Laser spectroscopy of neutron-rich indium isotopes beyond N=82

Shane Wilkins
on behalf of the CRIS collaboration

Motivation

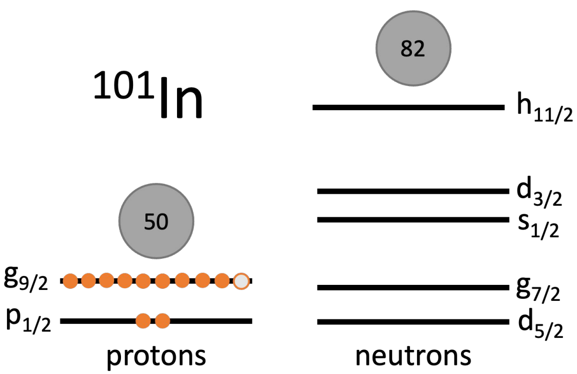
Indium isotopes (Z=49) encompass huge range of neutron numbers spanning entire major neutron shell between N=50 and N=82.

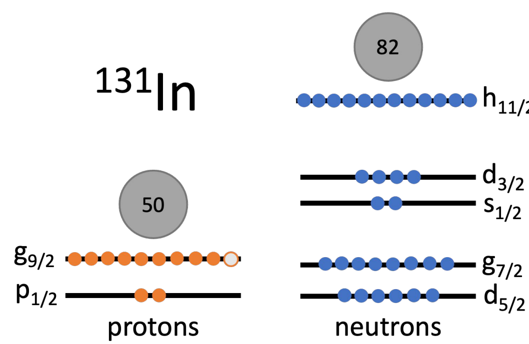
Proton hole in $g_{9/2}$ orbital can couple to valence neutrons in many different ways.

Opportunity to test multiple aspects in our understanding of nuclear structure.

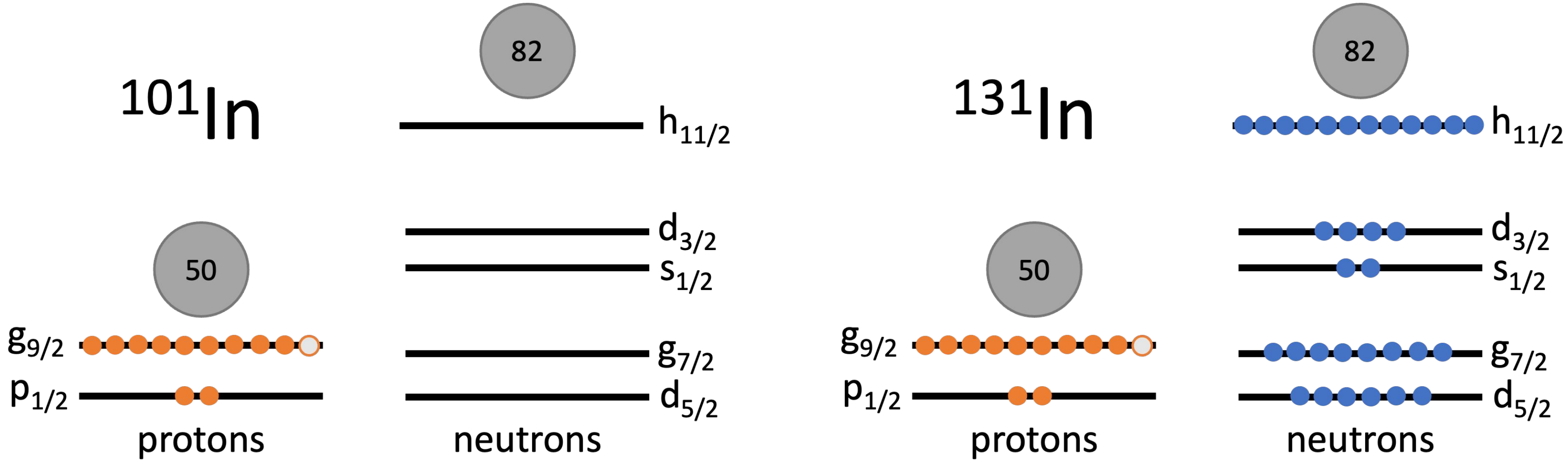
99Sn ε ?	100Sn 1.16 s ε = 100.00% εp < 17.00%	101Sn 1.7 s ε = 100.00% εp = 26.00%	102Sn 3.8 s ε = 100.00%
98In 32 ms ε	99In 3.0 s ε	100In 5.8 s ε = 100.00% εp = 1.70%	101In 15.1 s ε εp

131Sn 56.0 s β^- = 100.00%	132Sn 39.7 s β^- = 100.00%	133Sn 1.46 s β^- = 100.00% β^-n = 0.03%	134Sn 1.050 s β^- = 100.00% β^-n = 17.00%	135Sn 530 ms β^- = 100.00% β^-n = 21.00%	136Sn 0.290 s β^- = 100.00% β^-n = 28.00% β^-2n ?
130In 0.29 s β^- = 100.00% β^-n = 0.93%	131In 0.28 s β^- = 100.00% β^-n ≤ 2.00%	132In 0.207 s β^- = 100.00% β^-n = 6.30%	133In 165 ms β^- = 100.00% β^-n = 85.00%	134In 140 ms β^- = 100.00% β^-n = 65.00%	135In 92 ms β^- = 100.00% β^-n





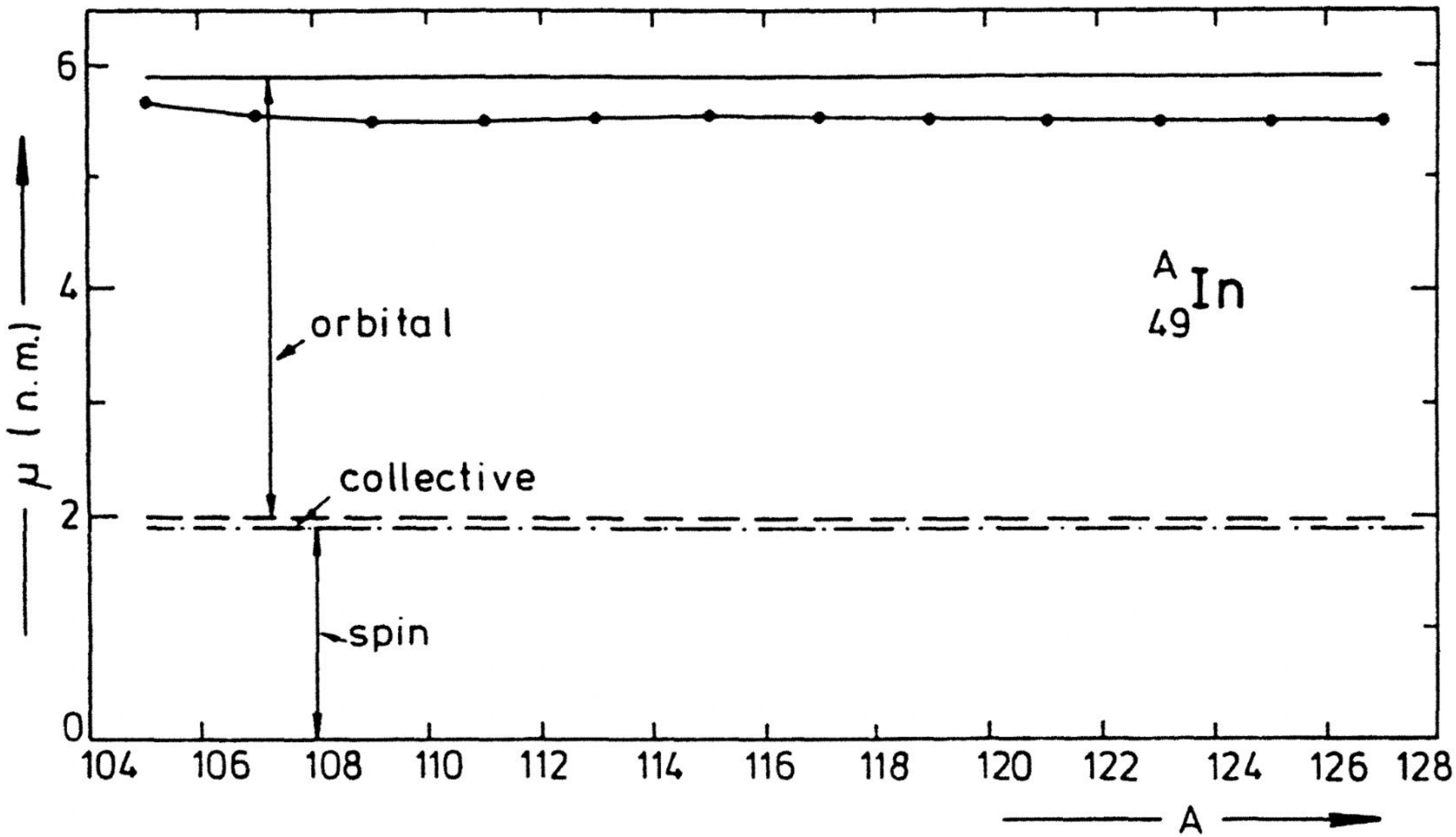
Motivation - single-particle behaviour in even-N ground states



Long, uninterrupted chain of $9/2^{+}$ ground states in even-N isotopes of indium across entire major neutron shell.

