Recent results from collinear resonance ionization spectroscopy (CRIS) at ISOLDE-CERN

Adam R. Vernon
(K.U. Leuven/CERN-ISOLDE)
On Behalf of the CRIS collaboration

Recent results from collinear resonance ionization spectroscopy (CRIS) at ISOLDE-CERN **(mostly neutron-rich indium isotopes)**

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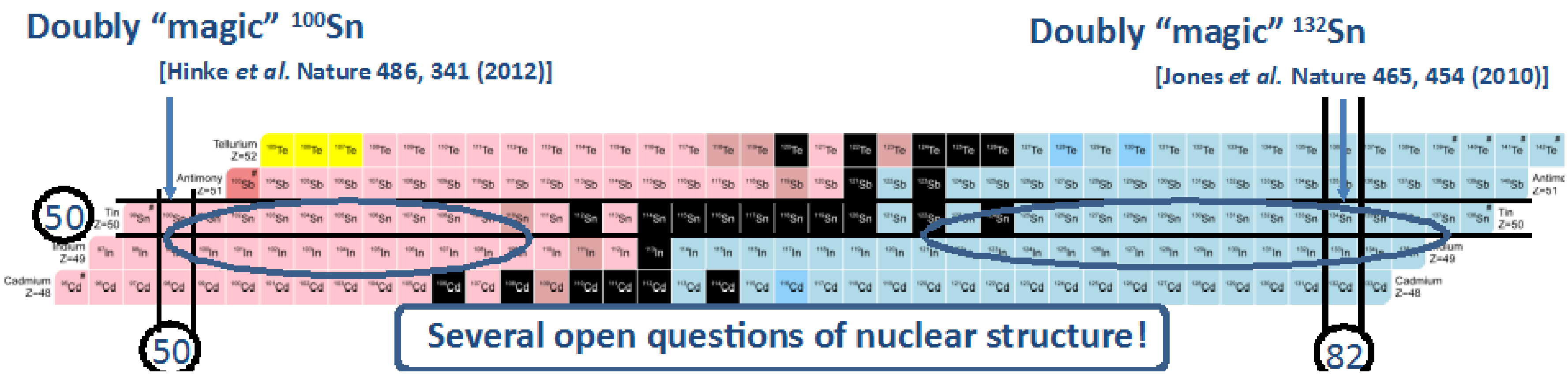
Overview

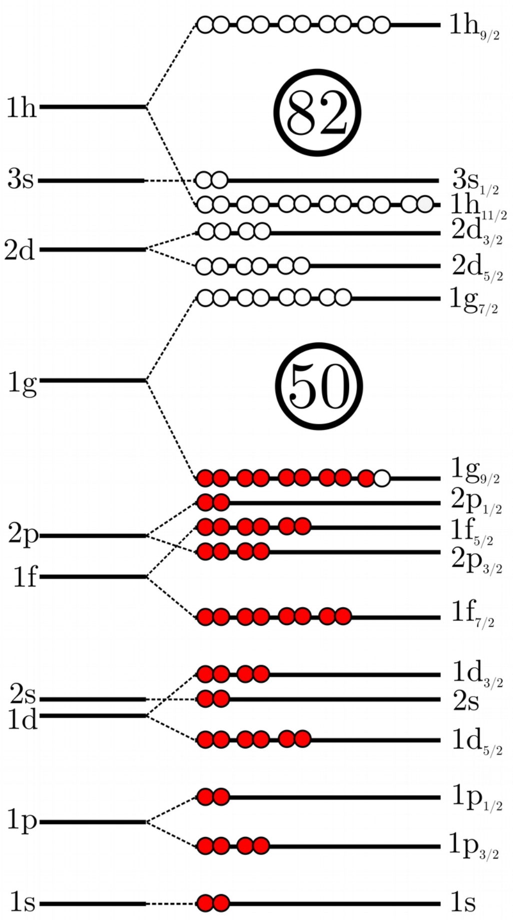


Proposals:
111-131In (Z=49): CERN-INTC-2017-025 (2017)
100-111In (Z=49): CERN-INTC-2017-055 (2017)
103-121Sn (Z=50): .CERN-INTC-2016-037 (2016)

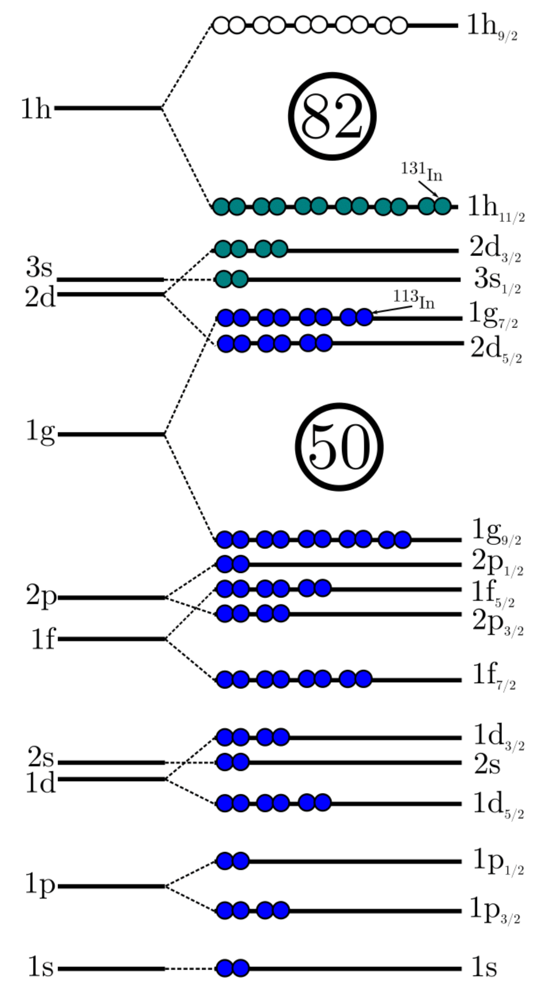
Robustness of N=Z=50, N=82 shell closures
Shell evolution towards N=Z=50, N=82
Ordering of shell-model orbit configurations
Proton-neutron correlations

Theoretical calculations around Z = 50 :
CC and IM-SRG - [T. D. Morris *et al.*, *Phys. Rev. Lett.*, vol. 120, no. 15, p. 152503, Apr. 2018.]
LSSM - [T. Togashi, Y. Tsunoda, T. Otsuka, N. Shimizu, and M. Honma, *Phys. Rev. Lett.*, vol. 121, no. 6, p. 062501, Aug. 2018.]

Indium (Z = 49) overview

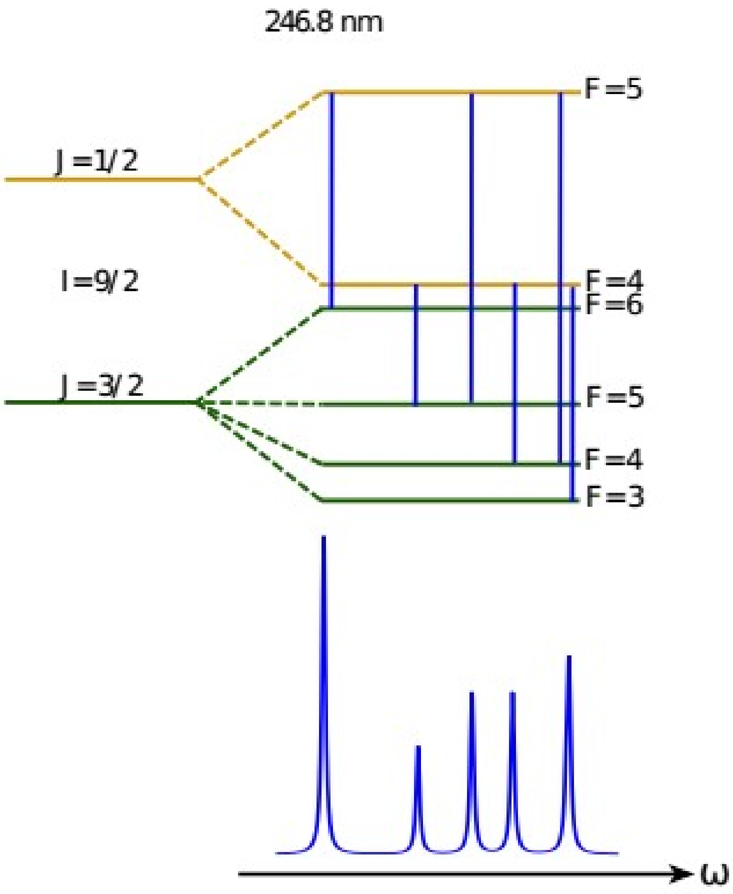


- Adjacent to Z = 50 shell closure
- Odd-Even In
  - $\pi g_{9/2}$ proton hole
  - Or $\pi p_{1/2}$ proton hole isomer
- Odd-Odd In
  - $\nu 1g_{7/2} \rightarrow \nu 3s_{1/2}$ couple with the proton holes
- Many high-spin isomers
- Evolution of nuclear structure properties N=50 to N=82 with proton (hole)-neutron interaction



