In-source laser spectroscopy of neutron-deficient lutetium isotopes

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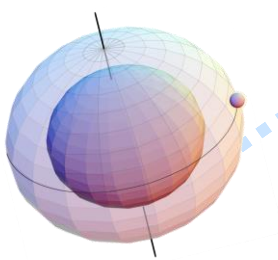
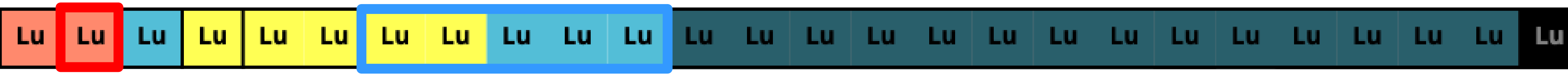
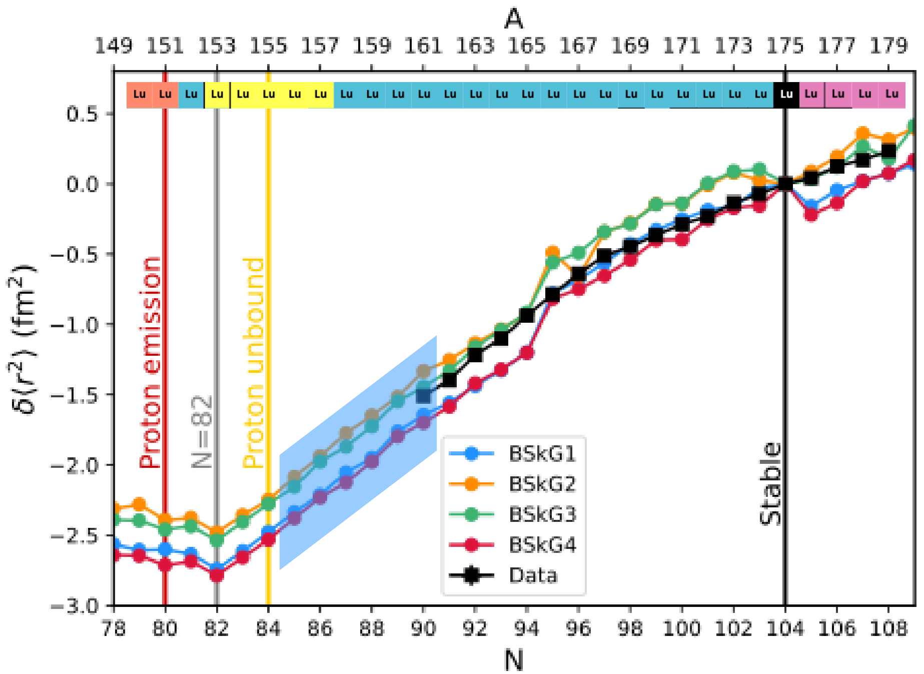


Introduction



- Plan: Perform in-source laser spectroscopy of Lu isotopes using PI-LIST from ^{161}Lu to ^{156}Lu



- Measure nuclear spins, magnetic moments, quadrupole moments and charge radii

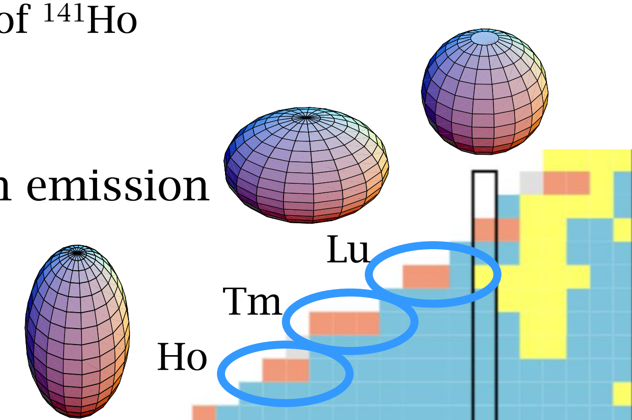
- Investigate evolution of nuclear deformation towards proton emitter ^{151}Lu

- Ultimate aim: measure the charge radius of ^{151}Lu after LS3

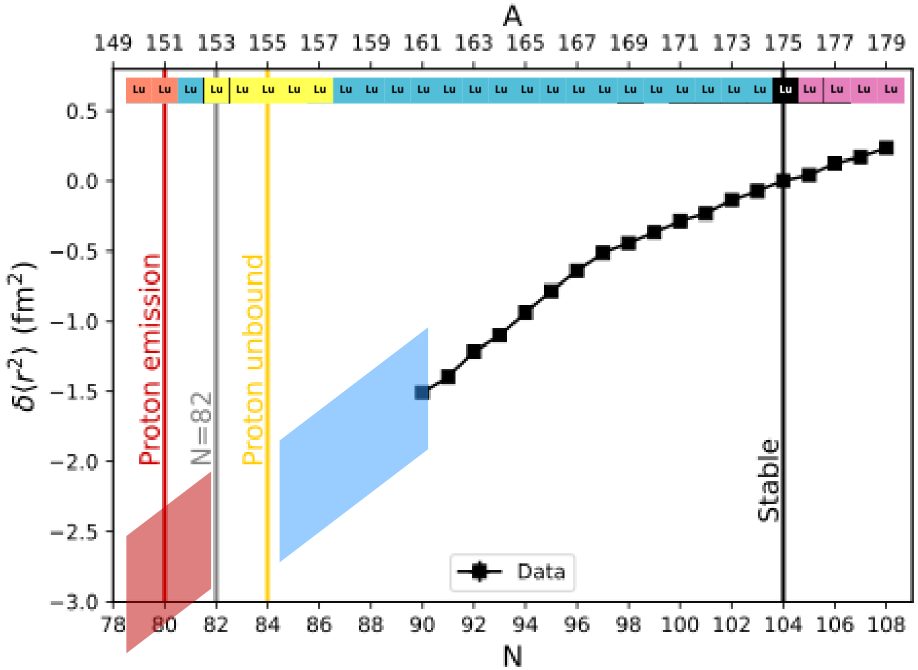
- This proposal: investigate triaxiality between *N*=84-92, as predicted by BSkG models

