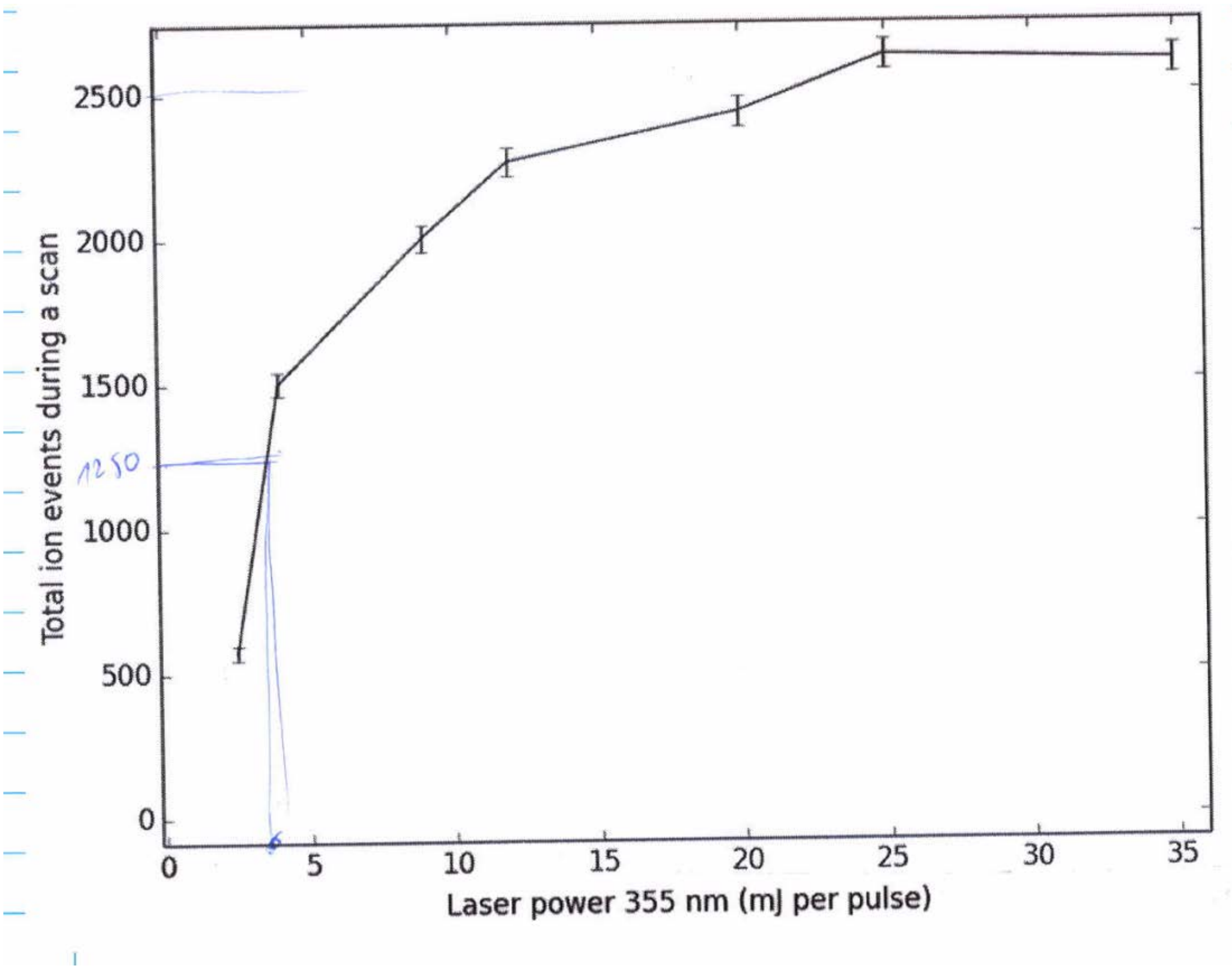
CRIS Beam line



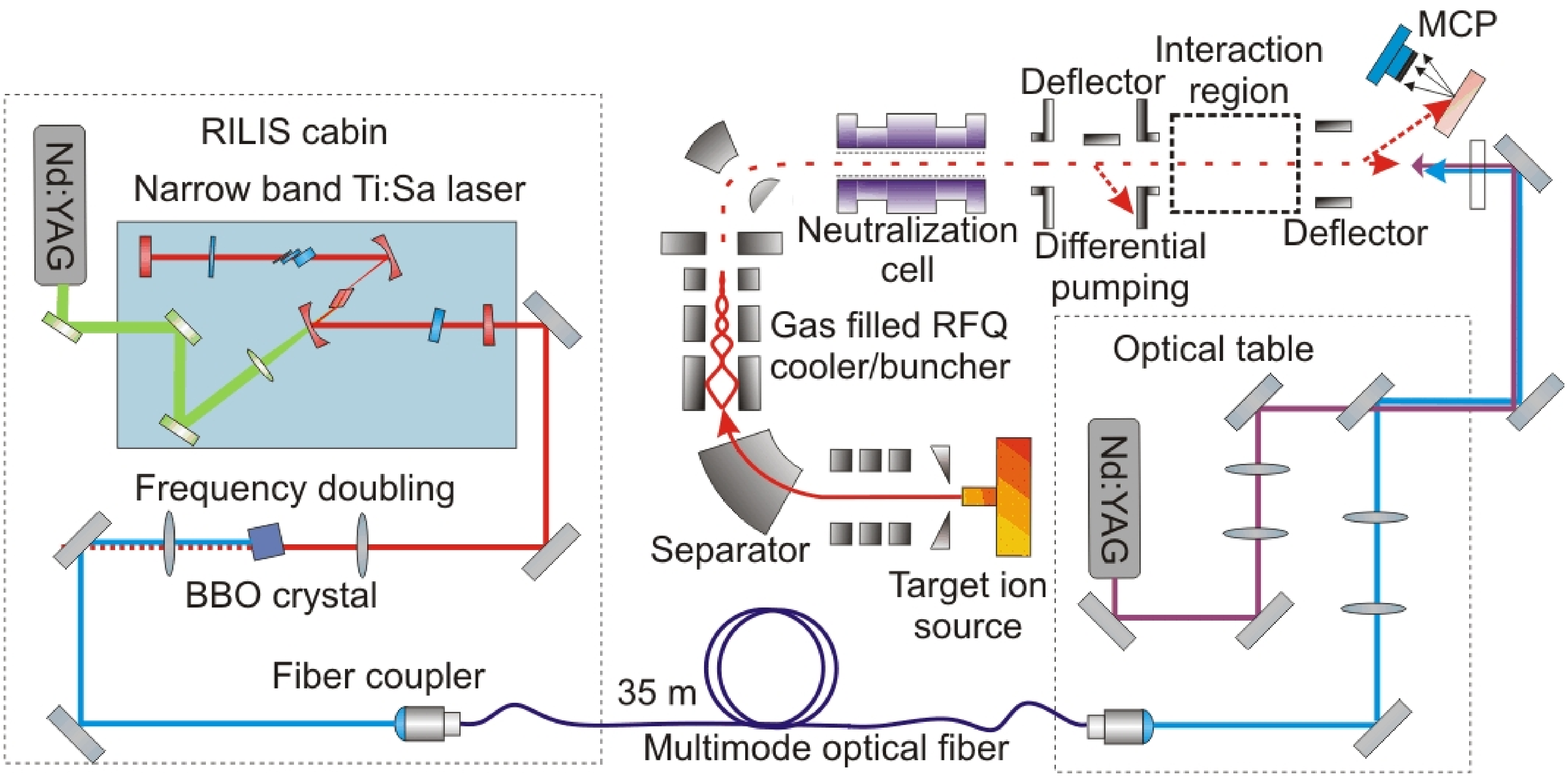
Excitation step can be saturated with cw laser (weak transition A = 2.8 10^6 Hz)



Pulsed laser -> second step

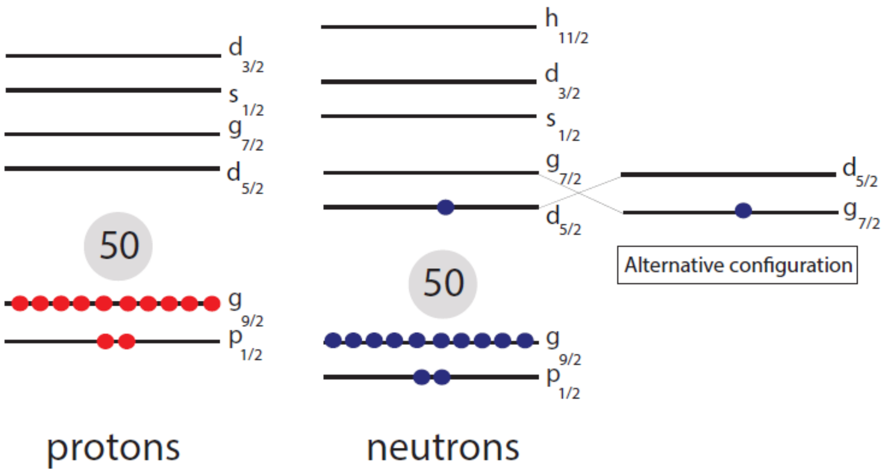


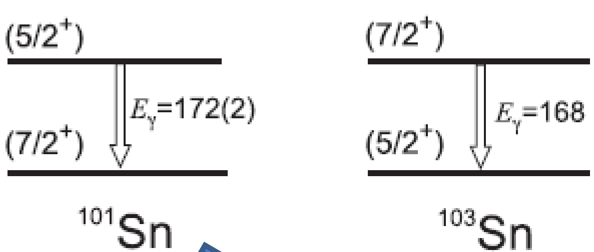