Hyperfine structure

- Atomic energy levels are split by the interaction nuclear magnetic dipole moment μ or by nuclear electric quadrupole moment Q interacting with the electron fields
- the nuclear spin I and electronic spin J to couple to create F energy levels
- Isotope shifts give changes in mean square charge radii $\delta\langle r^2\rangle$



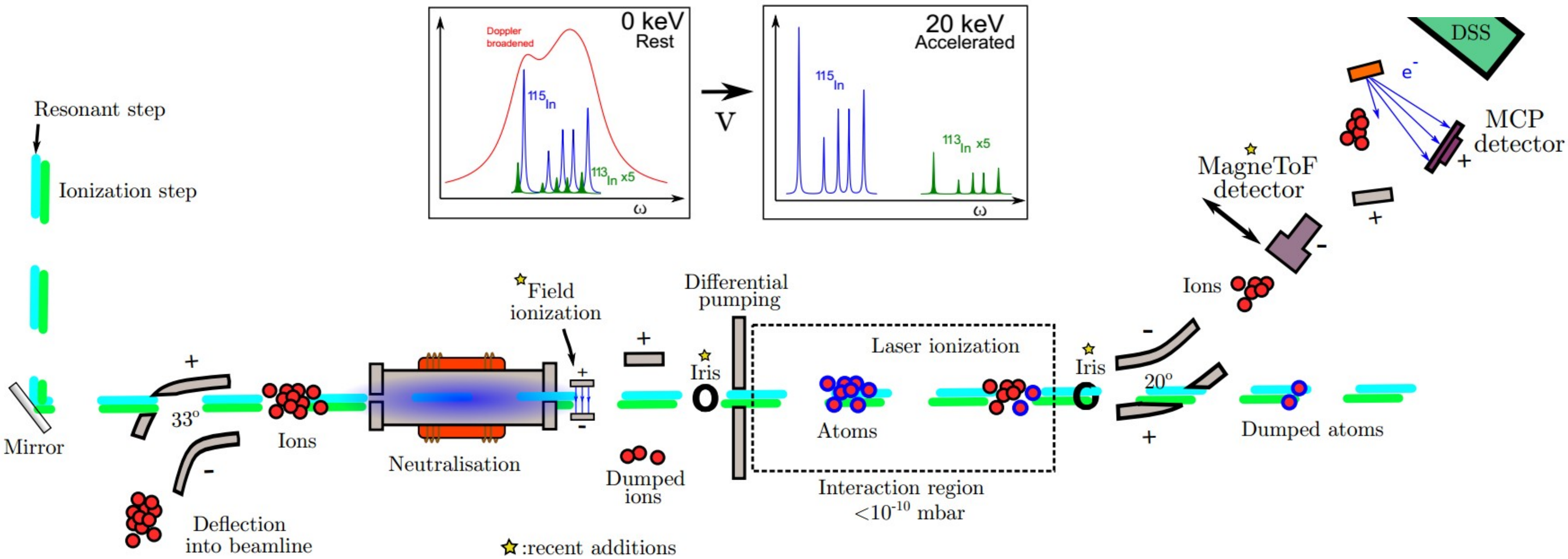
$$\Delta E_{HFS} = \Delta E_D + \Delta E_Q$$
$$= \frac{A}{2}C + \frac{B}{4}\frac{\frac{3}{2}C(C+1) - 2IJ(I+1)(J+1)}{IJ(2I-1)(2J-1)}$$

$$A = \mu\frac{B_e(0)}{IJ}$$

$$B = eQ_S\left\langle \frac{\partial^2 V}{\partial z^2}\right\rangle$$

Laser Spectroscopy using CRIS

- Combines the high-resolution of a collinear fast beam atom-laser geometry with the high-detection efficiency of ions after resonance ionization
- Also benefits from collecting the re-ionized species for decay spectroscopy
- Uses an ion cooler buncher (ISCOOL) to reduce energy spread and increase atom-laser overlap efficiency



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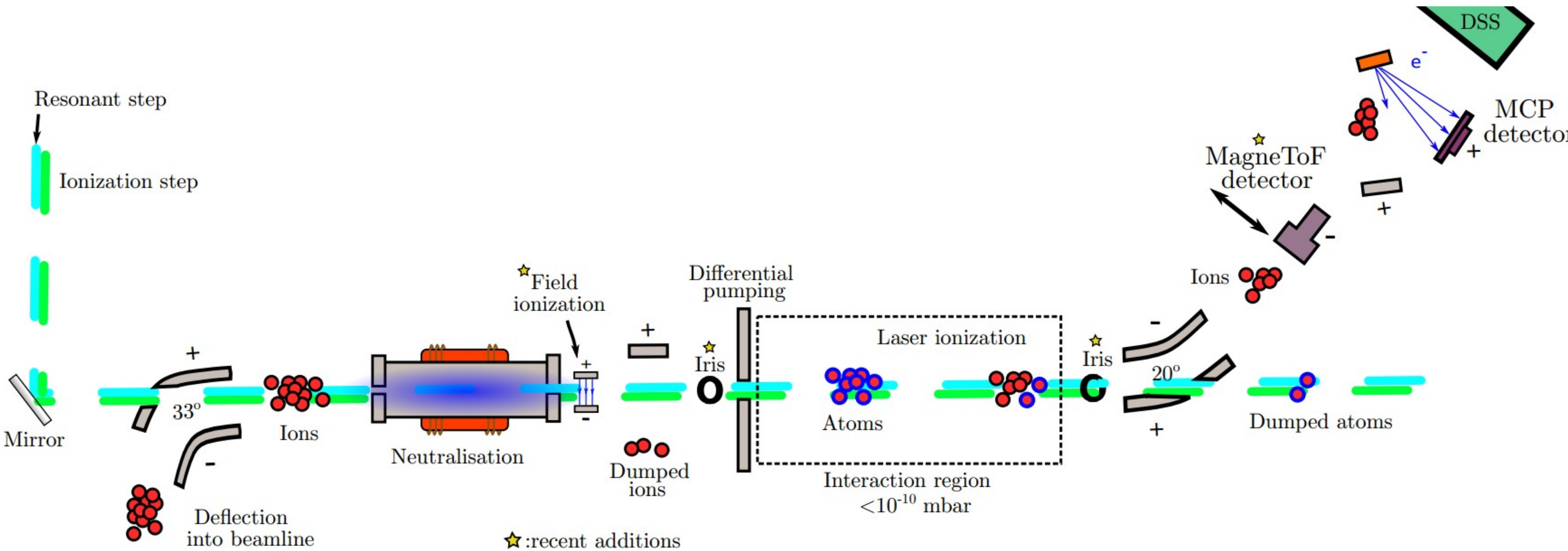