Motivation (1): Proton emitter

- Physics motivation endorsed by the INTC for Letter of Intent LOI278
- Proton emitter expected to have larger charge radius due to larger spatial extent of the proton distribution
- Exciting field of research in recent years
  - Laser spectroscopy reaching sensitivity needed and RIB facilities increasing production yields
- Proton decay rate extremely sensitive to nuclear spin and deformation
  - ^{150}Lu and ^{151}Lu only described by oblate deformations, despite expecting a spherical shape
  - Prolate deformation needed to describe proton decay rate of ^{141}Ho
    - Predictions based on axially symmetric models
- Recently, inclusion of triaxiality used to interpret proton emission
  - ^{140}Ho, ^{141}Ho, ^{144}Tm, ^{145}Tm and ^{149}Lu



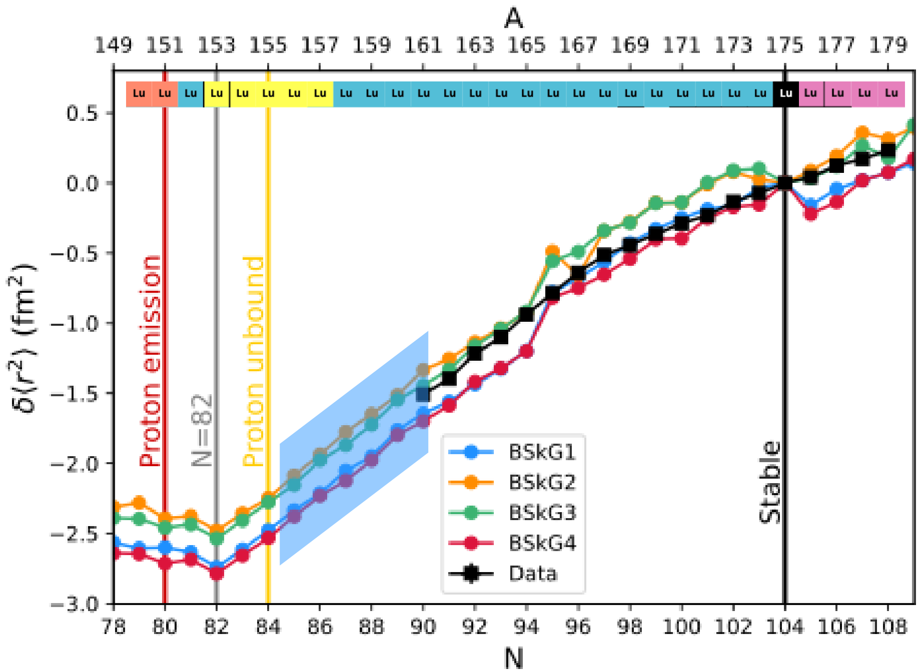
Motivation (1): Proton emitter



- Ultimate aim: to measure charge radius of proton emitter ^{151}Lu

- This proposal:
  1. Seeks to lay groundwork for measurement of ^{151}Lu after LS3
  2. Gain a thorough understanding of isotopic chain towards ^{151}Lu
  3. Investigate evolution of nuclear structure and presence of triaxiality between N=84-92

Motivation (2): Triaxiality



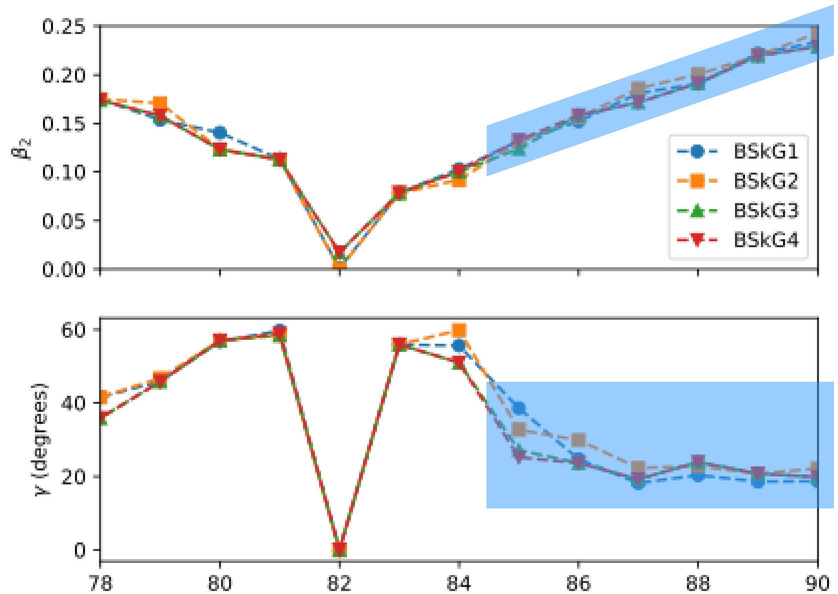
- Predictions of charge radii from BSkG1, BSkG2, BSkG3 and BSkG4 [1-4]

