

Collinear resonance ionization spectroscopy of silver between *N*=50 and *N*=82

Ruben P. de Groote, University of Jyväskylä and Helsinki Institute of Physics, Finland on behalf of the CRIS collaboration INTC meeting June 2020



Outline

Physics case

• Experimental setup

Beamtime request/ TAC comments



		SU SU	100Sn 1.16s	101Sn 1.97 s	102Sn 3.8 s	103Sn 78	¹⁰⁴ Sn 20.8 s	¹⁰⁵ Sn 34 s	106Sn 1152 s	¹⁰⁷ Sn 174 s	108Sn 10.3 m	109SN 18 m	110Sn 4.154.h	111Sn 35.3 m	112Sn	113Sn 115.09d	114Sn	¹¹₅Su	¹¹⁵Sn	117Sn	¹¹³Sn	119Sn	120Sn	121Sn 27.03 h	122Sn	¹²³ Sn 129.2 d	124Sn	125Sn 9.64 d	¹²⁶ Sn 290 ky	¹²⁷ Sn 126 m	¹²⁸ Sn 59.07 m	¹²⁹ Sn 133.8 s	¹³⁰ Sn 223.2 s	¹³¹ Sn 56 s	132Sn 39.7 s
^а ђп 100-ш	97 n 50 ms	98 n 37 ma	⁰⁰ In 3.1 s	¹⁰⁰ In 583 s	¹⁰¹ In 15.1 s	¹⁰² In 23.3 s	¹⁰³ In 60 s	104 n 108 s	¹⁰⁵ In 5.07 m	¹⁰⁶ In 6.2 m	¹⁰⁷ In ^{32.4 m}	¹⁰⁸ In 58 m	¹⁰⁹ 1 4.167 h	¹¹⁰ In 4.92 h	¹¹¹ In 67.3512 h	¹¹² IN 14.88 m	113In	¹¹⁴ In ^{71.9} s	115 n 441 Ty	116 n 141 s	¹¹⁷ In 43.2 m	118 n 55	¹¹⁹ In 144 s	¹²⁰ In 3.08 s	¹²¹ In ^{23,1} s	¹²² In 1.5 s	¹²³ in 6.17 s	¹²⁴ In 3.12 s	125 n 236 s	¹²⁶ in 1.53 s	¹²⁷ In 1.09 s	¹²⁸ In 816 ms	¹²⁹ In 570 ms	¹³⁰ In ²⁸⁴ ms	¹³¹ In 261 ms
95Cd 90ms	96Cd 880 ms	97Cd	98Cd 9.2.8	99Cd	¹⁰⁰ Cd 49.1 s	¹⁰¹ Cd 81.6 s	¹⁰² Cd 5.5 m	¹⁰³ Cd 7.3 m	¹⁰⁴ Cd 57.7 m	¹⁰⁵ Cd 55.5 m	106Cd	107Cd 6.511	¹⁰®Cd	¹⁰⁹ Cd 1.2637919 y	¹¹ºCd	111Cd	112Cd	¹¹³ Cd 8.04 Py	114Cd	¹¹⁵ Cd 53.46 h	¹¹⁶ Cd 28.7 By	¹¹⁷ Cd 149.4 m	¹¹⁸ Cd 50.3 m	119Cd 161.4a	¹²⁰ Cd 50.8 s	¹²¹ Cd 13.5 a	¹²² Cd 5.24 s	¹²³ Cd 2.1 s	¹²⁴ Cd 1.25 s	¹²⁵ Cd 680 ms	¹²⁶ Cd 513 ms	¹²⁷ Cd 330 ms	¹²⁸ Cd 246 ms	¹²⁹ Cd 151.5 ms	¹³⁰ Cd 126.8 ma
94Ag 37 ma	95Ag 1.76 s	96Ag 4.443	97Ag 25.5 s	98Ag 47.5 s	90Ag 124.2 s	100Ag 120.6 s	¹⁰¹ Ag 11.1 m	¹⁰² Ag 12.9 m	103Ag 65.7 m	¹⁰⁴ Ag 69.2 m	¹⁰⁵ Ag 41.298	¹⁰⁶ Ag 23.96 m	¹⁰⁷ Ag	¹⁰⁸ Ag 142.92 s	109Ag	¹¹⁰ Ag 24.56 s	¹¹¹ Ag 7.433 d	¹¹² Ag 187.8 m	113Ag 5.37 h	114Ag 4.65	¹¹⁵ Ag 20 m	¹¹⁶ Ag 229.8 s	117Ag 73.65	118Ag 3.76 s	110Ag 63	¹²⁰ Ag 1.52 s	¹²¹ Ag 780 ms	¹²² Ag 529 ms	123Ag 300 ma	¹²⁴ Ag 177.9 ms	¹²⁵ Ag 199 ms	126Ag 99.3 ma	¹²⁷ Ag ^{80 ma}	¹²⁸ Ag 50 ma	¹²⁹ Ag 49.9 ms
93Pd 1.15 s	°"Pd	95Pd 7.5 s	96Pd 122 s	97Pd 186 s	⁹⁸ Pd 17.7 m	99Pd 21.4 m	¹⁰⁰ Pd 87.12 h	¹⁰¹ Pd 8.47 h	¹⁰² Pd	¹⁰³ Pd 16.991 d	104Pd	¹º⁵Pd	106Pd	¹⁰⁷ Pd 6.5 My	108Pd	¹⁰⁹ Pd 13.7012 h	110Pd	¹¹¹ Pd 23.4 m	¹¹² Pd 21.04 h	113Pd 93 s	¹¹⁴ Pd 145.2 s	115Pd 25 s	116Pd 11.84	117Pd 43 s	118Pd 1.94	¹¹⁹ Pd 920 ms	¹²⁰ Pd 492 ma	¹²¹ Pd 290 ms	¹²² Pd 195 ms	¹²³ Pd 108 ms	¹²⁴ Pd 88 ms	¹²⁵ Pd 57 ms	¹²⁶ Pd 48.6 ms	¹²⁷ Pd 38 ma	¹²⁸ Pd 35 ms
92Rh 4.66 s	93Rh 13.9 s	94Rh 70.6 \$	95Rh 5.02 m	⁹⁶ Rh 9.9 m	⁹⁷ Rh ^{30,7 m}	98Rh 8.72 m	99Rh 16.1 d	¹⁰⁰ Rh 20.8 h	¹⁰¹ Rh 33y	102Rh 207 d	¹º³Rh	104Rh 42.3 s	105Rh 35.357 h	¹⁰⁶ Rh 30.07 s	¹⁰⁷ Rh 21.7 m	108Rh 16.8 s	¹⁰⁹ Rh 80 s	110Rh 3359	111Rh 112	112Rh 3.49	¹¹³ Rh 289	114Rh 1.85 s	115Rh 990 ms	116Rh 685 ms	¹¹⁷ Rh 421 ma	¹¹⁸ Rh 284 ms	119Rh 190 ms	¹²⁰ Rh 129.6 ms	¹²¹ Rh 76 ms	¹²² Rh 51 ms	¹²³ Rh ^{42 ms}	¹²⁴ Rh ^{30 ms}	125Rh 26.5 ms	¹²⁶ Rh ^{19 ms}	¹²⁷ Rh ^{28 ms}

