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.



- 1						
	131Sn 56.0 s	132Sn 39.7 s	133Sn 1.46 s	134Sn 1.050 s	135Sn 530 ms	136Sn 0.290 s
	β [.] = 100.00%	β [.] = 100.00%	β [.] = 100.00% β'n = 0.03%	β [·] = 100.00% β [·] n = 17.00%	β [.] = 100.00% β [.] n = 21.00%	β = 100.00% β n = 28.00% β 2n ?
	130In 0.29 s	131In 0.28 s	132In 0.207 s	133In 165 ms	134In 140 ms	135In 92 ms
	β [.] = 100.00% β [.] n = 0.93%	β [.] = 100.00% β⁻n ≤ 2.00%	β [.] = 100.00% β [.] n = 6.30%	β [·] = 100.00% β [·] n = 85.00%	β [.] = 100.00% β [.] n = 65.00%	β [.] = 100.00% β [.] n
	1		³¹ In	82	•••• h _{11/2}	
			50		d _{3/2} s _{1/2}	





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)

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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



Motivation - abrupt change of nuclear moments at N=82



Motivation - developments in nuclear theory



M. Mougeot *et al.*, Nat. Phys. **17** 1099–1103 (2021), A. Vernon *et al.*, Nature **607** 260-265 (2022) 10

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 ^{131m2-134}In!

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

New observables measured by this proposal: $121m^{21}$ (2.1 (2t) - 5 (2t)

^{131m2}In (21/2⁺): μ , Q_s , $\delta \langle r^2 \rangle$ ¹³²In (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 , $\delta \langle r^2 \rangle$ ¹³⁴In (7⁻): μ , Q_s , $\delta \langle r^2 \rangle$.



Progress around ¹³²Sn so far

\bigcirc			1371e	1381e	Rodriguez et al., INTC-P-561 (2020)
133Sb	134Sb	135Sb	136Sb	137Sb	Lechner <i>et al.</i> , Phys. Rev. C 104 439-443 (2021)
132Sn	133Sn	134Sn	135Sn	136Sn	Yordanov <i>et al.</i> , Commun. Phys. 3 107 (2020) Gorges <i>et al.</i> , Phys. Rev. Lett. 122 192502 (2019)
131In	132In	133In	134In	135In	Vernon <i>et al.</i> , Nature 17 439-443 (2021) Sahoo <i>et al.</i> , New J. Phys 22 012001 (2020)
129Cd 130Cd 131Cd 132Cd		132Cd	133Cd 134Cd		Hammen <i>et al.</i> , Phys. Rev. Lett 121 102501 (2018) Yordanov et al., Phys. Rev. Lett. 116 032051 (2016) Yordanov et al., Phys. Rev. Lett. 110 192051 (2013)
	1335b 1325n 131In 131In 130Cd 0	1335b 1345b 1325n 1335n 1325n 1335n 1311n 1321n 130cd 131cd 130cd 131cd	133Sb 134Sb 135Sb 132Sn 133Sn 134Sn 131In 132In 133In 130Cd 131Cd 132Cd 130cd 131Cd 132Cd	133Sb 134Sb 135Sb 136Sb 132Sn 133Sn 134Sn 135Sn 131In 132In 133In 134In 130Cd 131Cd 132Cd 133Cd 130cd 131Cd 132Cd 133Cd	133Sb 134Sb 135Sb 136Sb 137Sb 132Sn 133Sn 134Sn 135Sn 136Sn 131In 132In 133In 134In 135In 130Cd 131Cd 132Cd 133Cd 134Cd