K. Heyde, The Nuclear Shell Model (1994)

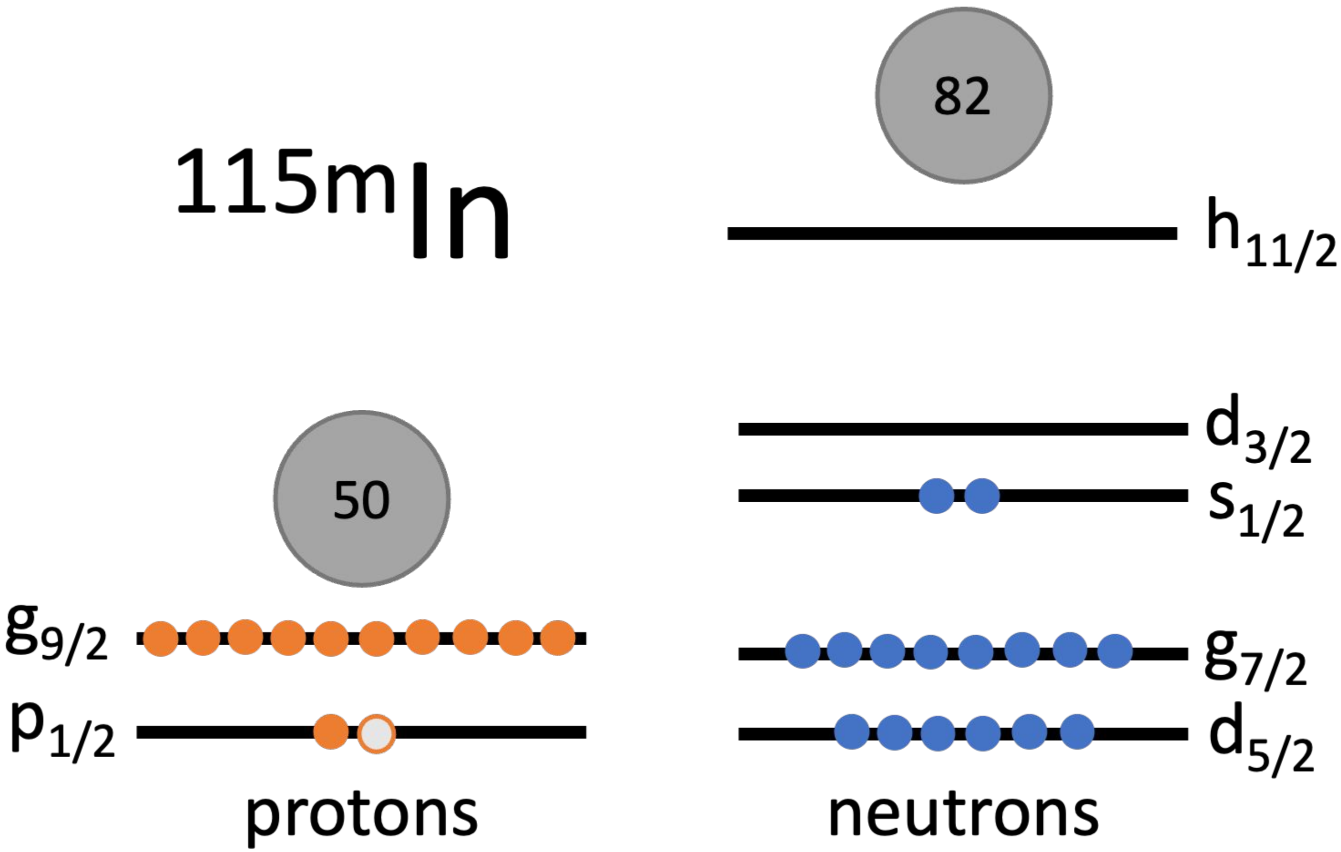
Motivation - single-particle behaviour in even-N ground states



Textbook example of single-particle behaviour in complex nuclei - identity of nucleus predominantly determined by $g_{9/2}$ proton.

K. Heyde, The Nuclear Shell Model (1994)

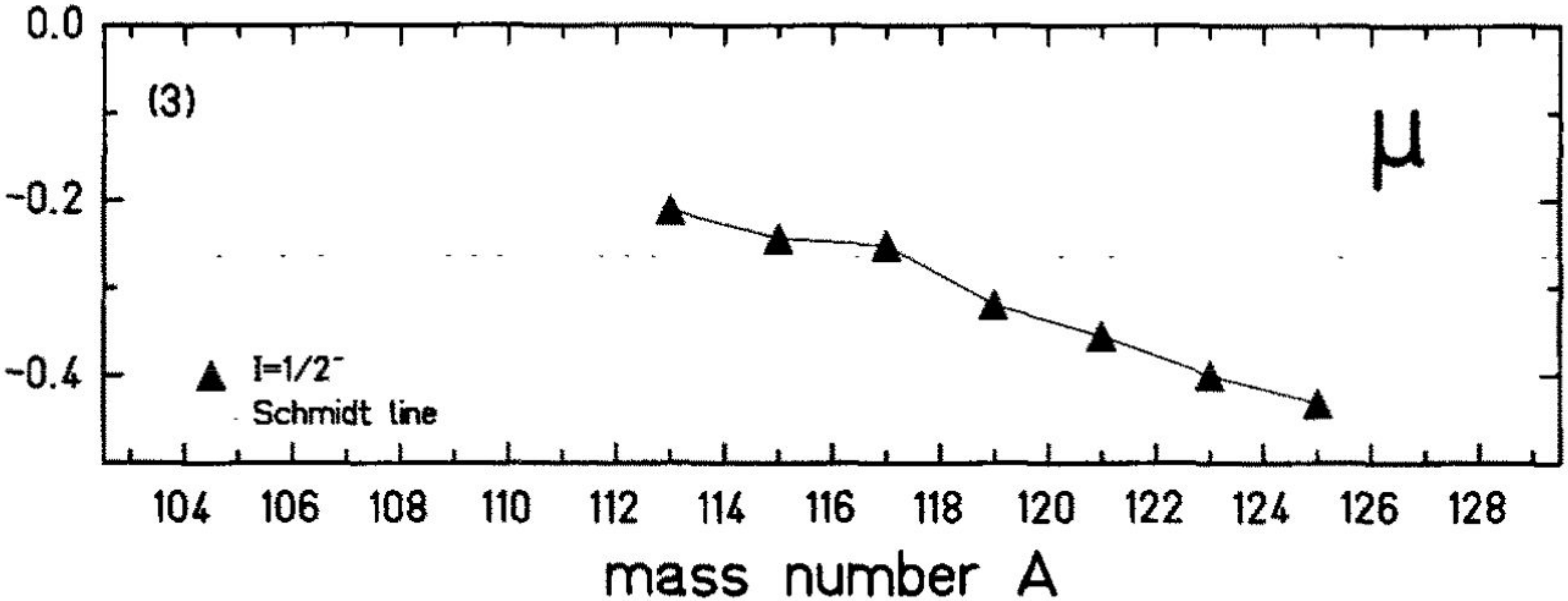
Motivation - complex magnetic behaviour of $p_{1/2}$ isomers



Long chains of $1/2^-$ isomeric states in even-N isotopes.

K. Heyde, The Nuclear Shell Model (1994)

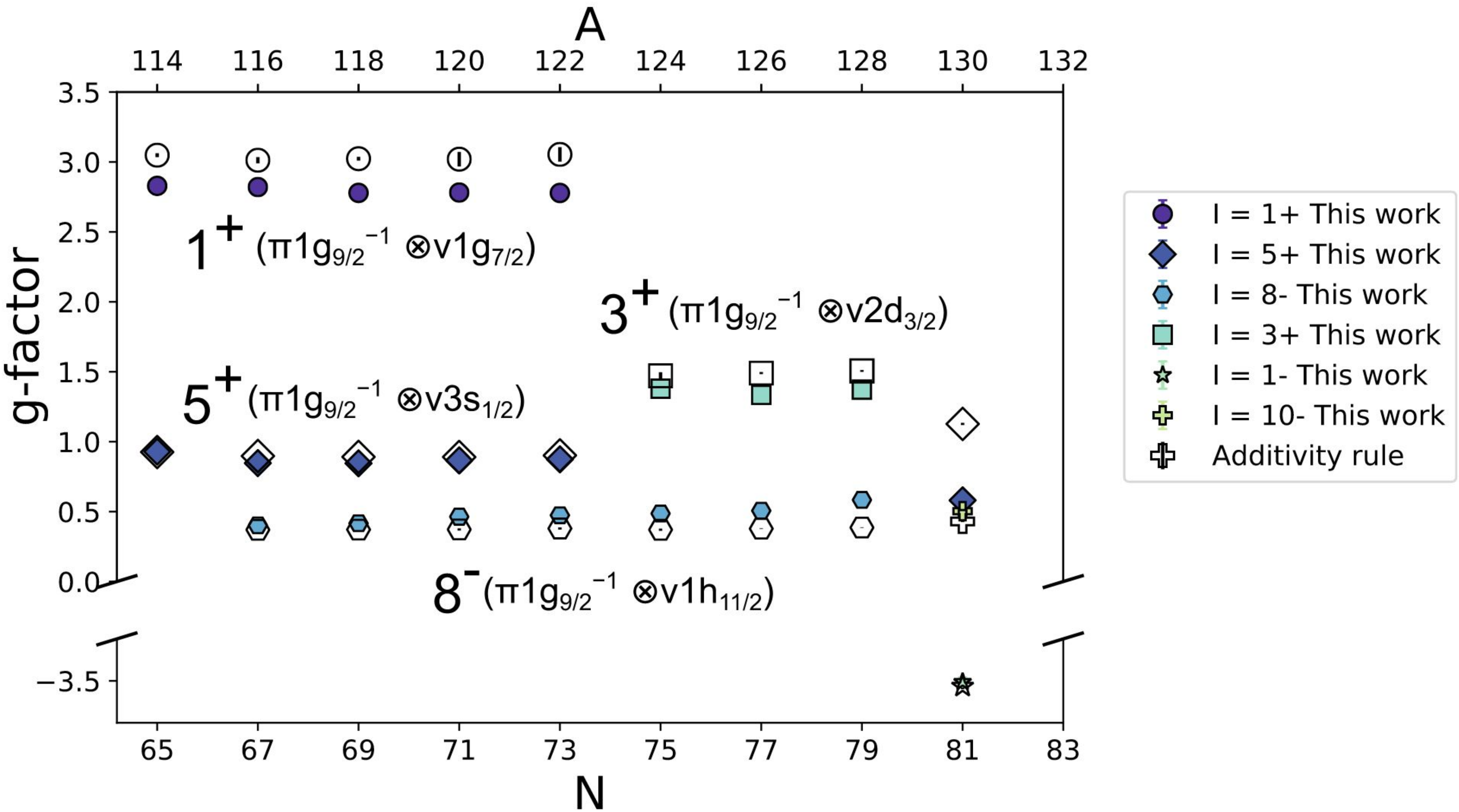
Motivation - complex magnetic behaviour of $p_{1/2}$ isomers



Complex behaviour of magnetic moments of $p_{1/2}$ isomers - long-standing puzzle in region.