Physics case

- Dipole moments
 - / Strength of shell closures, ordering of shell model orbits
 - / Establish leading configuration (esp. for odd-odd)
 - / Comparison with indium: role of collectivity

In data: C. Binnersley, A. Vernon, PhD Thesis, and in preparation for publication



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 - / Strength of shell closures, ordering of shell model orbits
 - / Establish leading configuration (esp. for odd-odd)
 - / Comparison with indium: role of collectivity
- Quadrupole moments
 - / Reflect collectivity in neutron mid-shell
 - / Decrease towards N=50, N=82: investigate strength of shell closure

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Charge radii: deformation, shell closures, manybody correlations, ...

- Dipole moments
- Quadrupole moments
- Nuclear charge radii
 - / Complimentary information on nuclear deformation, strength of shell closures
 - / Odd-even staggering: requires every isotope and longlived state to be measured; contains information on many-body correlations and local structure effects [1]
 - / Existing data obtained with various methods and optical transitions: systematics need to be tied together in a consistent way!





Charge radii: shell closures and deformation

- Dipole moments
- Quadrupole moments
- Nuclear charge radii
- Nuclear spins and unambiguous state identification, info on configuration...
 - / Especially for neutron-rich odd-odd isotopes, rich landscape of isomers with high spins
 - / Recent measurements at IGISOL found new isomers and erroneous spin assignments in literature
- Sets the stage also for future work towards ⁹⁴Ag



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We propose to measure these properties for 31 isotopes, ~70 nuclear states

Note on 'remeasurements': not all observables/all states studied in literature!