Measured

Published



Progress around ¹³²Sn so far

133Te	134Te	135Te	136Te	137Te	138Te	Rodriguez et al., INTC-P-561 (2020)					
132Sb	133Sb	134Sb	135Sb	136Sb	137Sb	Lechner <i>et al.</i> , Phys. Rev. C 104 439-443 (2021)					
131Sn	132Sn	133Sn	134Sn	135Sn	136Sn	Yordanov <i>et al.</i> , Commun. Phys. 3 107 (2020) Gorges <i>et al.</i> , Phys. Rev. Lett. 122 192502 (2019)					
130In	131In	132In	133In	134In	135In	Vernon <i>et al.</i> , Nature 17 439-443 (2021) Sahoo <i>et al.</i> , New J. Phys 22 012001 (2020)					
129Cd	130Cd	131Cd	132Cd	133Cd	134Cd	Hammen <i>et al.</i> , Phys. Rev. Lett 121 102501 (2018) Yordanov et al., Phys. Rev. Lett. 116 032051 (2016) Yordanov et al. Phys. Rev. Lett. 110 192051 (2013)					
M	Measured										

Published

Proposed



The CRIS technique





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)



Many resonant transitions tested.

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

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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 17

Two successful previous experiments on indium isotopes at CRIS:

- IS639 neutron-rich up to ¹³¹In (N=82).
- ÌS639Á neutron-deficient down to ¹⁰¹In (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).



Shift request

Isotope	Ι	Half life (ms)	Yield (ions/ μ C)	Shifts	$Q_{\beta} ({ m MeV})$
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 ${}^{2}S_{1/2}$, 9s ${}^{2}S_{1/2}$ states successfully acquired.

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

Background ions

(before grids)

Acceleration lenses

Field-ionization wires

a)

Segmented deflection

29

28

27

25

24

23 22 21

keV 26



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

Experimental setup - nuclear decay detection

131La 59 M a: 100.00%	132La 4.8 H z: 100.00%	133La 3.912 H z: 100.00%	134La 6.45 Μ ε: 100.00%	135La 19.5 H z: 100.00%	136La 9.87 M z: 100.00%	137La 6E+4 Y z: 100.00%	138La 102E+11 Y 0.08881% E:65.60% 8-34.40%	139La STABLE 99.9119%
-4.06E+3	-1.25E+3	-3.08E+3	-3.9E+2	-2027	4.7E+2	-1222.1	1052	-278
130Ba STABLE 0.106% 2z	131Ba 11.50 D z: 100.00%	132Ba ≻3.0E+21 Y 0.101% 2ε	133Ba 10.551 Y z: 100.00%	134Ba STABLE 2.417%	135Ba STABLE 6.592%	136Ba STABLE 7.854%	137Ba STABLE 11.232%	138Ba STABLE 71.698%
-5.63E+3	-2.91E+3	-4.71E+3	-2.06E+3	-3731	-1207	-2.85E+3	-580.5	-1742
129Cs 32.06 H	130Cs 29.21 M	131Cs 9.689 D	132Cs 6.480 D	133Cs STABLE 100%	134Cs 2.0652 Y	135Cs 2.3E+6 Y	136Cs 13.04 D	137Cs 30.08 Y
s: 100.00% -2436	ic:98.40% β∹1.60% 362	s: 100.00% -1375	£: 98.13% β∹ 1.87% 1282.3	-517.3	β∹ 100.00% ε: 3.0E-4% 2058.7	β-: 100.00₩ 268.9	β∹ 100.00% 2548.2	β∹ 100.00% 1175.63
128Xe STABLE 1.9102%	129Xe STABLE 26.4006%	130Xe STABLE 4.0710%	131Xe STABLE 21.232%	132Xe STABLE 26.9086%	133Xe 5.2475 D β-: 100.00%	134Xe >5.8E+22 Υ 10.4357% 2β-	135Xe 9.14 H β-: 100.00%	136Xe >2.4E+21 Υ 8.8573% 2β-
-3929	-1197	-2981	-355	-2126.3	427.4	-1234.667	1168	-90.5
127I STABLE 100%	128I 24.99 M	1291 1.57E+7 Y	130I 12.36 H	131I 8.0252 D	1321 2 295 H	133I 20.83 H	1341 52.6 M	1351 6.58 H
-662.3	β-: 93.10% ε: 6.90% 2122	β-: 100.00 % 189	β-: 100.00% 2944	β-: 100.00% 970.8	β-<100.00% 3575	β-: 100.00% 1785	0-: 100.00% -4092	β-: 100.00% 2634

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].