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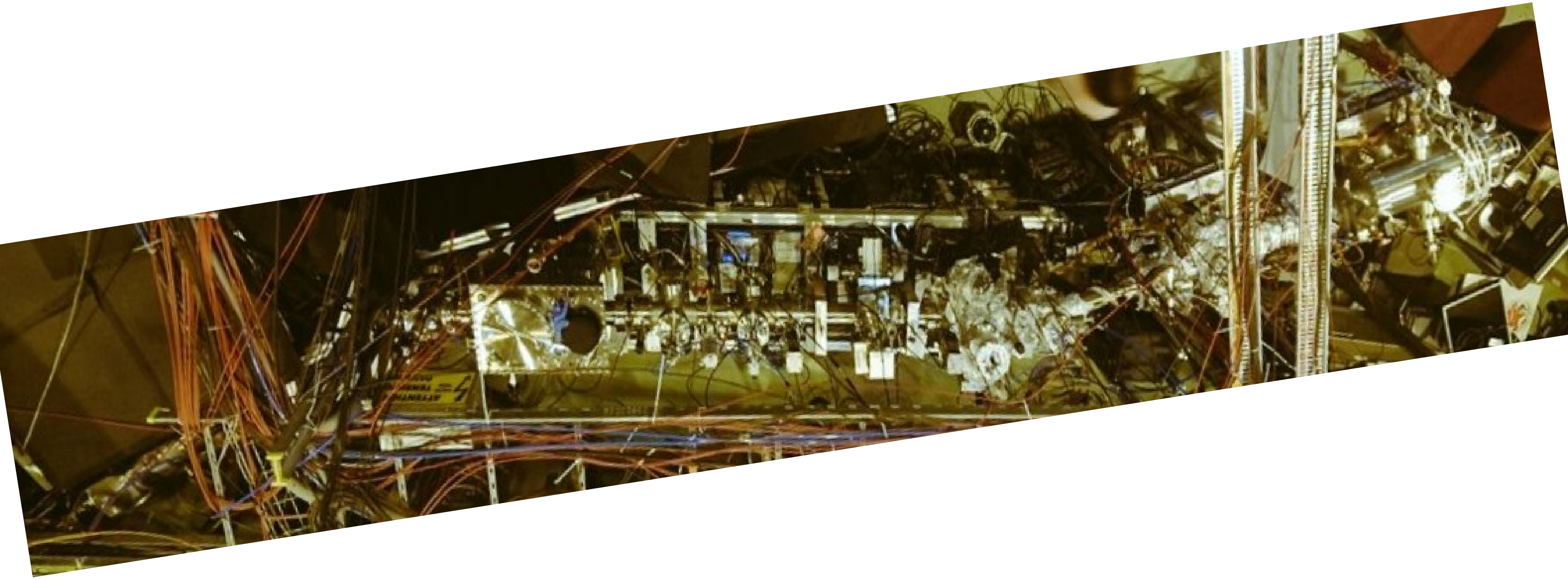
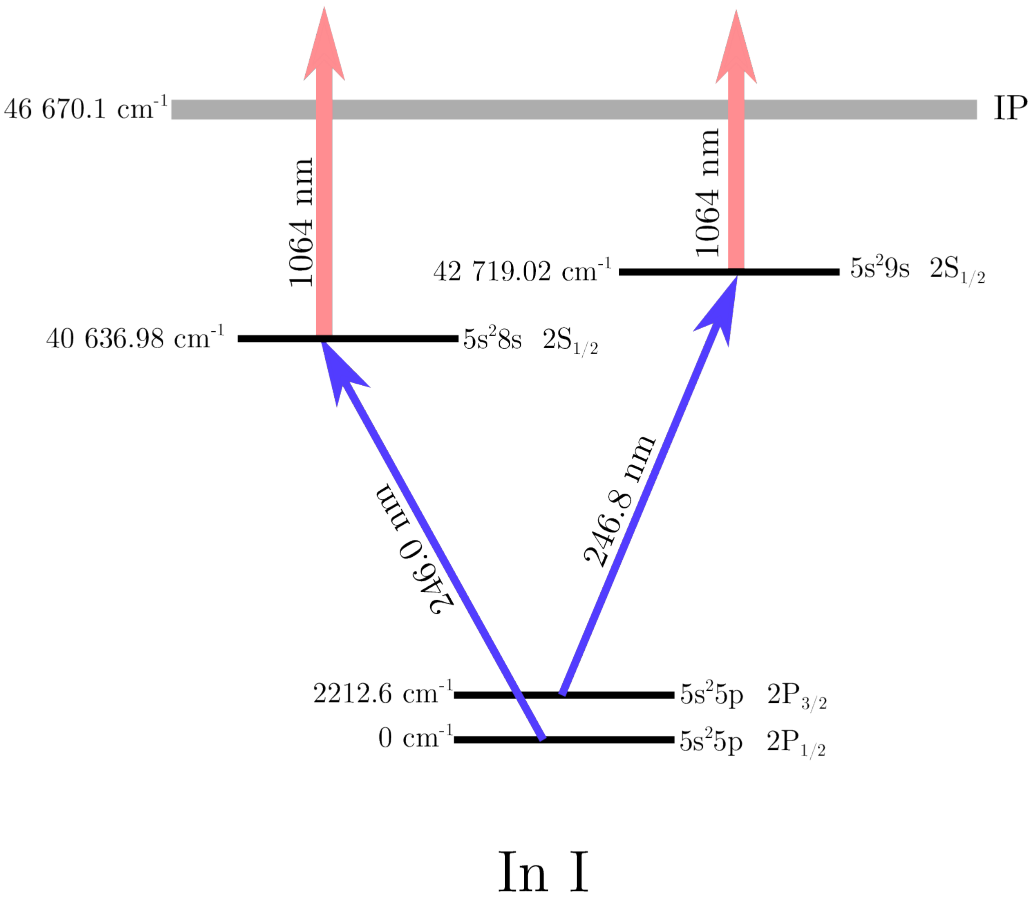


The laser ionization schemes



Measured using two transitions:

246.8 nm

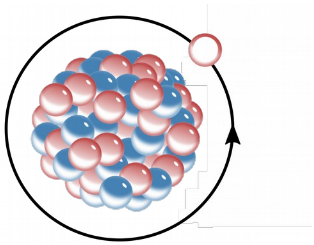
- $P_{3/2} \rightarrow S_{1/2}$ sensitive to I, μ, Q

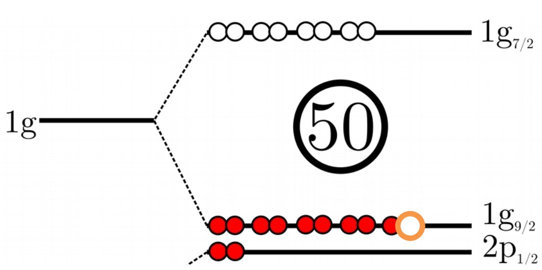
246.0 nm

- $P_{1/2} \rightarrow S_{1/2}$ unaffected by Q
- Large A splitting, acts as a constraint for μ and aids in resolving structure

Motivation

- Remarkably constant μ value 105 ≤ A ≤ 127 for the I=9/2+ state of the proton hole
- Single particle calculations for the odd-particle appear to reproduce the trend well (hole plus vibrating core shell model)
- Contribution from collective excitations of even-even Sn core considered to be very small
- The evolution of this "single-particle" trend towards N=82 will then give insight into its origin and the role collectivity is playing, if any