K. Heyde, The Nuclear Shell Model (1994)

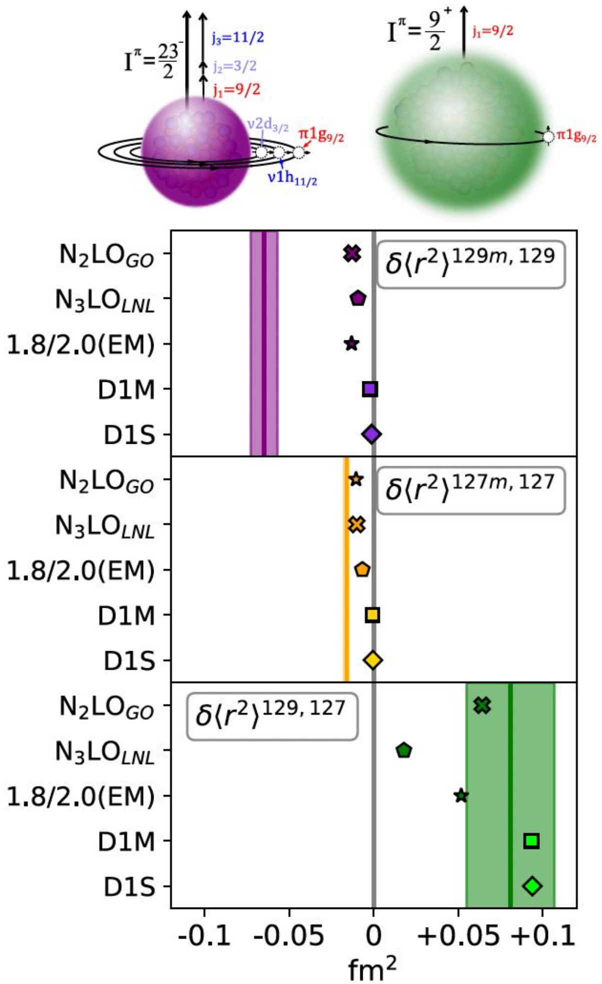
Motivation - rich isomerism in odd-N isotopes

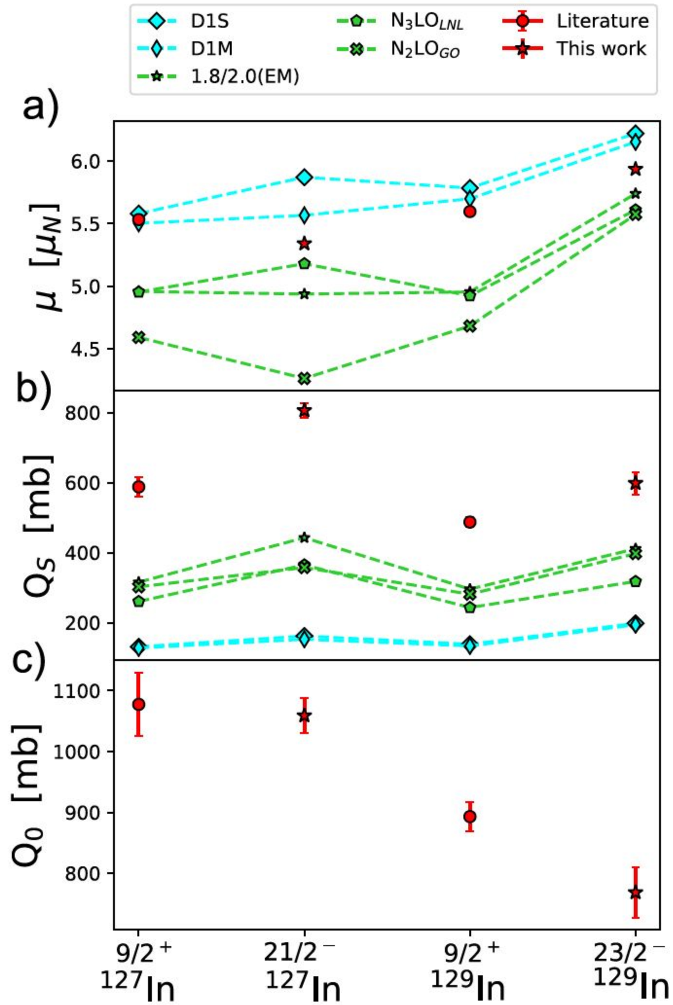


Odd-N isotopes exhibit rich isomerism from coupling between unpaired proton and neutrons can test p-n interaction.

A. Vernon, PhD thesis (2020)

Motivation - high-spin isomers close to N=82



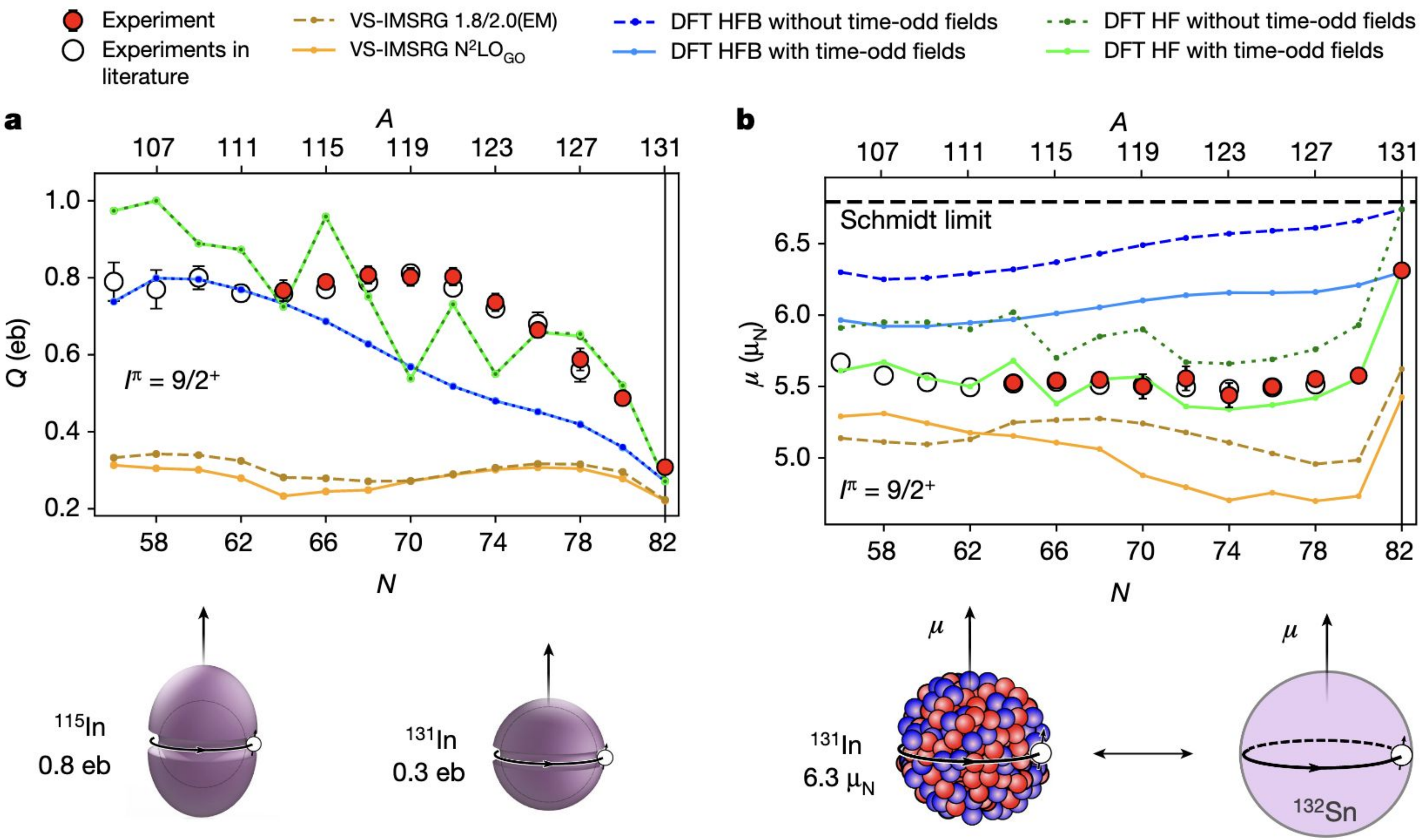


High-spin isomers from coupling between broken neutron pairs.