In general, these observables are good probes for nuclear structure and serve to test nuclear theory!

Chiral effective field theory, and density functional theory, large-scale shell model, ...



Experimental setup



MagneToF **Collinear resonance ionization spectroscopy** detector Interaction region Field Ions 🔗 $< 10^{-10}$ mbar ionisation grids Differential pumping 6 kVNeutralisation 33 Dumped Rydberg atoms 00 Ions atoms Dumped 0 kV ions Collisional ions Deflection into beamline 120 cm 30 cm

- High spectral resolution: precise and accurate
- High efficiency
- High suppression of background events
- Very flexible choice of atomic transitions



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- Copper homologue (similar atomic structure)
- down to 20 pps production rate

R. P. de Groote, et al. Nat. Phys. 16, 620–624 - 2020



Collinear resonance ionization spectroscopy



- High spectral resolution: precise and accurate
- High efficiency (V)
- High suppression of background events
- Very flexible choice of atomic transitions



- Indium: similar mass range, target, ion source, so same contaminants ¹⁰¹⁻¹³¹In studied
- successfully

MagneToF

detector

BK Sahoo, et al., New Journal of Physics 22 (1), 012001



Laser ionization schemes for silver

- Silver has been very well studied over the years
 - / RILIS element
 - / In-gas-cell @ Louvain-la-Neuve
 - / In-source spectroscopy @ IGISOL
- Specific case of CRIS:
 - / 328 + 421 + 1064: easily saturated, high efficiency.





Beamtime request

Beamtime request

- Shaded cases: new data can be obtained!
- For high-yield (>10⁵ pps), request is not statistica limited
 - Given rich isomerism and large hyperfine structure, 0.5 shifts per mass estimated on average (3 scans per isoto)
 - This includes time for reference measurements as well
- For lower yields, request based on previous experience at CRIS
 - Efficient laser ionization
 - Background well understood from indium expts.

able 1: Calculated in-target, experimental and predicted yields per μC using a UC _x
rget. Also listed is the number of states with a lifetime $> 1 \text{ ms}$. No shifts are requested
or $A < 98$ since those isotopes are likely easier to study using a La _x target.

Α	Nr. of states	ABRABLA calc	Expt.	Predicted yield	Shifts
94	3	-		< 0.1	-
95	4	-		< 1	-
96	2	-		< 10	-
97	2	$8.4 \cdot 10^2$		80	-
98	2	$1.6 \cdot 10^4$		$1.5 \cdot 10^{3}$	2
99	2	$2.8 \cdot 10^5$		$2.8 \cdot 10^4$	1
100	2	$1.5 \cdot 10^{6}$		$1.5 \cdot 10^5$	0.5
101	2	$1.0 \cdot 10^{7}$	$2.0 \cdot 10^{5}$	$1.0 \cdot 10^{6}$	0.5
102	2	$4.5 \cdot 10^{7}$		$4.5 \cdot 10^{6}$	0.5
103	2	$2.0 \cdot 10^8$	$1.6 \cdot 10^{6}$	$2.0 \cdot 10^{7}$	0.5
104	2	$5.9 \cdot 10^8$		$5.9 \cdot 10^{7}$	0.5
105	2	$1.3 \cdot 10^9$	$7.0 \cdot 10^{7}$	$1.3 \cdot 10^8$	0.5
106	2	$1.8 \cdot 10^9$	$7.0 \cdot 10^{7}$	$1.8 \cdot 10^8$	0.5
107	2	$3.4 \cdot 10^9$		$3.4 \cdot 10^8$	0.5
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109	2	$5.4 \cdot 10^9$	$6.0 \cdot 10^{8}$	$5.4 \cdot 10^8$	0.5
110	2	$4.7 \cdot 10^9$		$4.7 \cdot 10^8$	0.5
111	2	$6.4 \cdot 10^9$	$4.0 \cdot 10^{9}$	$6.4 \cdot 10^8$	0.5
112	1	$4.7 \cdot 10^9$	$2.3 \cdot 10^{9}$	$4.7 \cdot 10^8$	0.5
113	2	$6.3 \cdot 10^9$	$2.0 \cdot 10^{9}$	$6.3 \cdot 10^8$	0.5
114	2	$4.6 \cdot 10^9$	$1.0 \cdot 10^{9}$	$4.6 \cdot 10^8$	0.5
115	2	$5.4 \cdot 10^9$	$1.8 \cdot 10^{8}$	$5.4 \cdot 10^8$	0.5
116	3	$3.6 \cdot 10^9$		$3.6 \cdot 10^8$	0.5
117	2	$3.8 \cdot 10^9$	$7.0 \cdot 10^{8}$	$3.7 \cdot 10^8$	0.5
118	3	$1.9 \cdot 10^{9}$		$1.7 \cdot 10^{8}$	0.5
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121	2	$3.1 \cdot 10^8$	$3.0 \cdot 10^{7}$	$2.1 \cdot 10^{7}$	0.5
122	3	$7.6 \cdot 10^7$		$4.3 \cdot 10^{6}$	0.5
123	2	$3.5 \cdot 10^{7}$		$1.2 \cdot 10^{6}$	0.5
124	2-3?	$8.5 \cdot 10^{6}$		$1.4 \cdot 10^5$	0.5
125	2	$6.1 \cdot 10^{6}$		$1.0 \cdot 10^{5}$	0.5
126	2-3?	$1.5 \cdot 10^{6}$		$6.4 \cdot 10^2$	4
127	2	$6.5 \cdot 10^5$		$1.4 \cdot 10^{3}$	3
128	1-3?	$1.1 \cdot 10^5$		62	5
129	2	$1.3 \cdot 10^4$	1	1	7
				Total	35