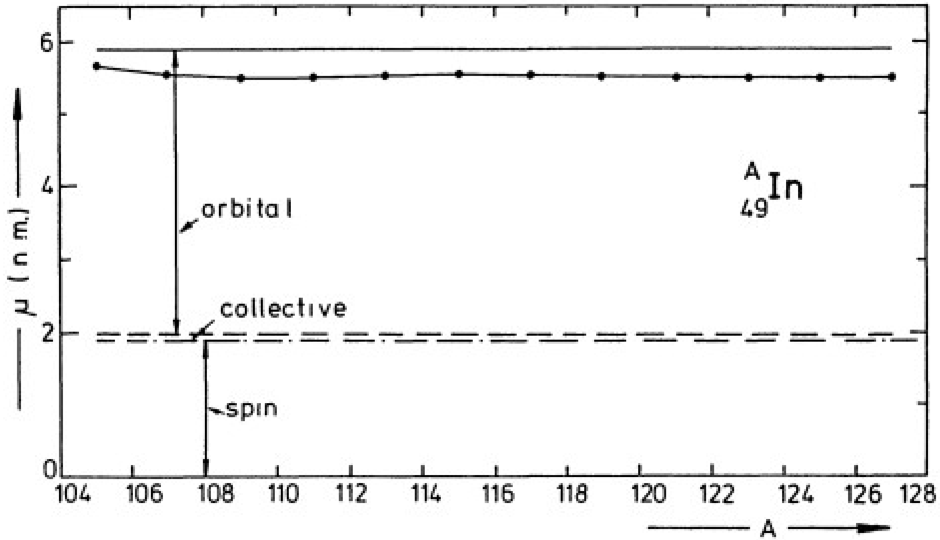
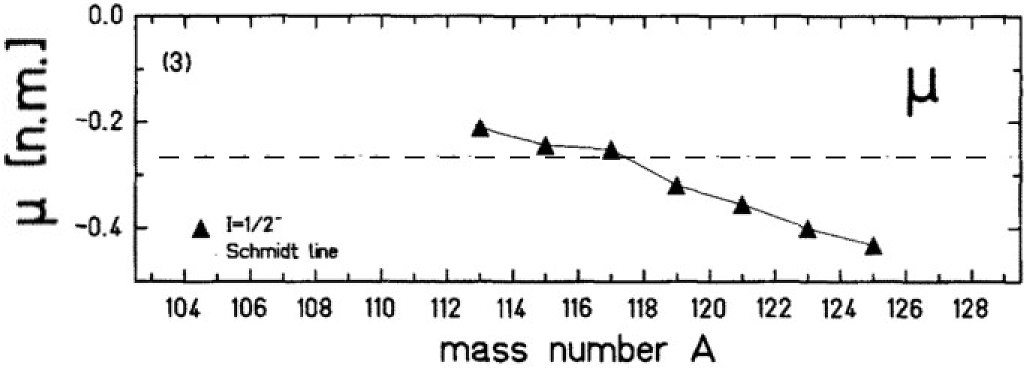


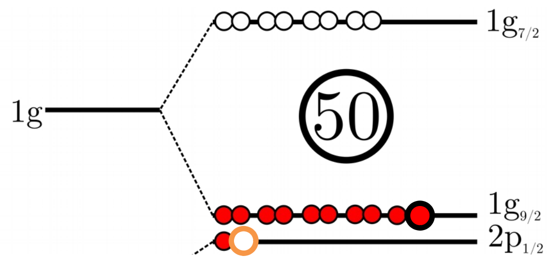
Fig. 4.11. The experimental dipole moments (μ_N) in the odd-A In nuclei with a single-hole moving in the $1g_{9/2}$ orbital below the $Z = 50$ shell closure [data taken from (Eberz 1987)]. The theoretical values [the separate contributions from orbital (g_l), spin (g_s) and collective admixtures] are shown (using $g_l = 1\mu_N$, $g_s^{\text{eff}} = 0.7 g_s^{\text{free}}$). The theoretical values have been derived in (Heyde 1978)

[Fig. 4.11 - Heyde, K. L. G. The nuclear shell model. (Springer-Verlag, 1994)]

Motivation



- The πp1/2 orbital is insensitive to first-order configuration mixing/core polarisation
- Deviation due to MECs or higher-order mixing?



$$\delta\mu \propto \frac{(l-1)l_1}{(2l+1)(2l_1+1)} \longrightarrow 0$$

"Still, the unusual magnetic moments of the $I=\frac{1}{2}$ isomeric states represent an unresolved puzzle and may require a reconsideration of the overall nuclear structure of these isotopes." -[Eberz, J. et al. Nucl. Phys. A 464, 9–28 (1987)]

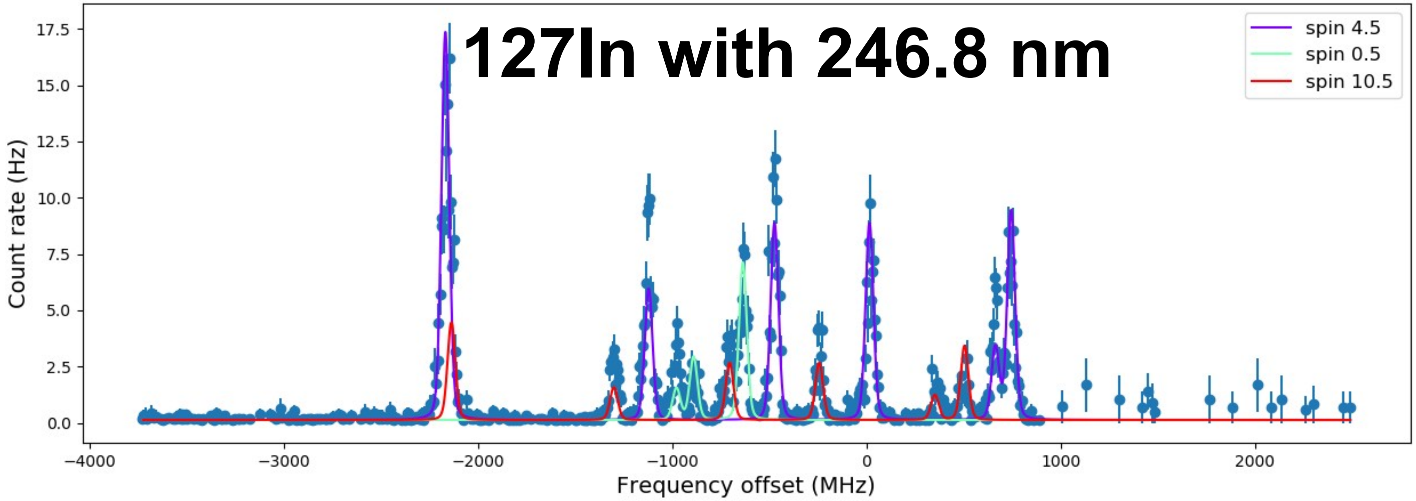
1st order config. mixing - [Arima, A. & Horie, H Prog. Theor. Phys. 12, 623–641 (1954)]

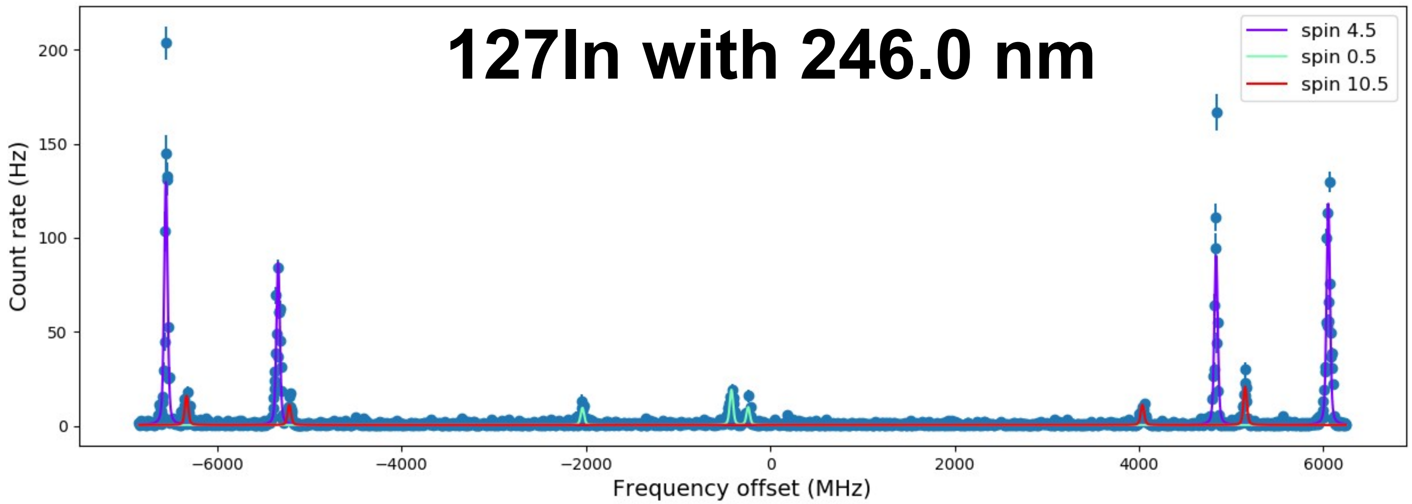
New results ($^{113\text{-}131}$In)