- BSkG models: mean-field calculations with a Skyrme energy density functional
  - Fitted to nuclear masses and charge radii
  - Allow for triaxial and octupole deformation

- BSkG models suggest rapidly varying deformation from ^{150,151}Lu to Tm and Ho

[1] G. Scamps et al., EPJ A **57** 333 (2021)
[2] W. Ryssens et al. EPJ A **58** 246 (2022)
[3] G. Grams et al. EPJ A **59** 270 (2023)
[4] G. Grams et al. arXiv: 2411.08007 (2024)

Motivation (2): Triaxiality



- Predictions for Lu:
- Quadrupole deformation expected to decrease with decreasing neutron number
- Triaxiality angle expected to increase:
  - From 20º (triaxial) at *N*=90
  - To 60º (oblate) at *N*=84
  - Predict triaxiality between *N*=85-92

[1] G. Scamps et al., EPJ A **57** 333 (2021)
[2] W. Ryssens et al. EPJ A **58** 246 (2022)
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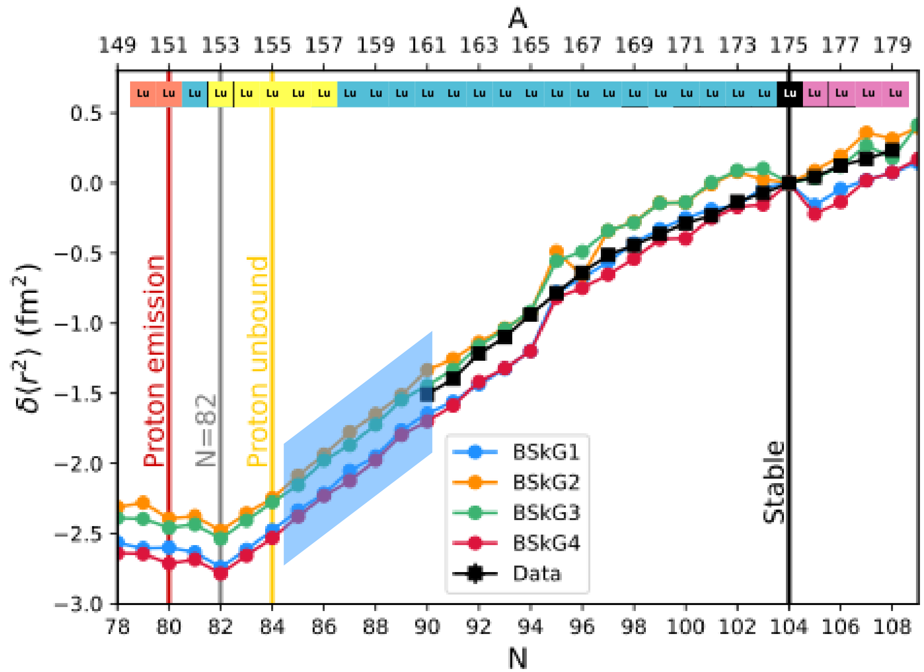
Motivation (2): Triaxiality



- Challenge theoretical predictions by measuring quadrupole moment and charge radii
    - Quadrupole moments – static deformation
    - Change in charge radii – dynamic deformation

- Comparison of theoretical predictions of charge radii with/without triaxiality

- Measure evolution of static and dynamic deformation towards proton emitter

Nuclear observables with laser spectroscopy

- Laser spectroscopy provides nuclear-model independent measurement of nuclear shape

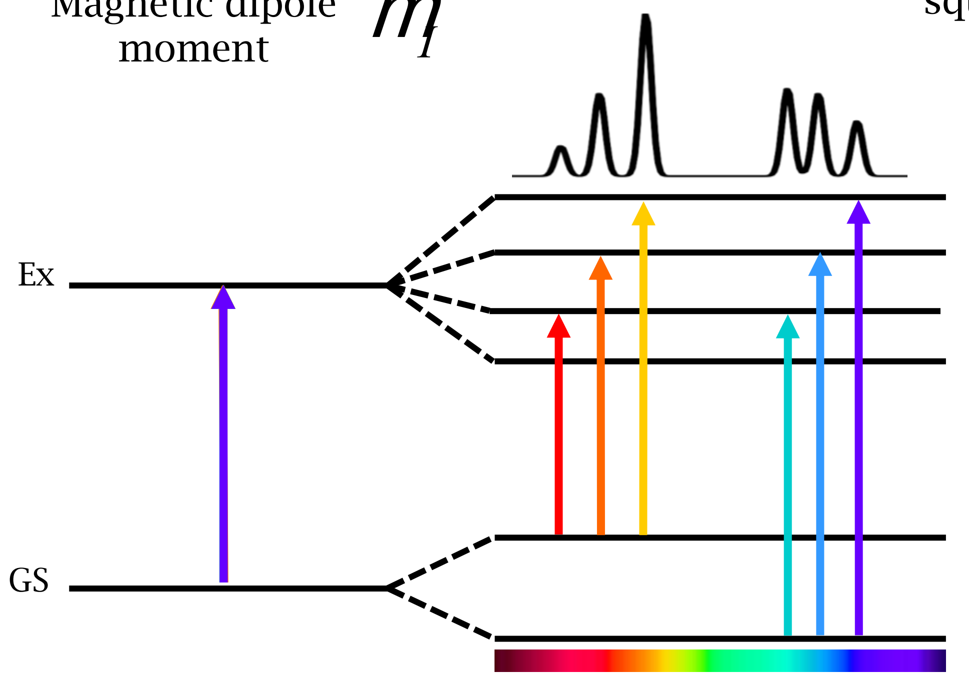
- Probe the hyperfine structure of the energy levels of the electron