Beamtime request

- In summary: two experiments, both with fresh UC_x
 - Run 1: explore exotic isotopes and cover wide mass range: check internal systematics and tie data in with all literature datasets
 - Run 2: dedicated to most challenging cases, with overlap with run 1 for systematics
 Measurements on less exotic cases are required to define the experimental uncertainties and evaluate systematics!
- Neutron-deficient isotopes: yields for deficient isotopes would be better with LaC_x, BUT:
 - For all except 98,99 shift request is not statistically limited anyway
 - Two UC_x runs in any case required
 - Future proposal/addendum: as n-deficient as possible + a few overlapping cases for systematics

Table 1: Calculated in-target, experimental and predicted yields per μ C using a UC_x target. Also listed is the number of states with a lifetime > 1 ms. No shifts are requested for A < 98 since those isotopes are likely easier to study using a La_x target.

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TAC comments

- RILIS required for the experiment
 - / Different laser settings required for GS/isomers; we suggest dynamic changing of settings as CRIS measurements progress
 - / Same atomic transition is used for CRIS which will simplify this
 - / Previously, good experience for e.g. indium and radium proves this feasible
- Intensity of beams with high dose rates would be reduced to minimize contamination
 - / Intensity would be reduced to $\sim 10^5$ pps (also to mitigate cooler and DAQ saturation)
- Priorities and UC_x/LaC_x: addressed in previous slides
 - / 2x UC_x required
 - / In any case a third experiment would be needed for the n-deficient isotopes A<98



Some additional slides



Yield estimates

• Quoting TAC: "The yield estimate has been well prepared for the Ag chain from a UCx unit."



silver yields (UCx)

Data in literature

- ⁹⁶⁻¹⁰⁴Ag: only one out of two states have all moments and radii
- ¹⁰⁴⁻¹¹⁰Ag: either very imprecise/not all states/not all observables
- ¹¹⁵⁻¹²¹Ag: all states and all observables measured in literature

New physics to extract; all masses should be measured again

- At least three required for good systematic check (=> 3/6 shifts in any case required)
- Furthermore, several odd-odd where spin assignment requires much higher statistics
- Odd-even staggering requires all states and all masses to be measured consistently
- Even better control over internal systematics of CRIS measurements



Charge radii: shell closures and deformation

- Dipole moments
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 - / Ordering of shell model orbits
 - / Comparison with indium: role of collectivity
- Quadrupole moments
 - / Reflect collectivity in neutron mid-shell
 - / Decrease towards N=50, N=82: investigate strength of shell closure
- Nuclear charge radii
 - / Complimentary information on nuclear deformation
 - / Strength of shell closures



Field ionization at CRIS

- Rather than use high-power nonresonant step, excite to high-lying atomic state (Rydberg state)
- Strong E-field can then ionize the atom
- Advantage:
 - / No laser-induced background*
 - / Smaller ionization volume reduces collisional background
 - / Total: factor 5 obtained offline; further improvement up to a few 100 will be pursued

* Previous campaigns on indium with 1064 nm laser not limited by this background, and for silver we go for lower mass numbers



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- First steps already made offline @ IGISOL

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