$^{113\text{-}131}$In →

- x26 new isomer shifts (**$\delta\langle r^2\rangle^{g,m}$**),
- x16 new **μ**s,
- x14 new **Q**s,
- x4 new isotope shifts (**$\delta\langle r^2\rangle^{A,A'}$**)

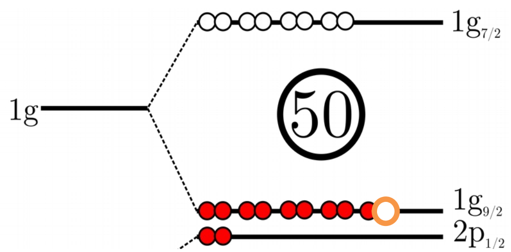
New results ($^{113\text{-}131}$In)





$I = \frac{9}{2}^{+}$ magnetic dipole moments

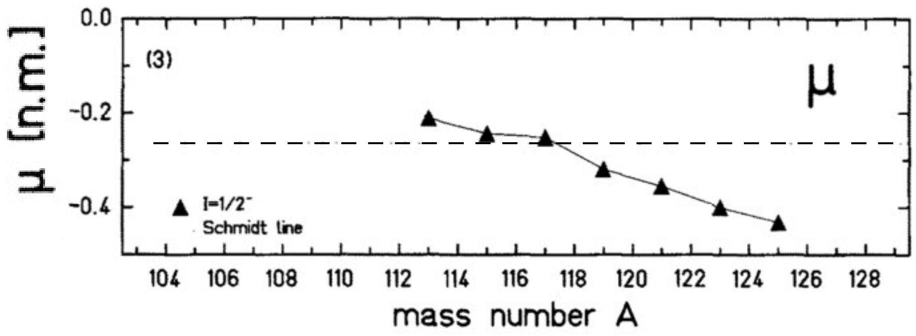
- Previously the constant μ value was reproduced by hole + vibrating core model with $g_{eff}=0.7g_{free}$
- More recent phonon-coupling excitation models also do not predict the abrupt change



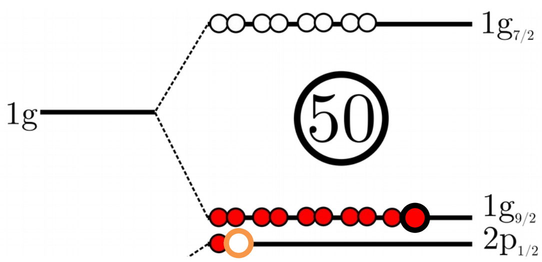
[E. E. Saperstein, et al. *EPL*, vol. 11, p. 42001 2013]
[Heyde, Phys. Rev. C 17, 1219–1243 1978]
[A.R. Vernon et al. - in preparation 2019]

$I = \frac{1}{2}^{-}$ magnetic dipole moments

- Unexpected crossing of the I =1/2- magnetic dipole moments across the Schmidt value is reversed and is significantly reduces at the shell closure



[Eberz, J. et al. Nucl. Phys. A 464, 9–28 (1987)]

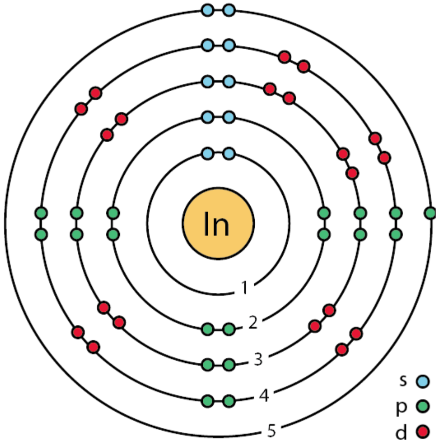


Benchmarking atomic factor calculations

- High accuracy calculations of the atomic parameters in indium is of interest to the atomic physics community for searches for eEDM searches
- Relativistic coupled-cluster calculations of the three-electron system of atomic indium were benchmarked with newly measured hyperfine magnetic dipole constants, A (8s, 9s) → gives an evaluation in the accuracy of the calculations
- Led to improved accuracy of the calculations used to evaluation the electric field gradients, needed for extraction of the nuclear quadrupole moments

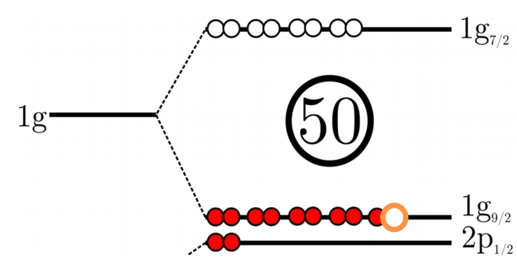
$$A = \mu \frac{B_e(0)}{IJ}$$

$$B = eQ_S \left\langle \frac{\partial^2 V}{\partial z^2} \right\rangle$$



[R. F. Garcia Ruiz, A.R. Vernon et al., “High-Precision Multiphoton Ionization of Accelerated Laser-Ablated Species,” *Phys. Rev. X*, vol. 8, no. 4, p. 041005, Oct. 2018.]
[**B. K. Sahoo**, R. Pandey, and B. P. Das, “Search for a permanent electric-dipole moment using atomic indium,” *Phys. Rev. A*, vol. 030502, no. 84, pp. 5–8, 2011.]

$I = \frac{9}{2}^{+}$ electric quadrupole moments



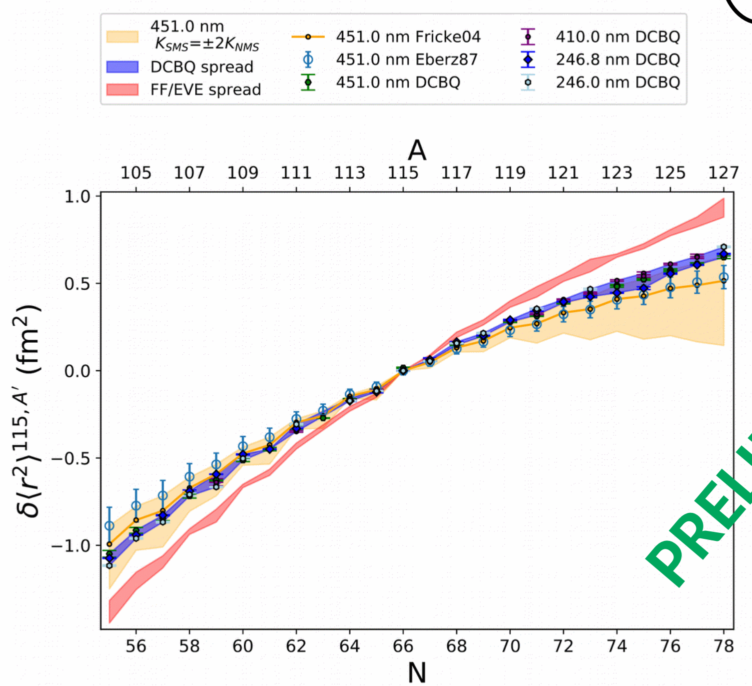
[E. E. Saperstein, et al. *EPL*, vol. 11, p. 42001, 2013.]
[Heyde, Phys. Rev. C 17, 1219–1243 (1978)]