CRIS Experiment 2012



Importance of the ^{100}Sn region

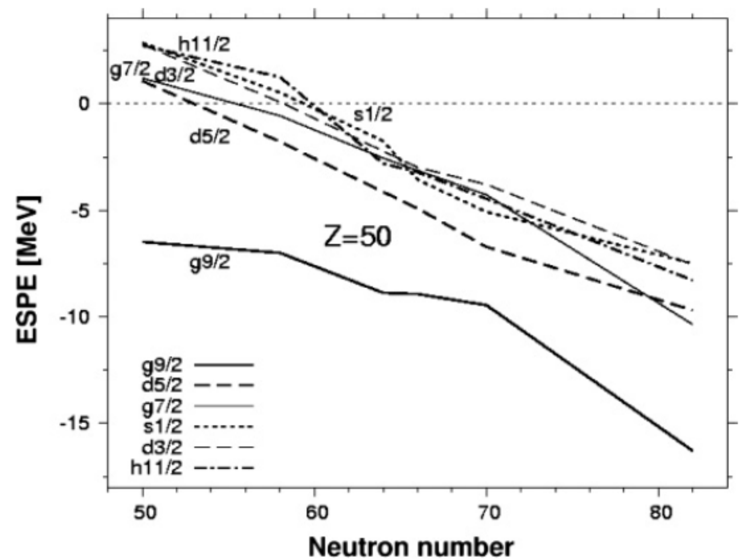
- **Shell evolution around N=Z=50**





[Darby *et al.* PRL 105, 162502 (2010)]

Ordering of the d5/2 - g7/2 orbits ?



[BANU *et al. PRC 72, 061305(R) (2005)*]

Contradictory evidence!