1311 8.0252 D	132I 2.295 H	133I 20.83 H	134I 52.5 M	1351 6.58 H	136I 83.4 S	137I 24.5 S	138I 6.23 S	139I 2.280 S
β-: 100.00%	β-: 100.00%	β∹ 100.00 %	β-: 100.00 %	β∹ 100.00 %	β-: 100.00 %	β-: 100.00% β-:: 7.14%	β-: 100.00% β-r: 5.56%	β-: 100.00% β.m. 10.00%
970.8	3575	1785	4082	2634	6884	6027	7992	7174
130Te ≥3.0E+24 Y 34.08%	131Te 25.0 M	132Te 3.204 D	133Te 12.5 M	134Te 41.8 M	135Te 19.0 S	136Te 17.63 S	137Te 2.49 S	138Te 1.4 S
2β-: 100.00%	β-: 100.00 %	β-: 100.00%	β∹ 100.00%	β-: 100.00 %	β-: 100.00 %	β-: 100.00% β-n: 1.31%	β-: 100.00% β-π- 2.99%	β-: 100.00% β-n: 6.30%
-417	2231.7	515	2921	1510	6050	5120	7053	6284
129Sb 4.366 H	130Sb 39.5 M	131Sb 23.03 M	132Sb 2.79 M	133Sb 2.34 M	134Sb 0.78 S	135Sb 1.679 S	136Sb 0.923 S	137Sb 492 MS
β∹ 100.00 %	β-: 100%	β-: 100.00 %	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00%	β-: 100.00% β.τ. 49.00%
2376	5067	3229.6	5553	4014	8513	8038	9918	9.24E+3
128Sn 59.07 M	129Sn 2.23 M	130Sn 3.72 M	131Sn 56.0 S	132Sn 39.7 S	133Sn 1.46 S	134Sn 1.050 S	135Sn 530 MS	136Sn 0.290 S
β-: 100.00%	β-: 100.00%	β+: 100.00 %	β-: 100.00 %	β-: 100.00 %	β-: 100.00% β-n- 0.03%	β-: 100.00% β-r: 17.00%	β-: 100.00% 8-p: 21.00%	β-: 100.00% β-r: 28.00%
1268	4.04E+3	2153	4717	3089	8050	7587	9058	8.6E+3
127In 1.09 S	128In 0.84 S	129In 611 MS	130In 0.29 S	131In 0.28 S		133In 165 MS	134in 140 MS	135in 92 MS
β∹ 100.00% β-n≤ 0.03% 6575	β∹ 100.00% β-n < 0.46% 9.22E+3	β-: 100.00% β-n: 0.23% 7753	β-: 100.00% β-n: 0.93% 1.025E+4	β∹ 100.00% β-ns 2.00% 9240	β 100.00% β-α. 6.30% 1.414E+4	B- 100.00% D-n. 85.00% 1.341E+4	8-100.00% P-tt 65.00% 1.48E+4	β~ 100.00% β-n 1.412+4



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)				
	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?								
Beam intensity/purity,									
targets-ion sources	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									
Safaty	Jse of lasers is currently rest	ricted at CRIS, follow up							
Salety	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								
TAC recommendation	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) 23



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.



Acknowledgements



M. Athanasakis-Kaklamanakis^{1,2}, S. Bai³, Y. Balasmeh², A. Candiello², T. E. Cocolios², J. Dobaczewski⁴, R. P. de Groote², A. Dorne², K. T. Flanagan^{5,6}, C. Fajardo², R. F. Garcia Ruiz⁷, G. Georgiev⁸, D. Hanstorp⁹, J. D. Holt¹⁰, J. Karthein⁷, U. Köster¹¹, Á. Koszorús¹, L. Lalanne², R. Lica¹², Y. Liu³, K. M. Lynch⁵, A. McGlone⁵, T. Miyagi¹³, G. Neyens², M. Nichols⁹, F. C. Pastrana Cruz⁷, S. Pelonis², H. Perrett⁵, J. R. Reilly⁵, J. Trujillo², B. van den Borne², A. R. Vernon⁷, S. Wang³, J. Wessolek^{5,14}, X. F. Yang³

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