Nuclear spin I

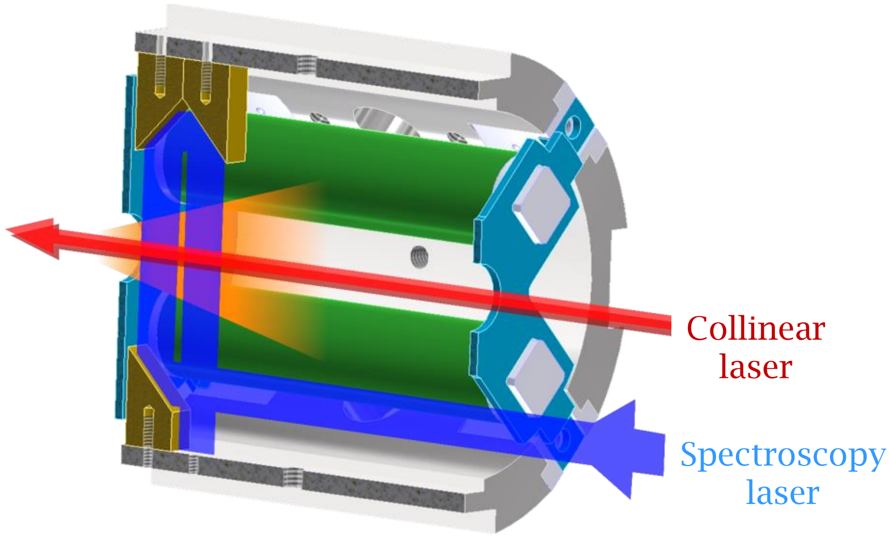
Electric quadrupole moment Q_S

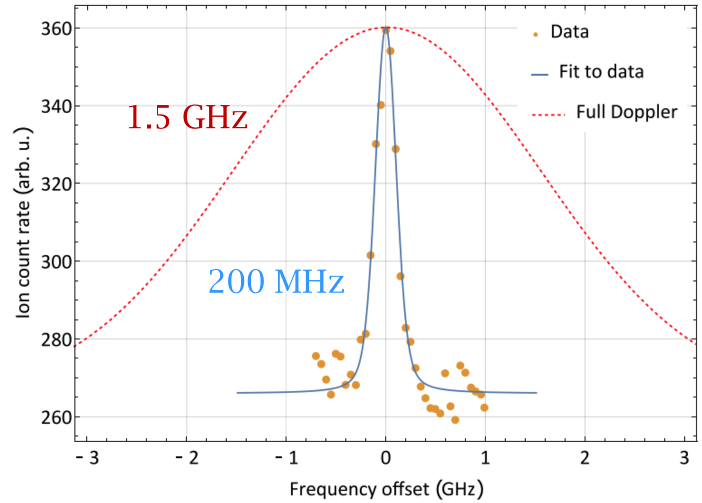
Change in mean-square charge radii $\delta\langle r^2\rangle^{A,A'}$

Magnetic dipole moment μ_I



In-source laser spectroscopy with PI-LIST





R. Heinke et al. NIM B 541 8-12 (2023)

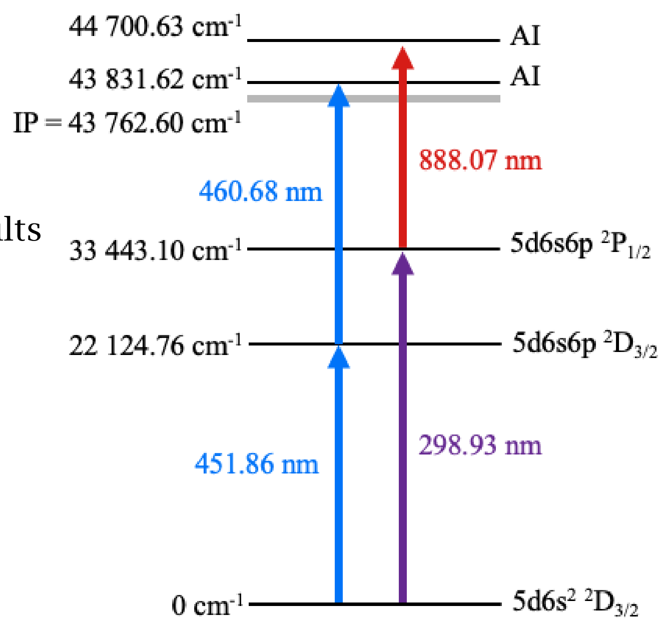
- Perform in-source laser spectroscopy with PI-LIST

- Resolution increased due to ionising the atoms in a perpendicular geometry
  - Factor of 10 improvement compared to collinear LIST mode
  - Resolution of 200 MHz demonstrated for ^{227}Ac

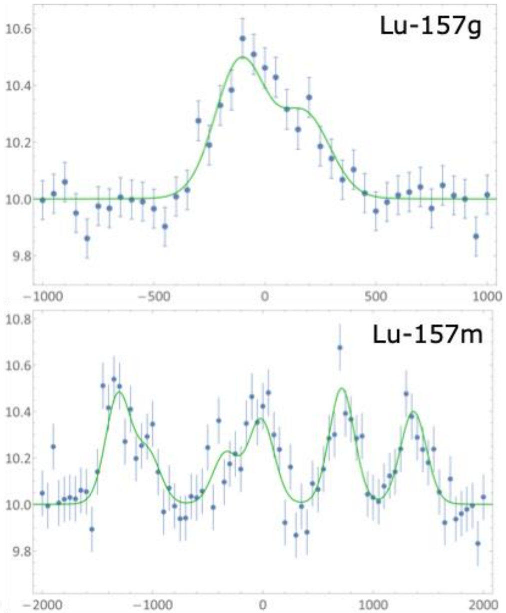
- Higher efficiency due to studying the isotopes at the point of creation
  - Consider factor of 20 loss cf. collinear LIST mode