A. Vernon *et al.*, In preparation

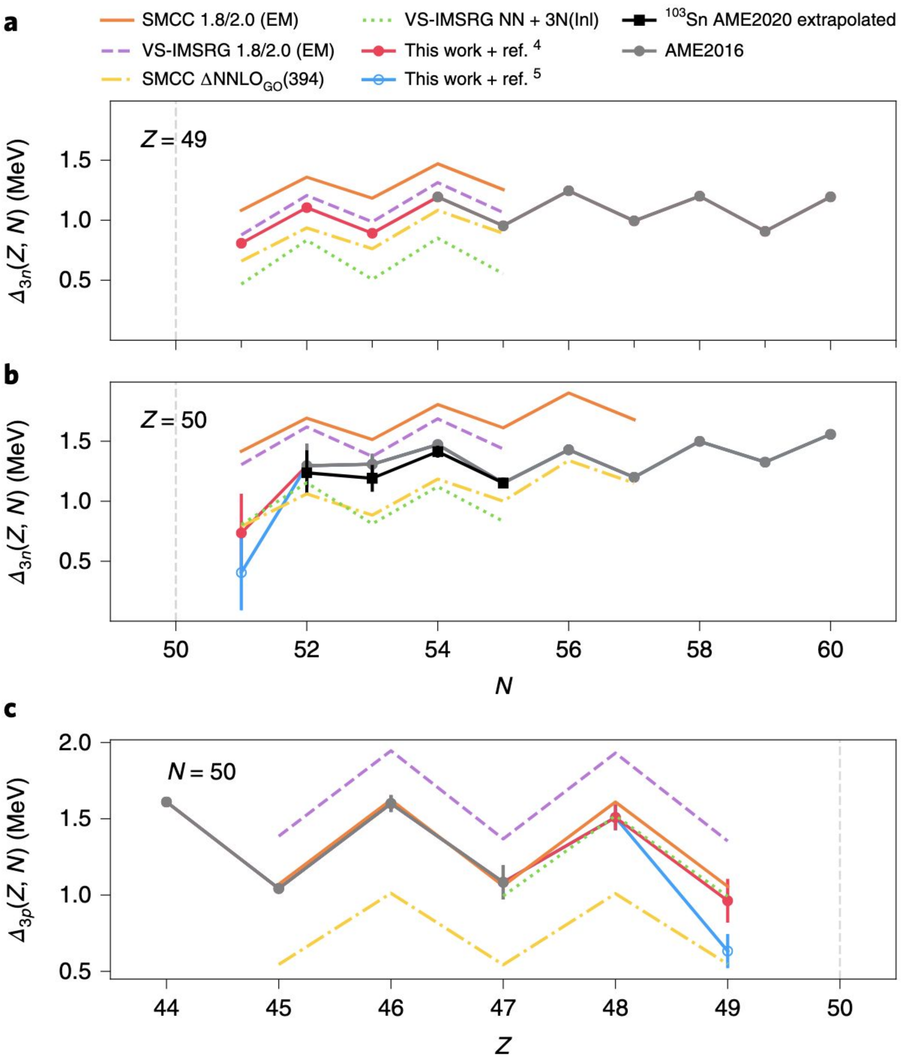
CRIS

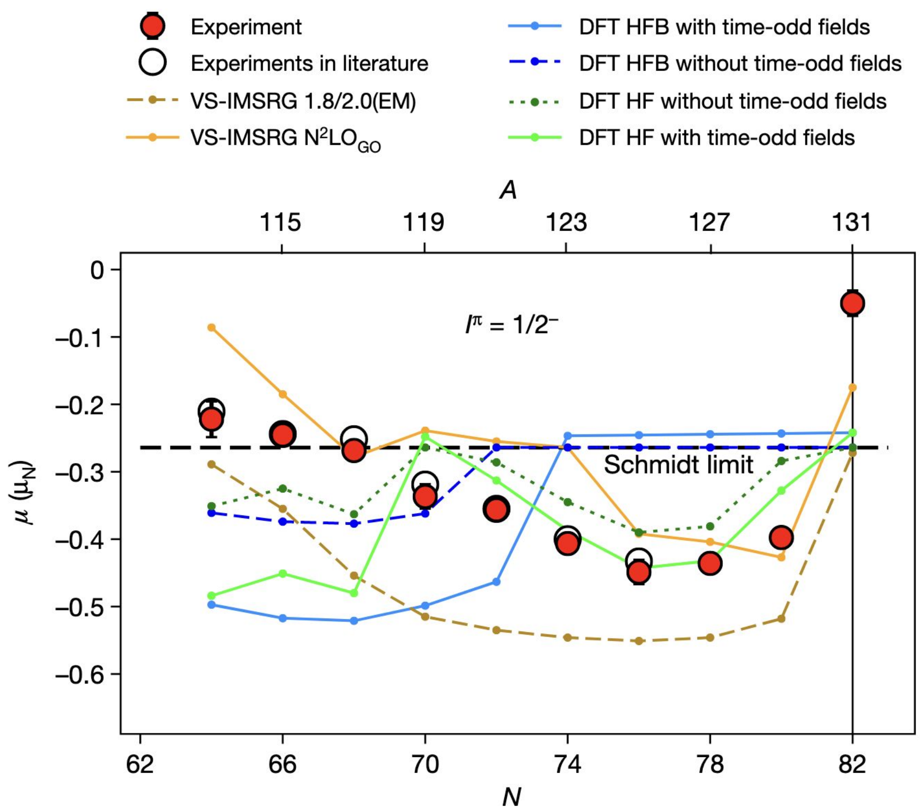
Motivation - abrupt change of nuclear moments at N=82



A. Vernon *et al.*, Nature **607** 260-265 (2022)

Motivation - developments in nuclear theory





Regions surrounding ^{100,132}Sn now accessible by *ab initio* computational methods!

M. Mougeot *et al.*, Nat. Phys. **17** 1099–1103 (2021), A. Vernon *et al.*, Nature **607** 260-265 (2022)

Proposal aims

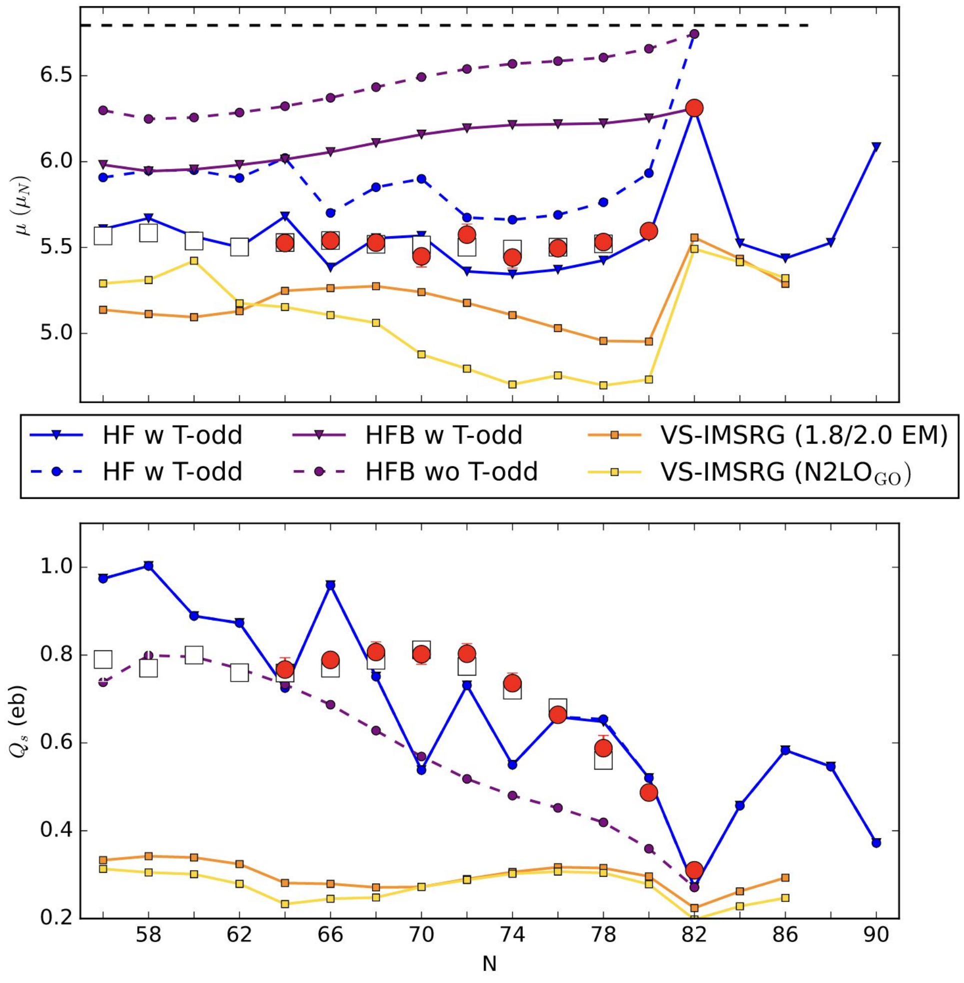
Aim to perform the furthest laser spectroscopy measurements beyond N=82 in vicinity of Z=50.

Measure up to 4 properties of ground states and isomers of $^{131m2\text{-}134}$In!