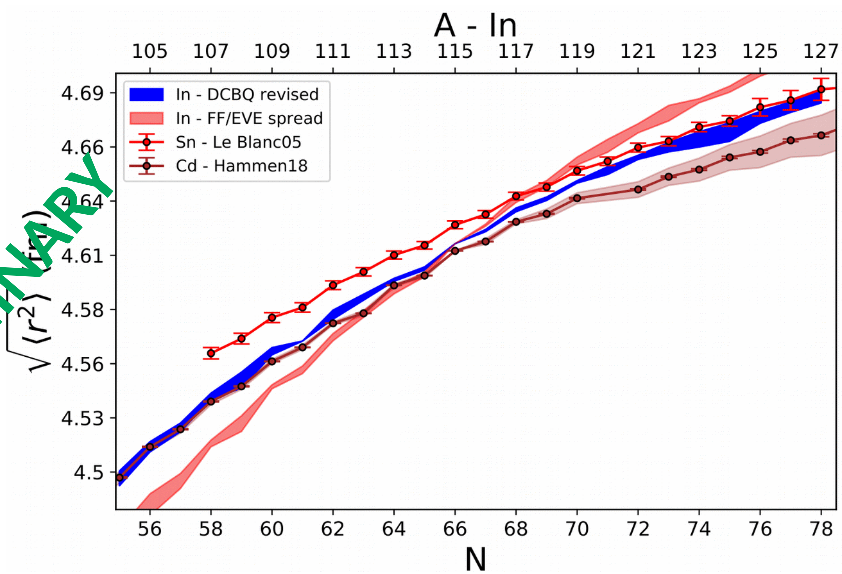
Extracting nuclear charge radii: isotope Shift factors for odd-Z isotopes

- Isotope shift factors in odd-Z nuclei rely on calculation, as the absolute charge radii of only few stable isotopes are available
- Isotope shift and high-precision isomer shift values allowed for isolation of field shift and specific mass shift contributions to the transitions used to measure indium
- Benchmarking on an ‘analytic response’ relativistic coupled-cluster method able to accurately calculate specific mass shift factors

$$\delta\nu^{A,A'} = \boxed{M}\frac{A'-A}{AA'} + \boxed{F}\delta\langle r^2\rangle^{A,A'}$$

M ← $K_{NMS} + K_{SMS}$

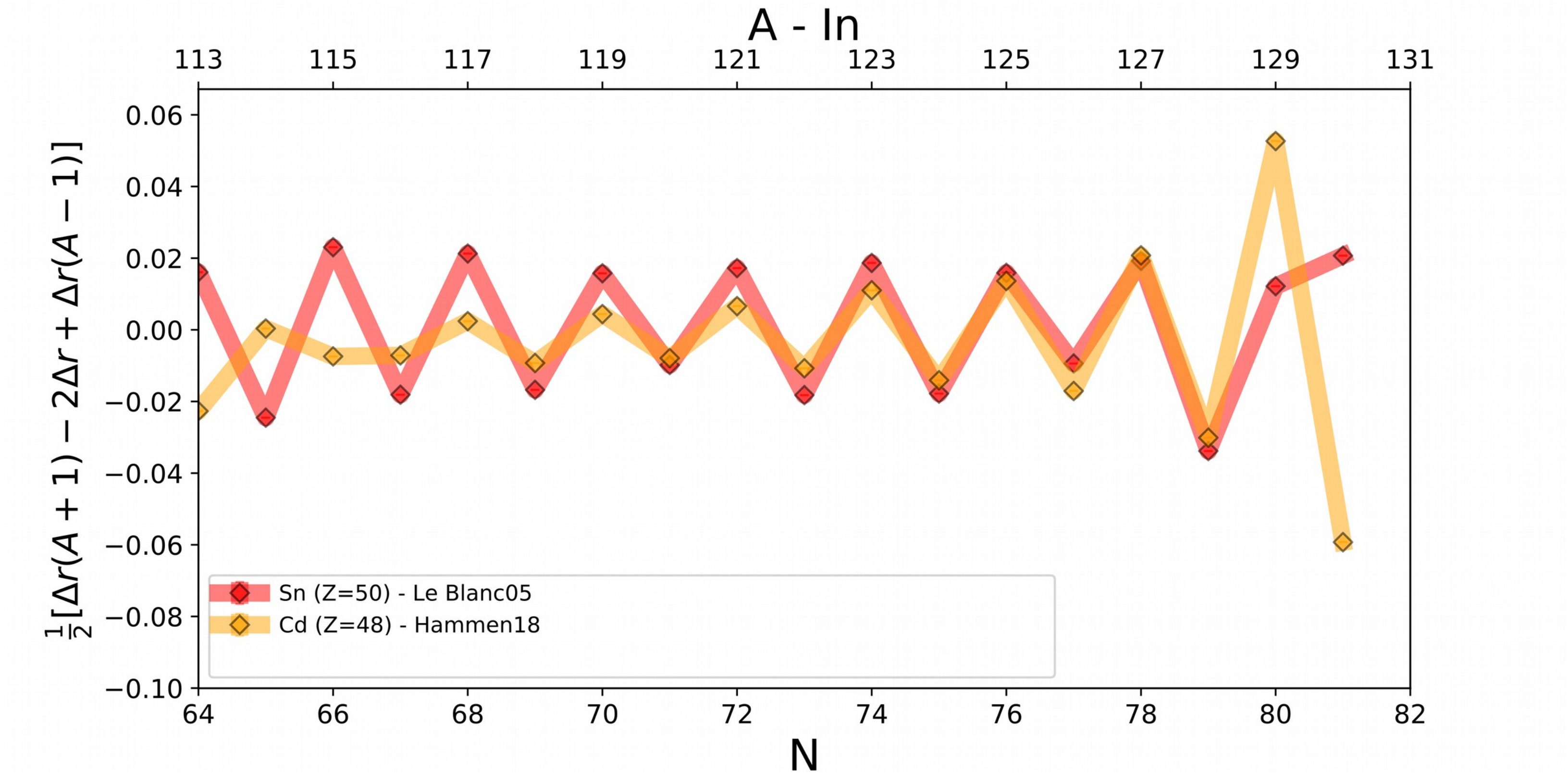




[B. K. Sahoo, A. R. Vernon et al., submitted PRL 2019.]

Odd-even staggering of nuclear charge radii

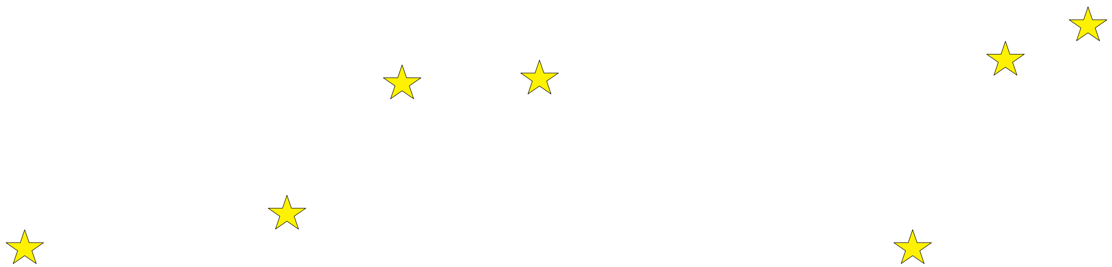
- Early disappearance of charge radii odd-even stagger previously seen in
- neighbouring Sn (Z = 50) but not Cd (Z = 48) isotopes
- Predicted to be at N=82 for Cd, but not yet measured



[M. Hammen *et al.*, *Phys. Rev. Lett.*, vol. 121, no. 10, p. 102501, 2018.]
[F. L. Le Blanc et al. Phys. Rev. C - Nucl. Phys., vol. 72, no. 3, pp. 1–7, 2005.]