Results from LoI278

- Letter of intent to measure yields of Lu and Ho isotopes in September 2024
  - Target already degraded and broke during tests
  - Focused on determining best RIS scheme for Lu
- In-source laser spectroscopy of Lu-175, 173, 171, 169, 167, 165, 163, 162
  - Determine sensitivity to isotope shift for 299+888-nm scheme
- Results:
  - 299+888-nm scheme not significantly more sensitive
    - Despite being slightly more efficient
  - Use 451+460-nm for this proposal
    - Benefit from well-known literature values to benchmark results
- Modes of operation:
  - PI-LIST mode: highest resolution, FWHM ~150-250 MHz
  - LIST-mode: highest efficiency, FWHM ~0.5-1.0 GHz
- Measure: ISOLDE Faraday cup or CB0 magnetof



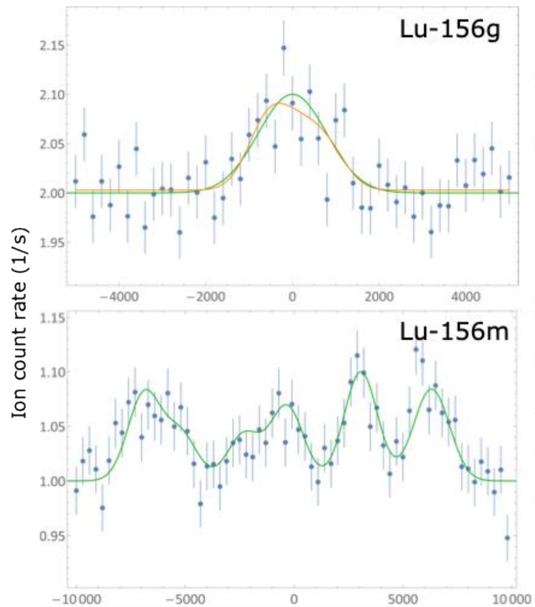
Shift request



- PI-LIST mode
- 250 MHz FWHM
- 3 shifts

- 10 ions/s signal
- 2 ions/s bkgnd

- 5% error on A
  50% error on B
- 100 MHz error
  on isotope shift



- LIST mode
- 1.5 GHz FWHM
- 5 shifts

- 0.1 ions/s signal
- 2 ions/s bkgnd

- 25% error on A
  300 MHz error
  on isotope shift

- Shift request based on simulated spectra
  - Realistic background conditions
  - Yield estimates based on calculations benchmarked by Tm yield measurements
  - PI-LIST mode assumes factor of 20 loss cf. yield estimates

- PI-LIST or LIST-mode chosen based on yields

Shift request

Isotope	Spin	Half-life	Estimated yield (ions/s)	Requested shifts	New results
^{175}Lu	$7/2^+$	Stable	>1,100	2	Setup, no protons
$^{175-161}$Lu	$7/2^+$ - $1/2^+$	Stable - 77 s	>1,100	3	Reference and benchmarking
^{160g}Lu ^{160m}Lu	? ?	36.1 s 40.0 s	2,200	2	I, μ, Q, $\delta\langle r^2\rangle$ I, μ, Q, $\delta\langle r^2\rangle$
^{159}Lu	?	12.1 s	340	1	I, μ, Q, $\delta\langle r^2\rangle$
^{158}Lu	$(2)^-$	10.6 s	140	1	I, μ, Q, $\delta\langle r^2\rangle$
^{157g}Lu ^{157m}Lu	$(1/2^+, 3/2^+)$ $(11/2^-)$	7.6 s 4.8 s	8	3	I, μ, Q, $\delta\langle r^2\rangle$ I, μ, Q, $\delta\langle r^2\rangle$
^{156g}Lu ^{156m}Lu	$(2)^-$ $(9^+, 10^+)$	494 ms 198 ms	0.04	5	$\delta\langle r^2\rangle$ I, μ, Q, $\delta\langle r^2\rangle$

- Request a Ta-foil LIST target with RILIS
    - 15 shifts requested for in-source laser spectroscopy of neutron-deficient Lu isotopes
    - 2 shifts requested for setup (no protons)