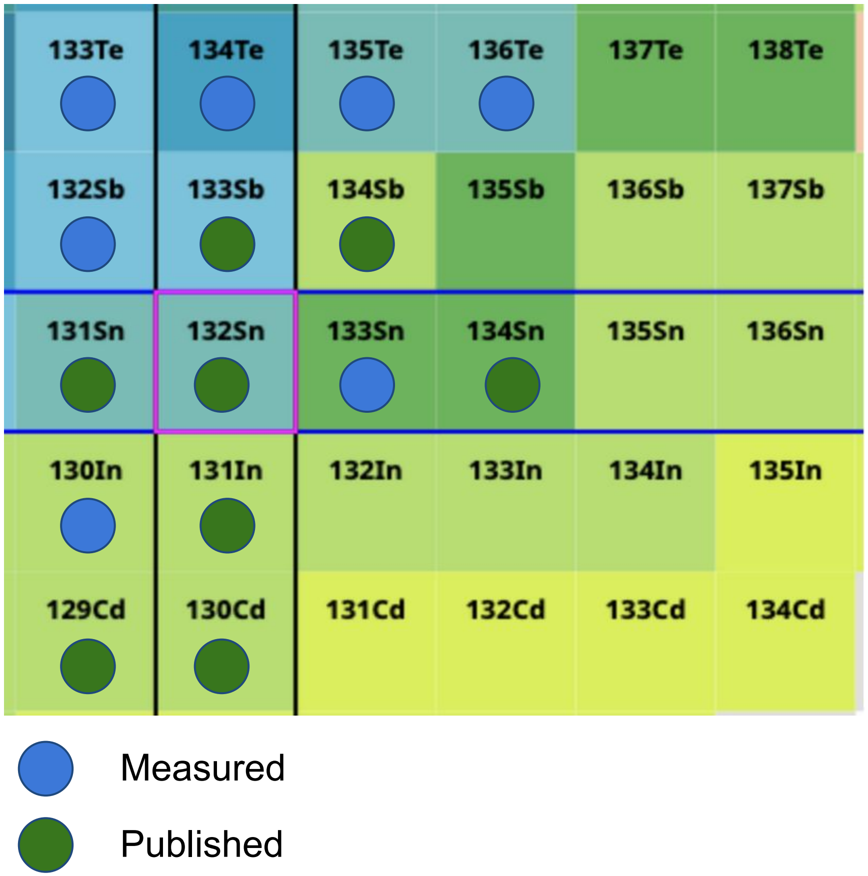
Test predictions from Density Functional Theory and *ab initio* Valence Space In-Medium Similarity Renormalization Group.

New observables measured by this proposal:

^{131m2}In ($21/2^+$): μ, Q_s, $\delta\langle r^2\rangle$
^{132}In (7^-): μ, Q_s, $\delta\langle r^2\rangle$
^{133g}In ($9/2^+$): μ, Q_s, $\delta\langle r^2\rangle$
^{133m}In ($1/2^-$): I, μ, $\delta\langle r^2\rangle$
^{134}In (7^-): μ, Q_s, $\delta\langle r^2\rangle$.



Progress around ^{132}Sn so far



Rodriguez *et al.*, INTC-P-561 (2020)

Lechner *et al.*, Phys. Rev. C **104** 439-443 (2021)

Yordanov *et al.*, Commun. Phys. **3** 107 (2020)
Gorges *et al.*, Phys. Rev. Lett. **122** 192502 (2019)

Vernon *et al.*, Nature **17** 439-443 (2021)
Sahoo *et al.*, New J. Phys **22** 012001 (2020)

Hammen *et al.*, Phys. Rev. Lett **121** 102501 (2018)
Yordanov et al., Phys. Rev. Lett. **116** 032051 (2016)
Yordanov et al., Phys. Rev. Lett. **110** 192051 (2013)

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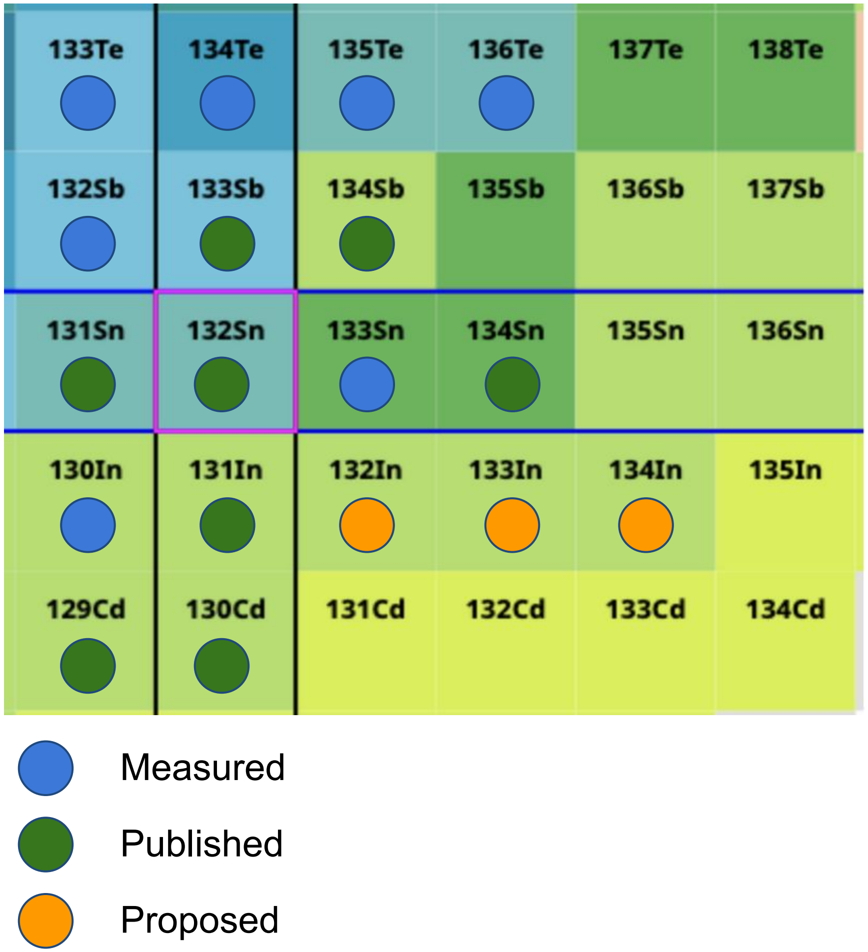

Rodriguez *et al.*, INTC-P-561 (2020)

Lechner *et al.*, Phys. Rev. C **104** 439-443 (2021)

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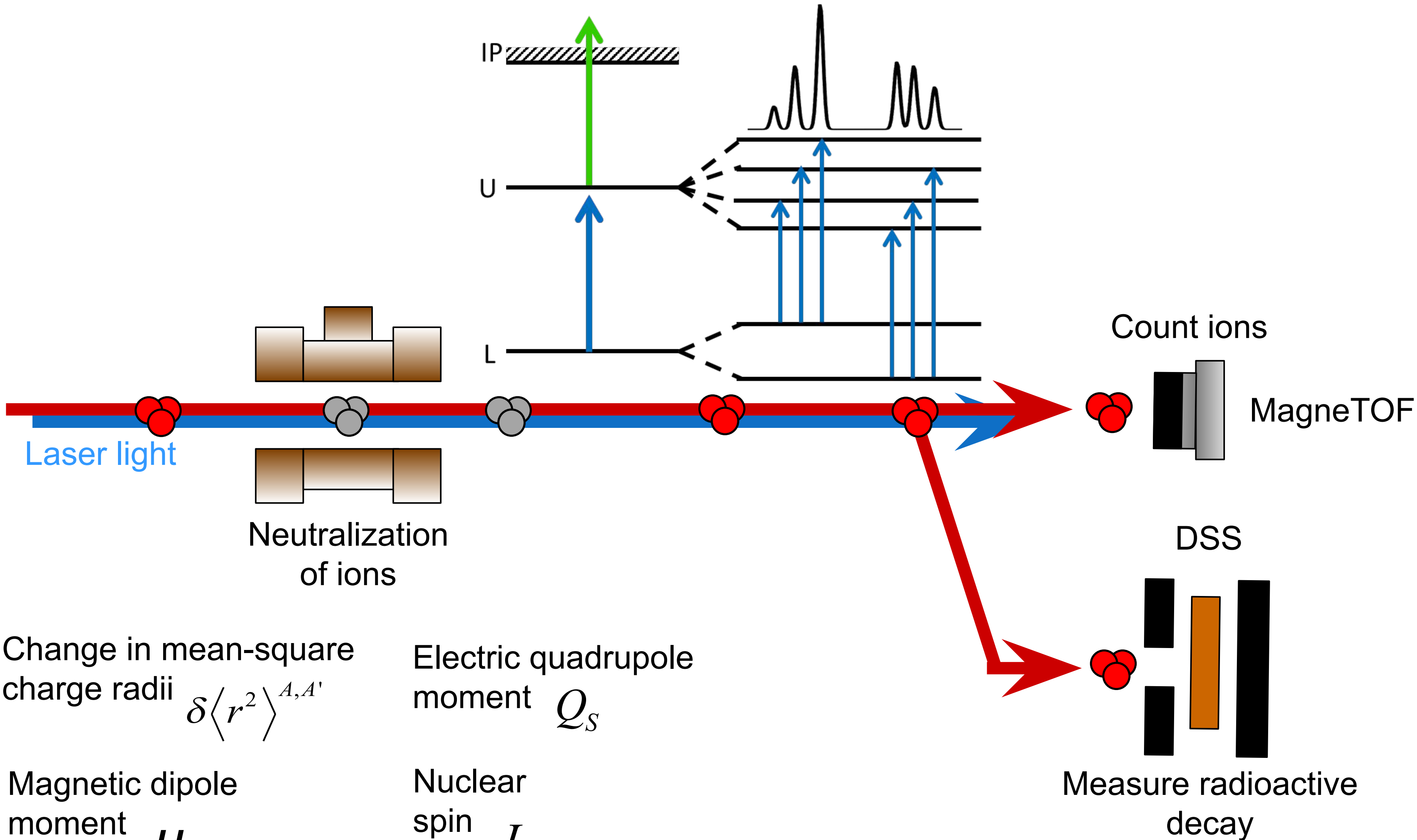
The CRIS technique