Odd-even staggering of nuclear charge radii

- Early disappearance of OES observed for the indium ground states
- Observed to a lesser extent for the accompanying isomer chain



[M. Hammen *et al.*, *Phys. Rev. Lett.*, vol. 121, no. 10, p. 102501, 2018.]
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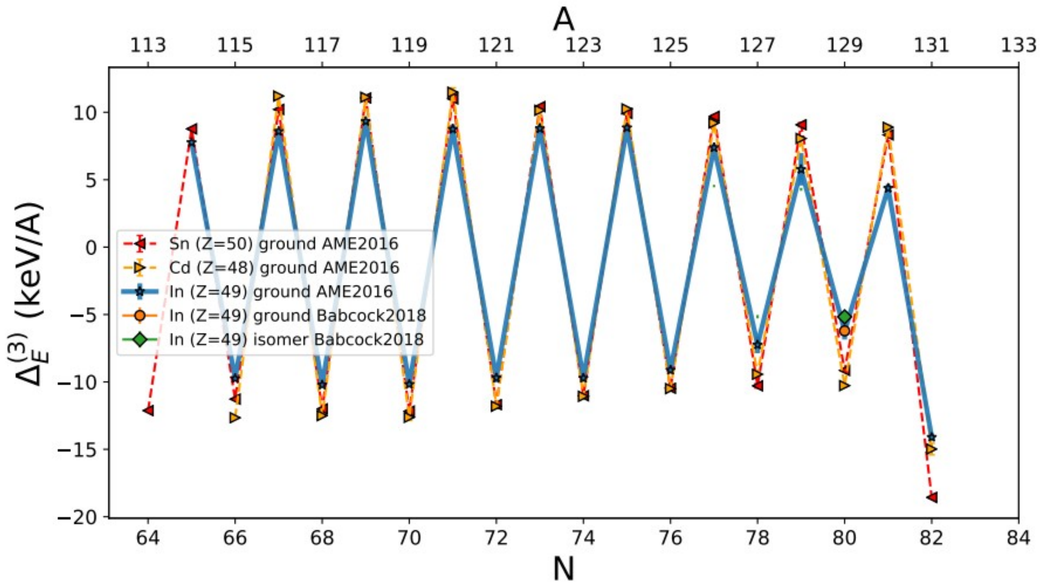


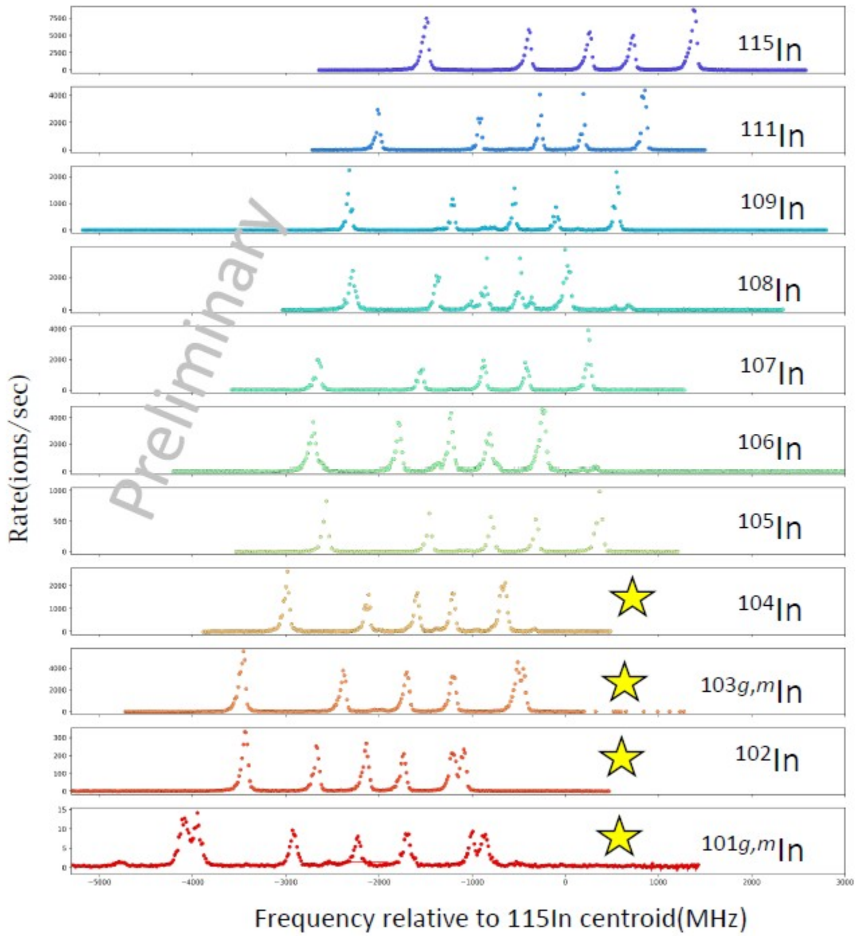
[M. Hammen *et al.*, *Phys. Rev. Lett.*, vol. 121, no. 10, p. 102501, 2018.]
[F. L. Le Blanc et al. Phys. Rev. C - Nucl. Phys., vol. 72, no. 3, pp. 1–7, 2005.]

Conclusions: Odd-mass neutron-rich indium isotopes

- Constant value of the I = 9/2 magnetic dipole moments shows first change in over 24 isotopes
  - What is the origin of the stability over the mid-shell and the abrupt onset?
- Trend of the I=1/2 magnetic dipole moment changes and passes the Schmidt value
  - Origin of the deviation in the I = 1/2 magnetic dipole moments still needs to be pinned down
- Calculation of challenging atomic factors has allowed the first nuclear data independent evaluation of the changes in the nuclear charge radii of indium
- Changes in OES
  - Pairing appears to be playing an important role
- Other nuclear observables not discussed:
  - Magnetic dipole moments, quadrupole moments of odd-odd indium isotopes and high spin isomers
  - Isomer charge radii
- Ab initio IM-SRG calculations for the electromagnetic moments and charge radii are underway for these isotopes

Neutron-deficient indium isotopes

- Aim of the experiment:
  - Extend In measurements to N=50 (99In)
- What we measured :
  - Hyperfine structures of 115-101In (N=52)
  - Again using the 246.0 nm and 246.8 nm transitions
  - New measurements of nuclear ground states and entirely new isotope measurements <105In
  - Unexpected isomer transitions at 102,101In



Talk by C. Ricketts following this one!

Neutron-rich potassium isotopes

- Aim of the experiment:
  - To measure 52,53K for the N=32, 34 shell closures
- What we measured :
  - Hyperfine structures of $^{38,41,42,47-51}$K using conventional ion detection
  - Hyperfine structure 52K using a newly constructed Beta detection station to suppress stable Cr contamination background (10^6 suppression)

PRELIMINARY

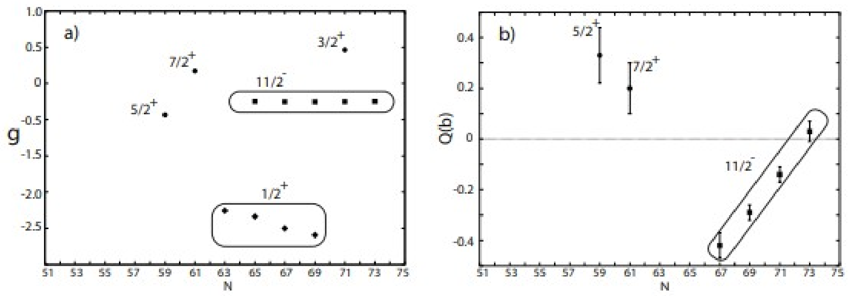
^{52}K

Hyperfine structure of ^{52}K obtained by detecting the beta decay of resonantly ionized ^{52}K isotopes