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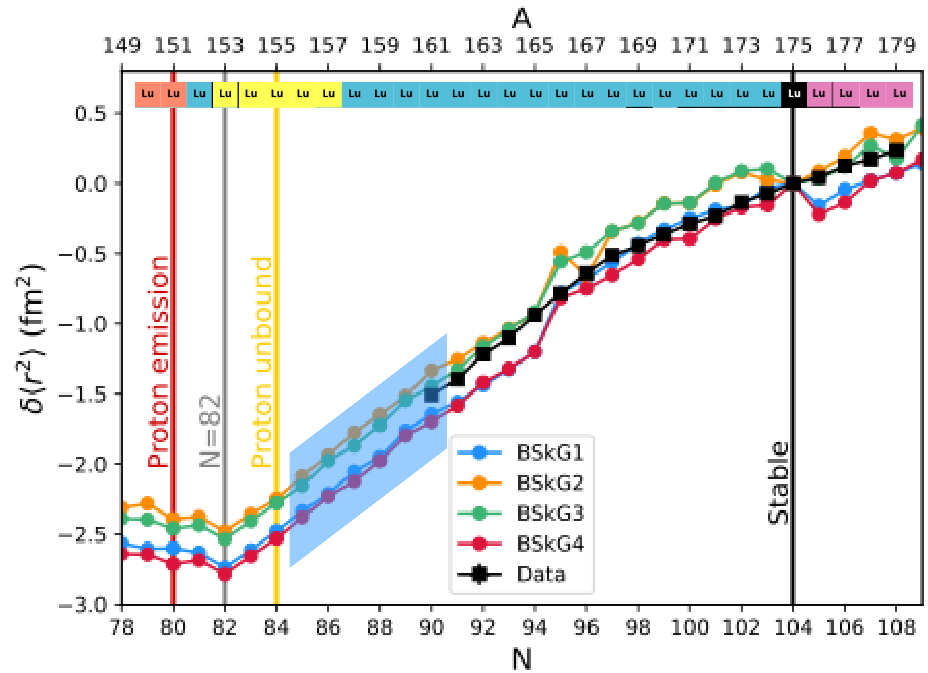
TAC comments

In-source laser spectroscopy of neutron-deficient lutetium isotopes					
CDS#	**Proposal #**	**IS #**	**Setup**	**Shifts**	**Isotopes**
INTC-P-730	INTC-P-730		CRIS/RILIS	15	156-161Lu
Beam intensity/purity, targets-ion sources	**Realistic estimates but no guarantees.** - Ta-foil + LIST target - Please do not overheat the target too early due to risk of sintering! In September 2024, this happened after 2-3 days of operation already. - Target material development could be interesting to maintain target integrity also at higher temperatures required for release: o Shape / arrangement of the foils o Sintering inhibitors (alternating with W) - 2024 Lu yield measured with #853 in degraded conditions.				
General implantation and setup					
General Comments	- Synergies with other approved Ta-LIST experiments - LIST targets require larger efforts in setting up and operating, to be considered while scheduling				
Safety					
TAC recommendation	**The TAC notes that the requested yields are realistic, though not guaranteed, based on the September 2024 experiment. However, there is a concern about the rapid degradation of the target material, which currently compromises the feasibility of a long run.**				

- Risk associated with long run can be mitigated by running target conservatively

Summary

- Investigate evolution of nuclear deformation towards proton emitter ^{151}Lu
- Ultimate aim: measure charge radius of ^{151}Lu after LS3
- This proposal:
- Investigate triaxiality between N=85-92, as predicted by BSkG models
- Gain a thorough understanding of isotopic chain towards ^{151}Lu
- Guide PI-LIST developments during LS3



- Nicely complements Pm and Tm proposals this year
  - Lu proposal can be scheduled after

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Thank you

Thanks to the 'PI-LIST' collaboration, including…

K.M. Lynch[1], T.E. Cocolios[2], R. Heinke[1,4], A. Ajayakumar[4], M. Au[4], M. Bender[5] C. Bernerd[4], S. Casci[2,6], B. Cheal[3], K. Chrysalidis[4], J. Cubiss[7], M. Elle[2,4], R. Ferrer[2], S. Geldhof[9], Harshithbabu[2], M. Heines[2], A.A.H. Jaradat[1,4], D.T. McElroy[1], S. Mohammed[2], W.W.M.M. Phyo[2], J. Reilly[1,4], M. Reponen[10], L.V. Rodríguez[11,12], A. de Roubin[8], W. Ryssens[13,14] J. Shaw[2], J. Warbinek[11], J. Wessolek[1,4]

[1]The University of Manchester, [2]KU Leuven, [3]University of Liverpool, [4]CERN, [5]Universite Claude Bernard Lyon, [6]Peking University, [7]University of Edinburgh, [8]Normandie Universite, [9]GANIL, [10]University of Jyvaskyla, [11]CERN, [12]Max-Planck-Institut fur Kernphysik, [13]Universite Libre de Bruxelles, [14]Brussels Laboratory of the Universe

Thank you for your consideration!

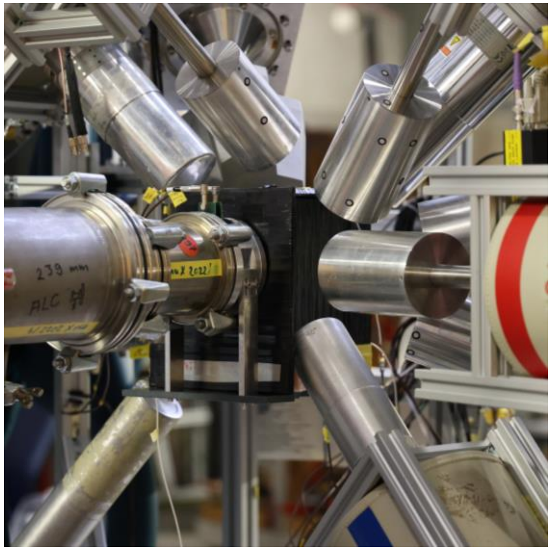
Muonic x-ray of ^{175,176}Lu

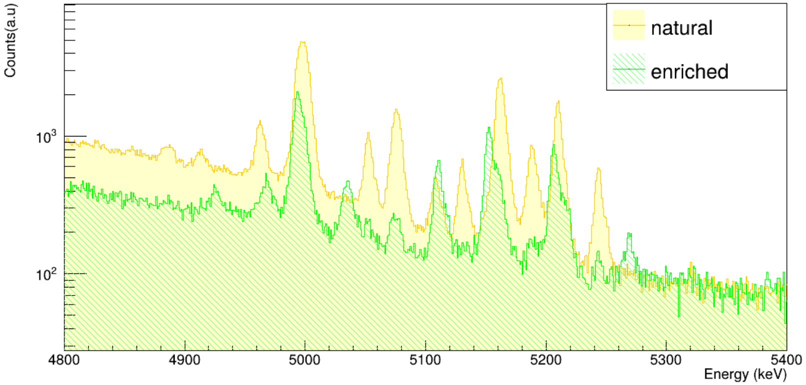
- Complementary work is ongoing at PSI to measure the muonic x-ray of ^{175,176}Lu