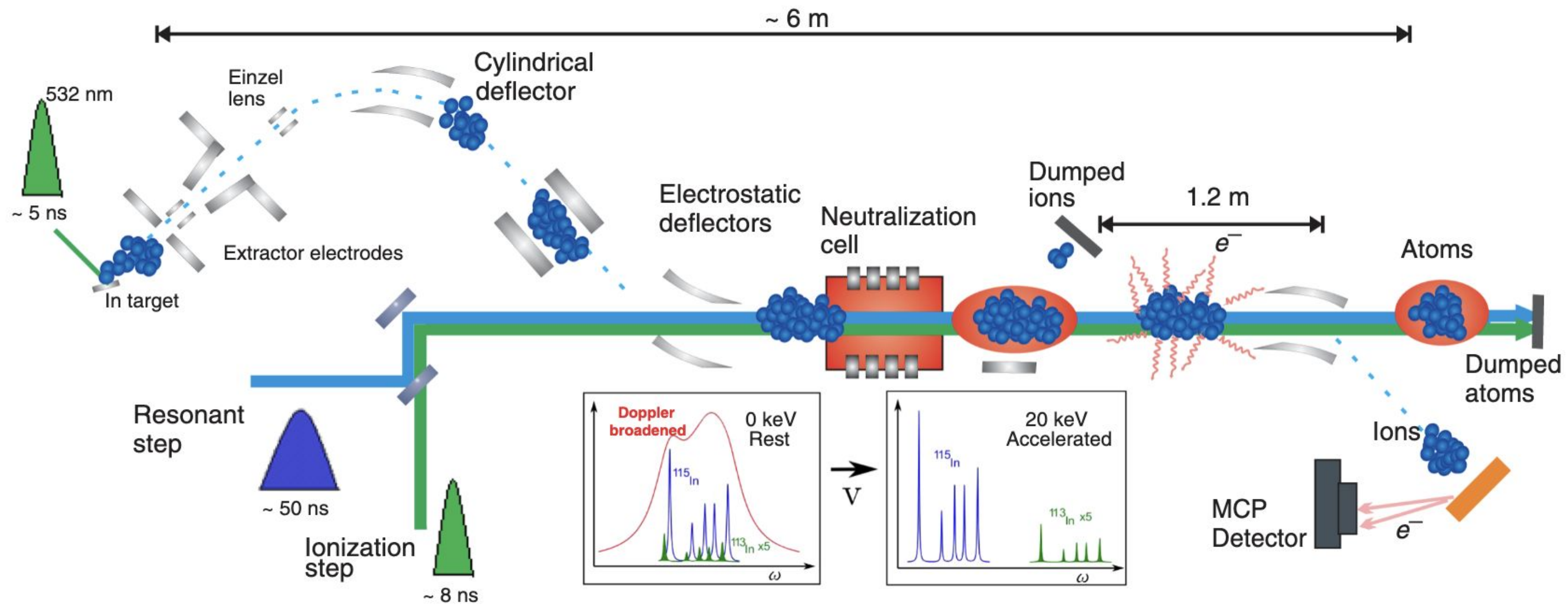
Change in mean-square charge radii $\delta\langle r^2\rangle^{A,A'}$

Electric quadrupole moment Q_S

Magnetic dipole moment μ_I

Nuclear spin I

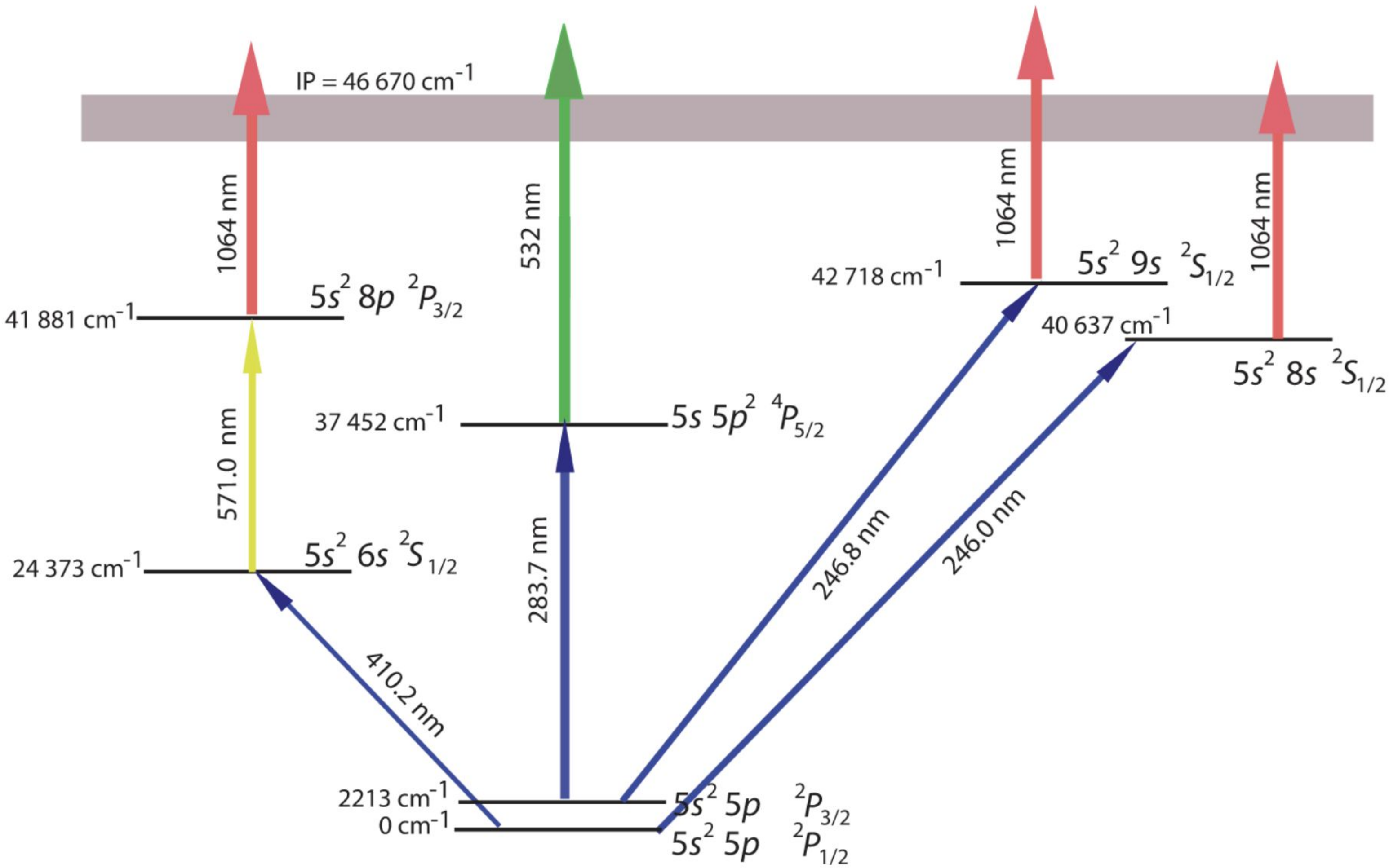
Previous indium experiments at CRIS



Indium is a very well-known atomic system at CRIS with extensive off-line developments and 2 on-line experiments performed to date.

R. Garcia Ruiz, Phys. Rev. X **8** 041005 (2018)

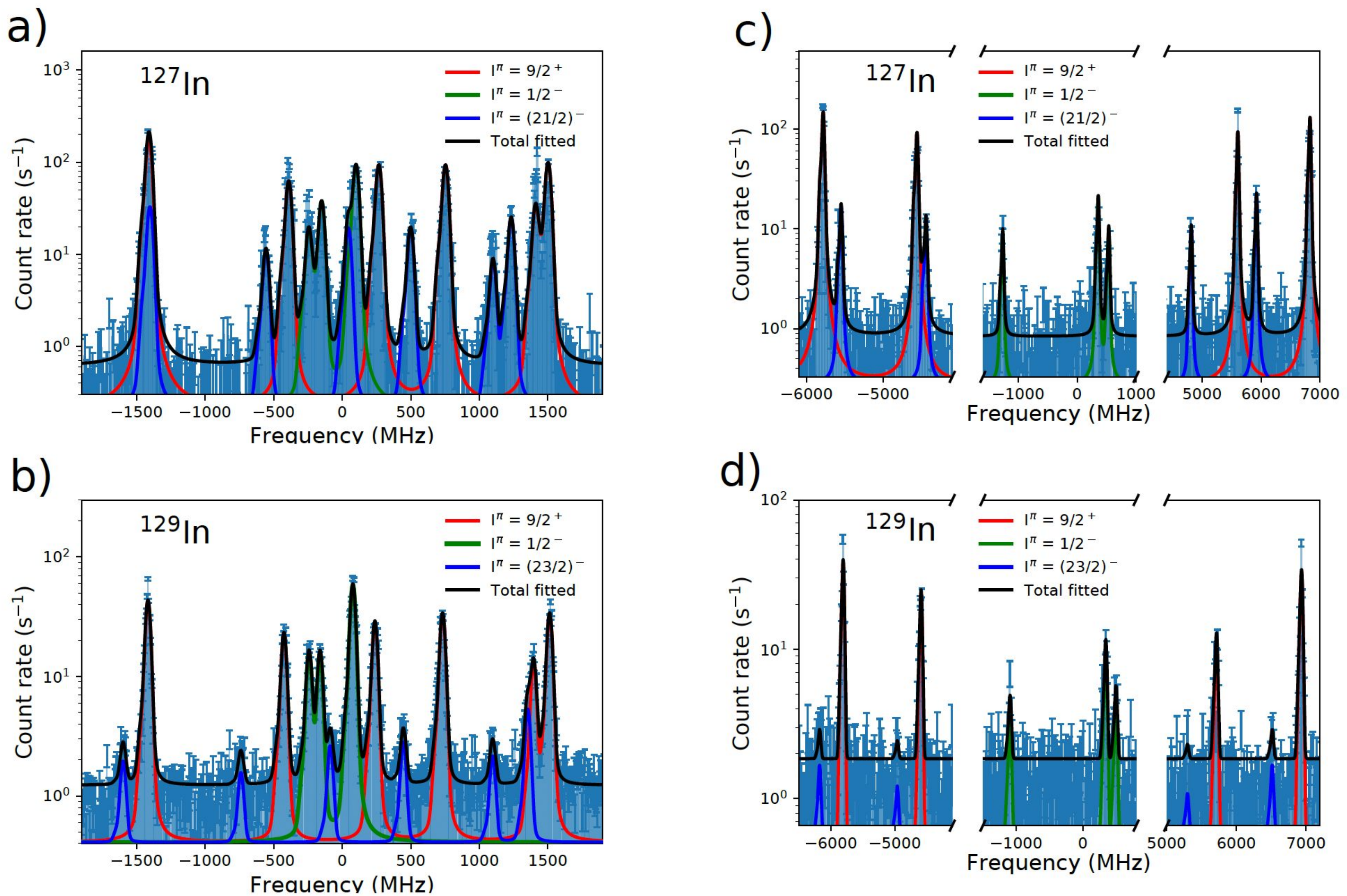
Previous indium experiments at CRIS



Many resonant transitions tested.