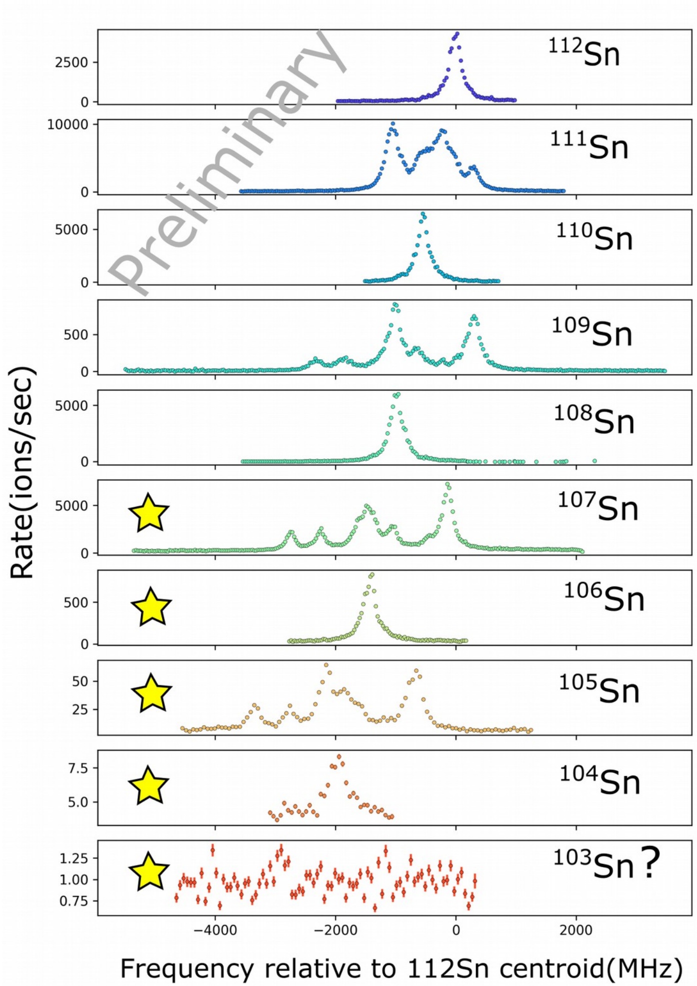
Analysis underway by A. Koszorus

Neutron-deficient tin isotopes

- Aim of the experiment:
  - Measurements towards N=50 shell closure
  - Ordering of neutron configurations νd5/2 -νg7/2 101-107Sn
  - Confirmation of simple trends in g-factors and electric quadrupole moments
- What we measured :
  - Hyperfine structures of 120-104Sn



Analysis underway by F. P. Gustavson



RaF molecular spectroscopy

Fluoride molecules offer high sensitivity for fundamental symmetry studies- enhanced in heavy octupole deformed nuclei

Aim of the experiment:

- Exploratory study for feasibility of collinear molecular measurements
- Measure the excitation energy of RaF from the vibrational ground states (1000 cm^{-1} uncertainty on theoretical prediction of energies)
- → more benchmarking of atomic theory!

~10^6 /s

^{226}RaF

~1000 cm^{-1} (30 THz) → <u>only 4 hours!</u>

[T. A. Isaev, S. Hoekstra, and R. Berger, “Laser-cooled RaF as a promising candidate to measure molecular parity violation,” Phys. Rev. A, vol. 82, no. 5, p. 52521, Nov. 2010]

RaF molecular spectroscopy

~10^6 /s

^{226}RaF

PRELIMINARY

~1000 cm^{-1} (30 THz) → <u>only 4 hours!</u>

^{223}RaF (T$_{1/2}$~11 days)

^{224}RaF (3 days)

^{225}RaF (15 days)

^{226}RaF (1600 y)

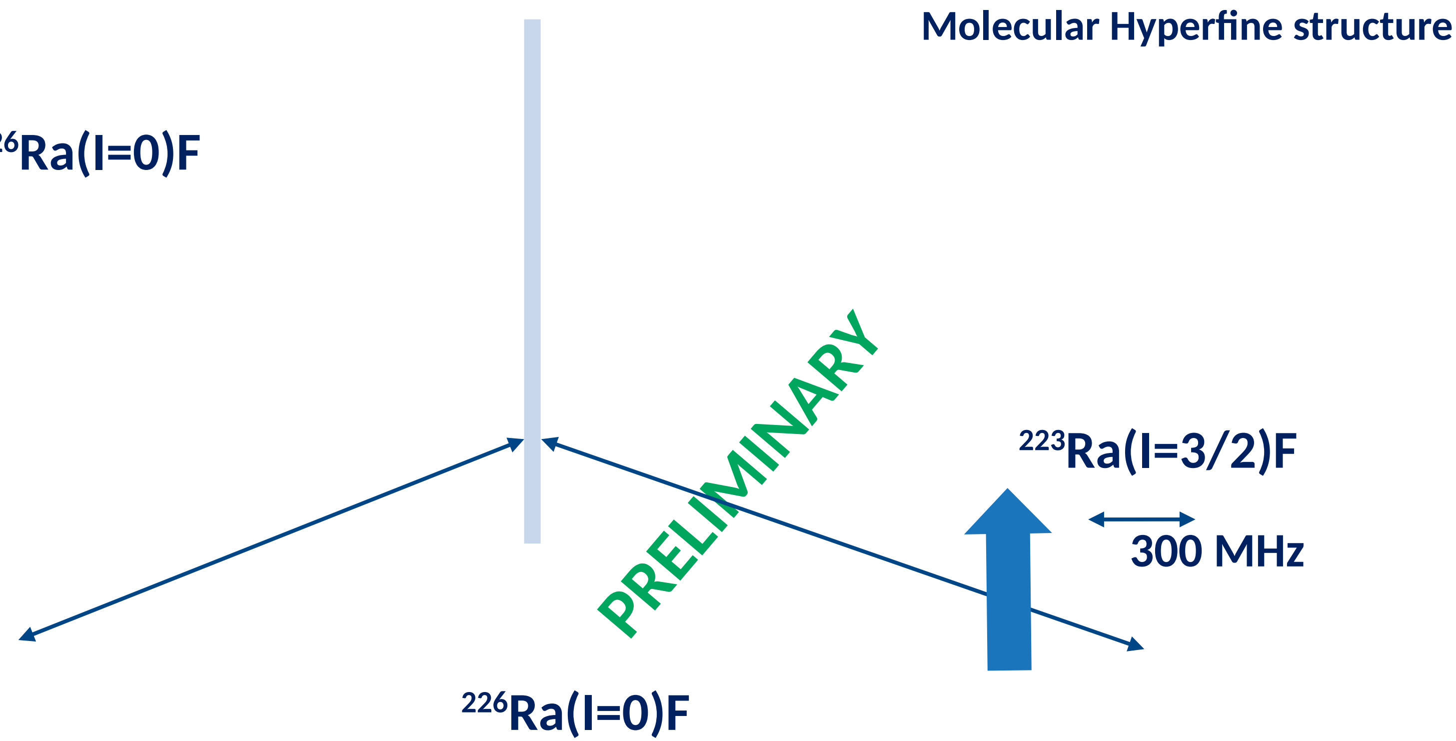
^{226}RaF (T$_{1/2}$=1600 days)

counts

Frequency

[Garcia Ruiz et al. In preparation (2019)]

RaF molecular spectroscopy



~ 15 GHz

[Garcia Ruiz et al. In preparation (2019)]

RaF molecular spectroscopy

?

IP= 39990(50) cm^{-1}

PRELIMINARY

? ?

? ? ? ? ? ?

- **The first laser spectroscopy of synthetic radioactive molecules!**
- Vibrational transitions of ^{226}RaF and ^{228}RaF, ^{226}RaF, ^{223}RaF, ^{225}RaF
- Ionization potential of RaF
- Transitions to higher molecular excited states
- High-resolution measurements of vibrational structure, including ^{223}Ra (I = 3/2)
- → **A suitable laser cooling scheme for RaF molecules has been established!**

[Garcia Ruiz et al. In preparation (2019)]

Thanks, collaboration!

The CRIS collaboration:

J. Billowes, C. Binnersley, T.E. Cocolios, B. Cooper, K.T. Flanagan, S. Franchoo, V. Fedosseev, B.A. Marsh, M. Bissell, R.P. De Groote, R.F. Garcia Ruiz, A. Koszorus, G. Neyens, H. Perrett, F. Parnefjord Gustafsson, C. Ricketts, H.H. Stroke, **A. Vernon,** K. Wendt, S. Wilkins, X. Yang

And to these funding bodies and organisations for allowing the research:

[Thanks to Kara Lynch for the CRIS PowerPoint template]

Thanks for listening!