- Measurement has been performed on natural Lu (97.4% ^{175}Lu) and enriched Lu (75% ^{176}Lu)
  - September 2024 campaign of ReferenceRadii
  - Analysis ongoing

- Should provide the absolute radii allowing us to:
  - benchmark the specific mass shift factor against experimental data
  - improve the extraction of the charge radii from the isotope shift

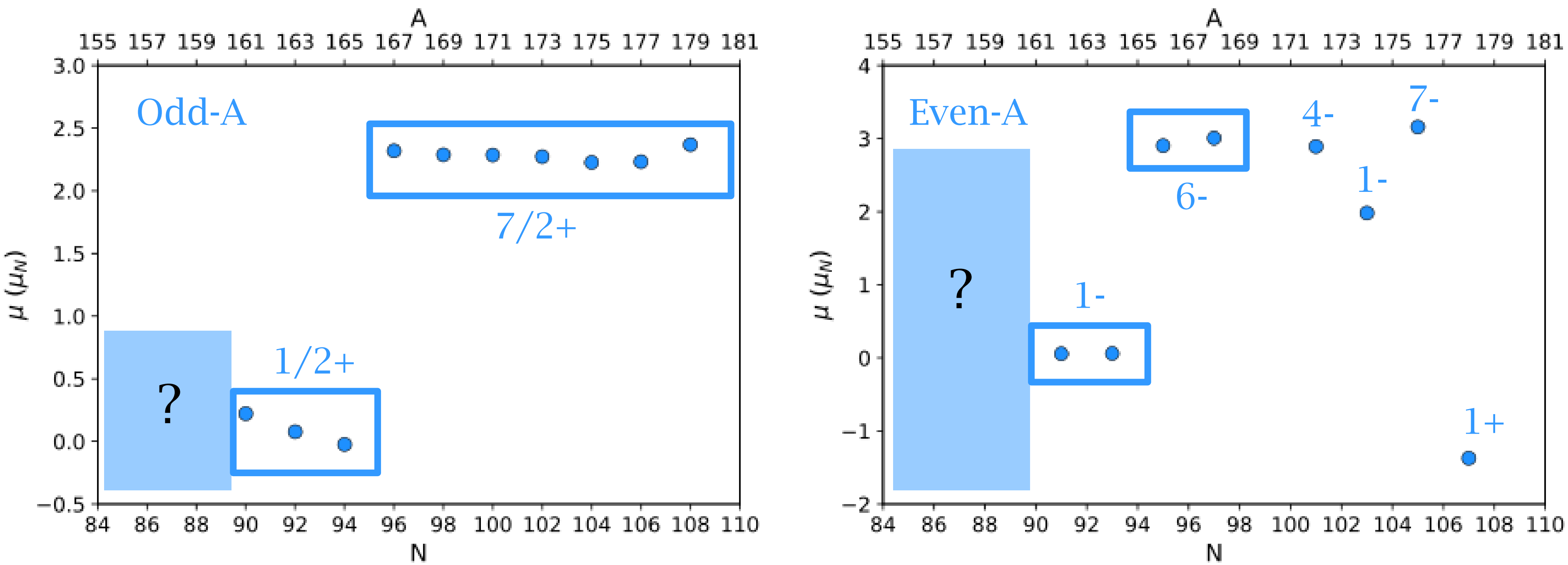
- The data should also provide absolute quadrupole moments for reference





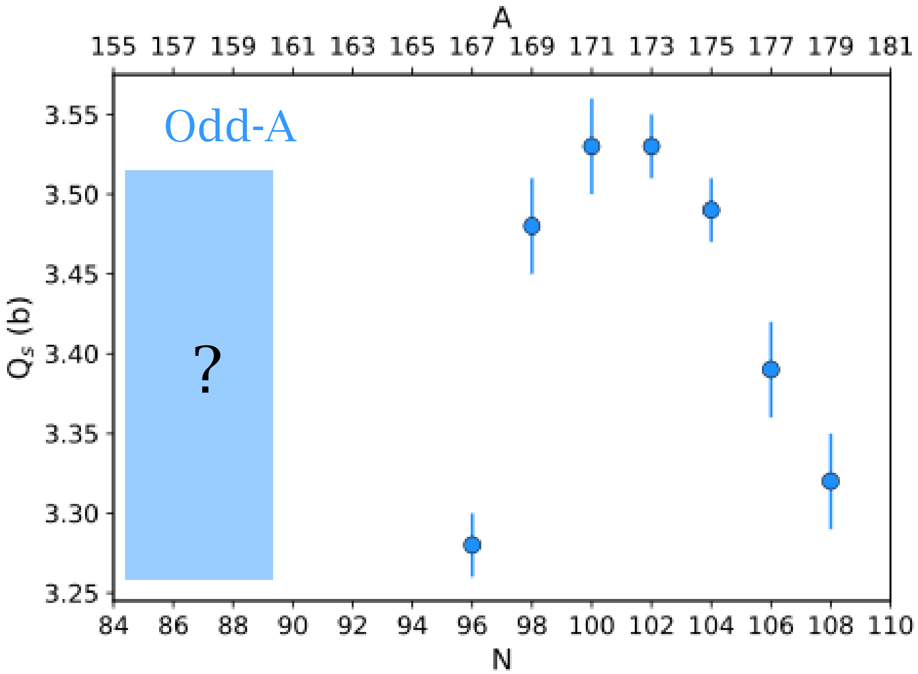
Images courtesy from D. Hengstler (Heidelberg) and W.W.M.M.P. (KU Leuven)