R. Garcia Ruiz, Phys. Rev. X **8** 041005 (2018)

Previous indium experiments at CRIS



Two transitions employed possess excellent sensitivity to observables of interest and allow combined use helps assign hyperfine components to nuclear states.

A. Vernon *et al.*, In preparation

Previous indium experiments at CRIS

Two successful previous experiments on indium isotopes at CRIS:

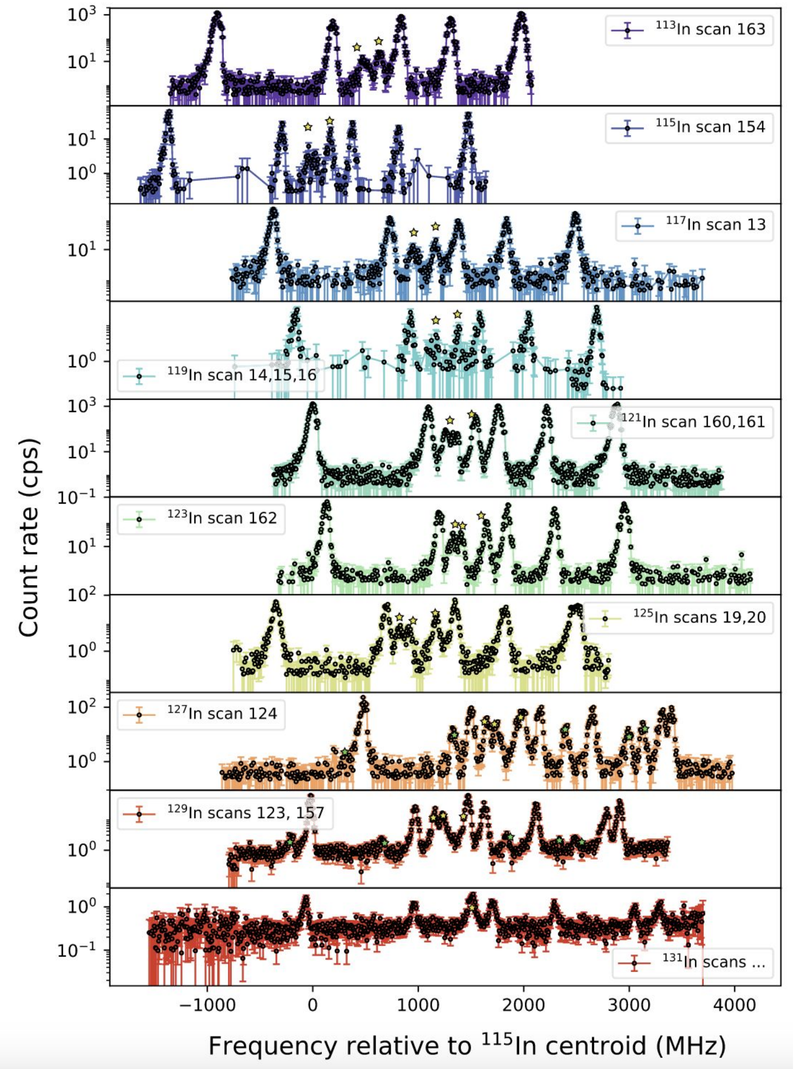
- IS639 - neutron-rich up to ^{131}In (N=82).
- IS639A - neutron-deficient down to ^{101}In (N=52).

IS639 run compromised by target being vented at high temperature - significantly reduced indium yield.

Plethora of new isotopes and observables measured.

2 articles so far in Nature and New J of Physics (1 in Phys. Rev. X for off-line developments).

Multiple additional articles in progress (2 in advanced stage).



A. Vernon, PhD Thesis (2020)

Shift request

Isotope	I	Half life (ms)	Yield (ions/μC)	Shifts	Q_β (MeV)
^{115}In	$9/2^+$	stable	$> 10^5$	3 (setup)	0
^{131m2}In	$(21/2^+)$	300	200	3	unknown
^{132}In	(7^-)	194(4)	8000	2	14.14 (6)
^{133g}In	$(9/2^+)$	162(2)	900	2	13.18 (20)
^{133m}In	$(1/2^-)$	162(2)	300	3	unknown
^{134}In	(7^-)	118(6)	100	6	14.46 (20)
height					

Table 1: Isotopes of interest, their spins and half-lives [31, 19, 13, 14], yields and shifts requested. The quoted yields for the ground states are taken from the ISOLDE Yield Database where a UC_x target with neutron converter is used in combination with RILIS. The yield of ^{131m,133m}In was estimated using experimentally observed ratios in ^{129,131}In during the IS639 experiment. The requested shifts include the time needed for regular calibration measurements with the reference isotope ^{115}In, however 3 shifts (without protons) preceding the experiment are requested for beam tuning, charge-exchange cell heating and laser/atom interaction optimization.

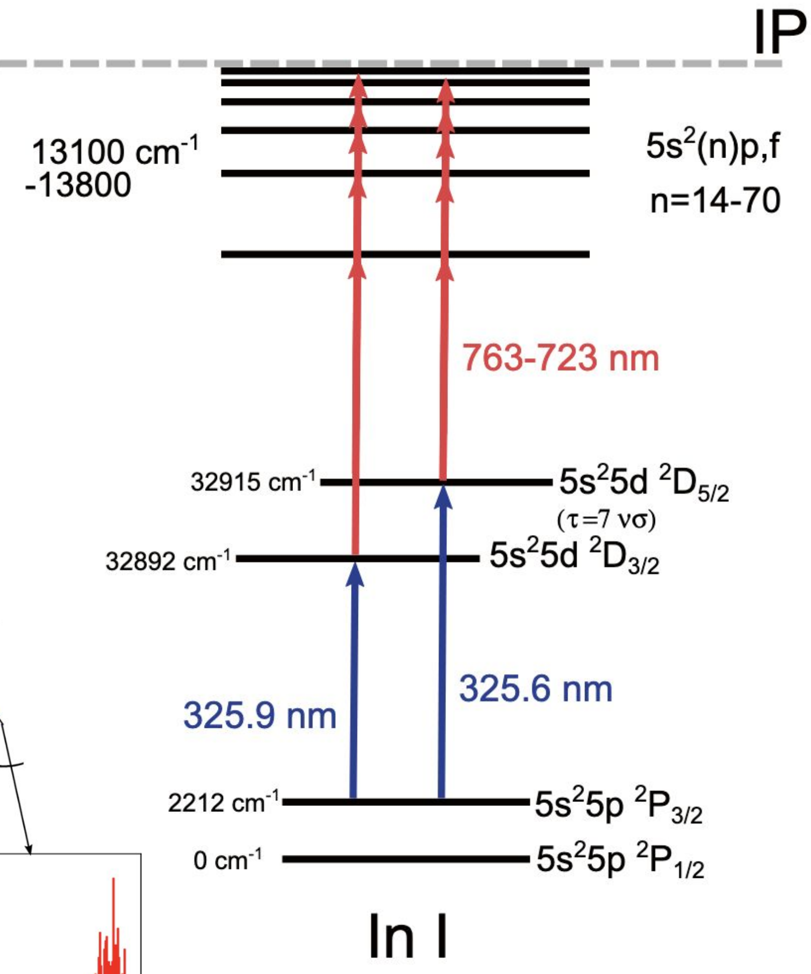
Total: 16 shifts with protons (+3 without)

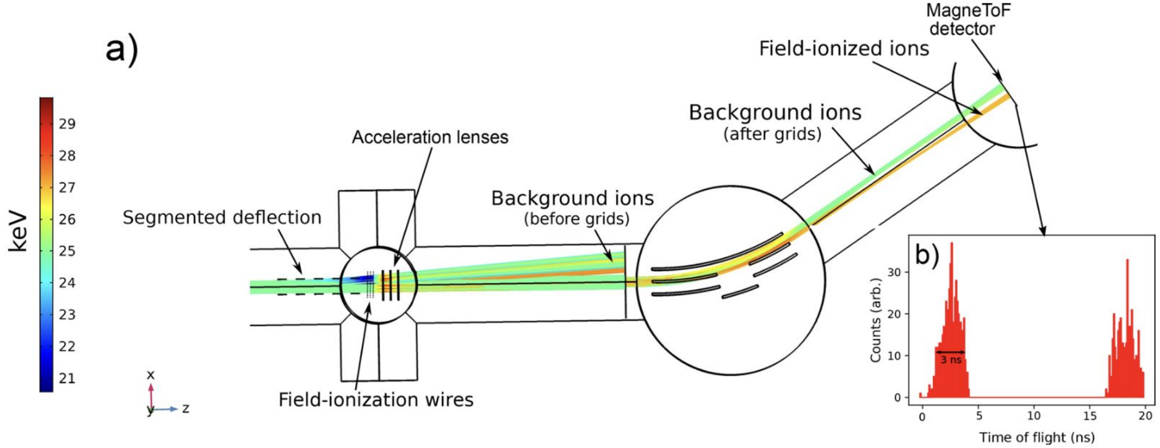
Experimental setup - field ionization

More sensitive ionization scheme through field ionization of high-lying Rydberg states [1].

Funding for OPO laser system to use technique from 8s $^2S_{1/2}$, 9s $^2S_{1/2}$ states successfully acquired.

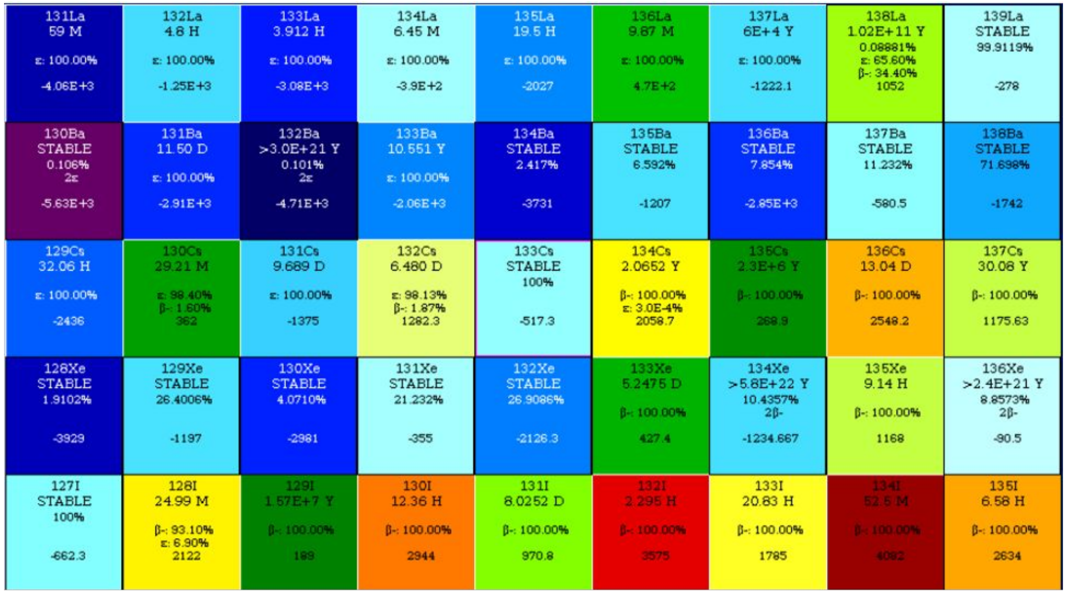
Reduce non-resonant laser and collisional background from intense expected Cs/Ba contamination.





A. Vernon *et al.*, Sci. Rep. **10** 12306 (2020)

Experimental setup - nuclear decay detection



Short half-lives and large Q_β (>14 MeV) compared to stable or long-lived contaminants (<3 MeV) open up possibility to use emitted betas for ion detection.

Scenario 1: Simple implantation onto thick window like used for ^{52}K and utilize difference in Q_β [1].

Á. Koszorús *et al.*, Nat. Phys. **17** 439-443 (2021)

Experimental setup - nuclear decay detection

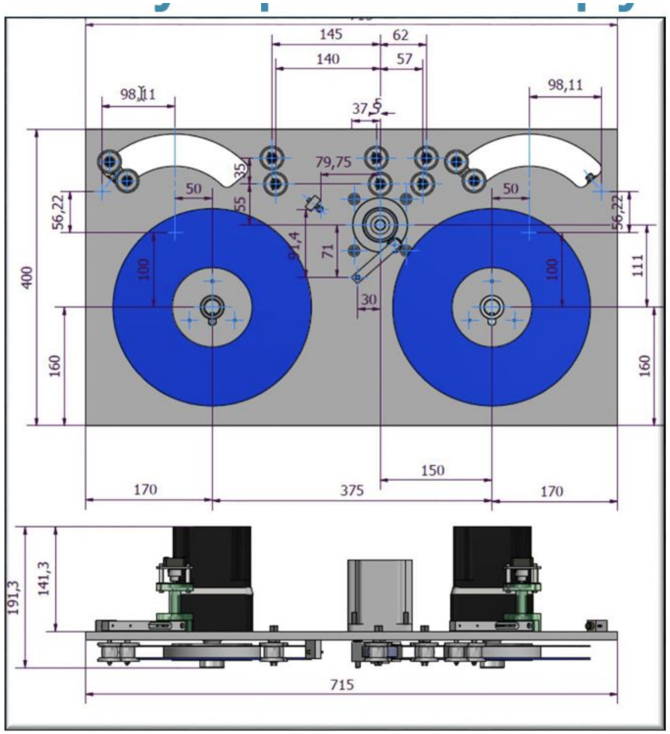
Development of new tape station for decay spectroscopy studies at CRIS - under construction at KU Leuven.

Final critical parts to be delivered by Christmas 2022.

To be employed on-line during Zn and Cr runs in 2023.

Scenario 2: Use new CRIS tape station. Able to do more than just beta-counting.

Scenario 3: ILL neutron detector can be added for additional physics and potentially cleaner detection (not needed for this proposal).



TAC comments

Laser spectroscopy of neutron-rich indium isotopes beyond N=82					
CDS#	**Proposal #**	**IS #**	**Setup**	**Shifts**	**Isotopes**
CERN-INTC-2022-048	INTC-P-646		CRIS	16	131-134In (and isomers)
Beam intensity/purity, targets-ion sources	The yields are quoted for on-convertor. The use of a quartz line is not clear especially as LIST is also mentioned. Which option is favoured? Is narrow band RILIS for isomer selectivity required? If so, please specify and provide corresponding data for shifts and isomer positions. This will also affect the yields and should be accounted for.				
General implantation and setup					
General Comments					
Safety	CRIS to be used without modification – EP 2022 Safety Clearance at EDMS 1807216. Use of lasers is currently restricted at CRIS, follow up laser safety inspection to be arranged (Nov).				
TAC recommendation	**The TAC requests that the use of quartz line or LIST ion source be clarified. In addition, the use of narrow band RILIS for isomer selectivity should be clarified: does the shift request take this possibility into account?**				

Use of LIST for neutron-rich indium its current form results in large 35-50 loss even when compared to on-converter yields [1].

Provisional: UC_x + neutron converter, RILIS and quartz line requested. Can TAC quantify efficacy of quartz line on Cs/Ba contamination reduction?

Possible: Use of LIST may be requested in future if developments significantly reduce this laser ion loss factor.

Narrowband RILIS **not** required as the atomic transitions employed by CRIS for indium have excellent nuclear-state separation. The broadest possible linewidth is requested for RILIS lasers such that entire hyperfine structure of all nuclear states is covered.

R. Heinke, Private communication (2022)

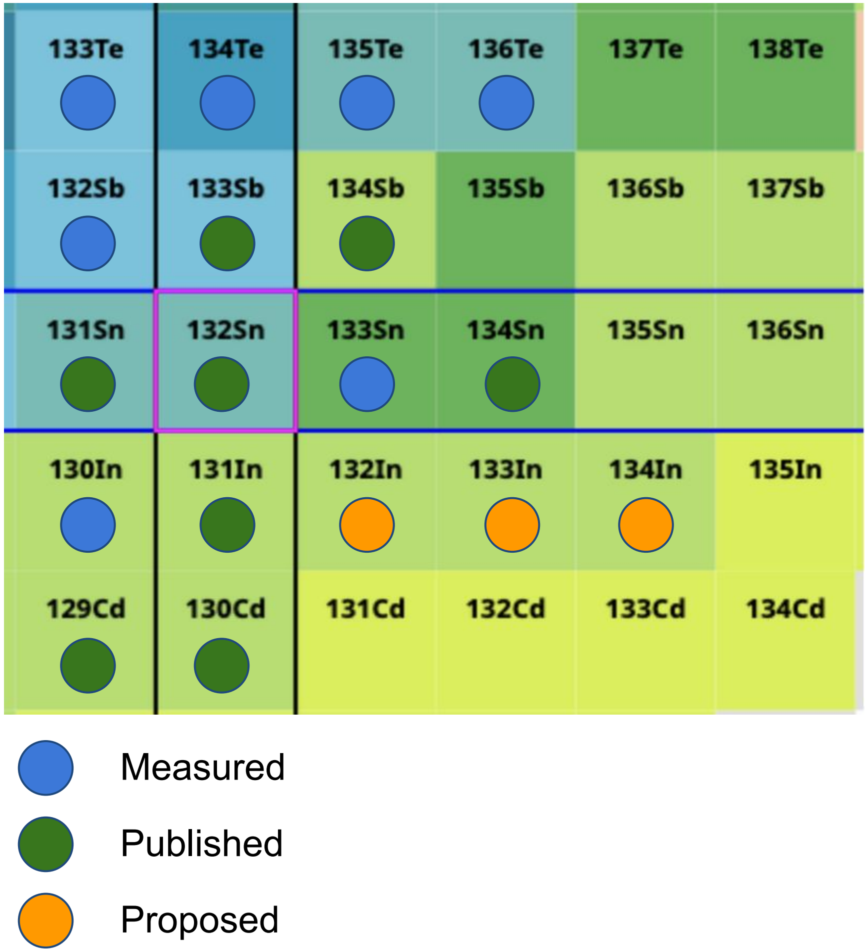
Summary

We propose to extend measurements of neutron-rich indium (Z=49) up to ^{134}In at N=85.

Measurements will provide complementary insights into how multiple facets of nuclear structure evolve beyond N=82.

Indium is a well-known and benchmarked system at CRIS.

More sensitive ionization schemes and/or decay detection methods will enable us to overcome challenges associated with isobaric background.



CRIS

Acknowledgements

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[1]EP Department, CERN, Switzerland, [2]KU Leuven, Belgium, [3]Peking University, China, [4]The University of York, United Kingdom, [5]The University of Manchester, United Kingdom, [6]Photon Science Institute, University of Manchester, United Kingdom, [7]Massachusetts Institute of Technology, USA, [15]University of Gothenburg, Sweden, [5]TRIUMF, Canada, [18]M-Squared Lasers, United Kingdom.