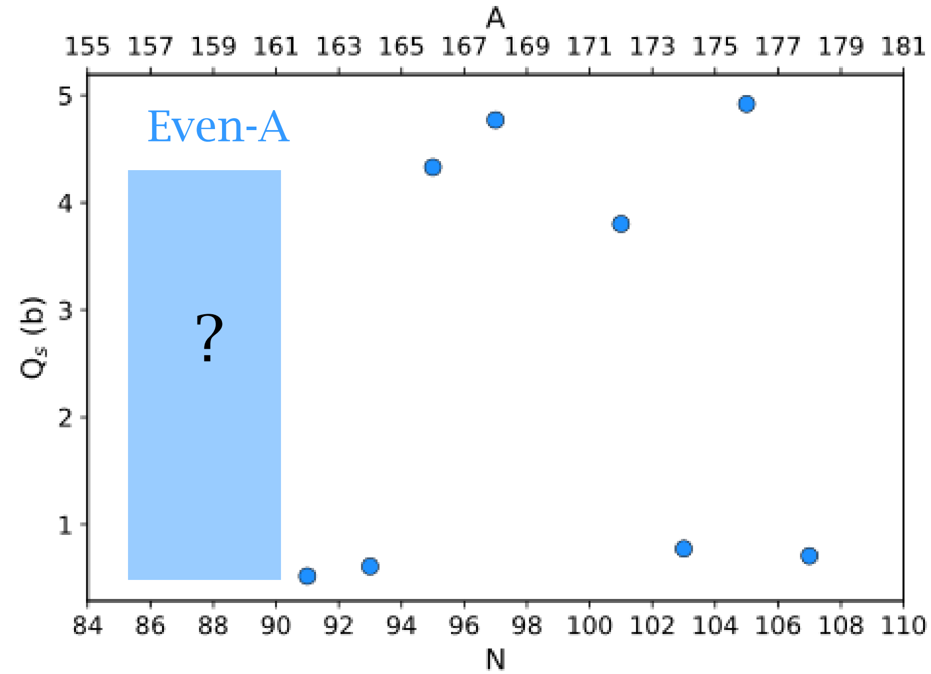
Magnetic moments of Lu



^{160g}Lu	?	36.1 s	2,200	2	$I, \mu, Q, \delta\langle r^2\rangle$
^{160m}Lu	?	40.0 s			$I, \mu, Q, \delta\langle r^2\rangle$
^{159}Lu	?	12.1 s	340	1	$I, \mu, Q, \delta\langle r^2\rangle$
^{158}Lu	$(2)^-$	10.6 s	140	1	$I, \mu, Q, \delta\langle r^2\rangle$
^{157g}Lu	$(1/2^+, 3/2^+)$	7.6 s	8	3	$I, \mu, Q, \delta\langle r^2\rangle$
^{157m}Lu	$(11/2^-)$	4.8 s			$I, \mu, Q, \delta\langle r^2\rangle$
^{156g}Lu	$(2)^-$	494 ms	0.04	5	$\delta\langle r^2\rangle$
^{156m}Lu	$(9^+, 10^+)$	198 ms			$I, \mu, Q, \delta\langle r^2\rangle$

Quadrupole moments of Lu

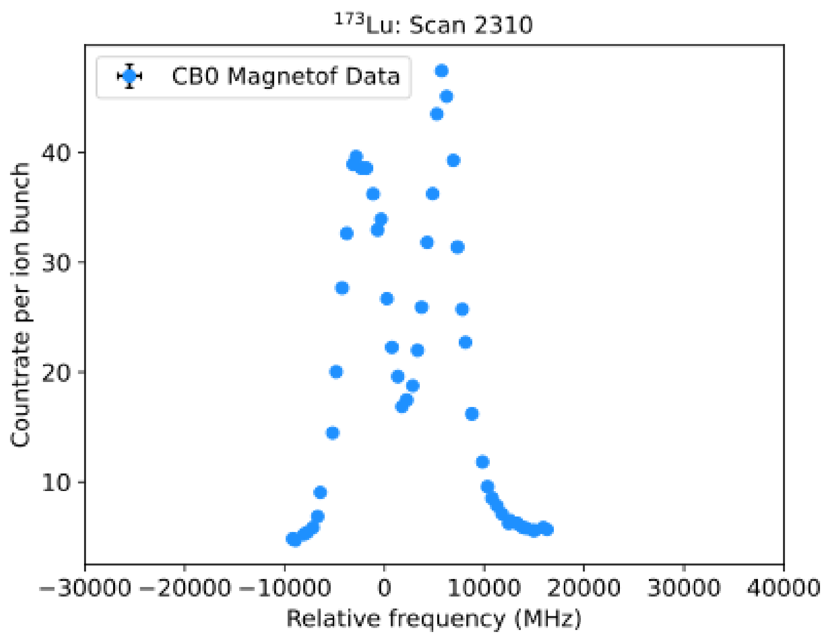


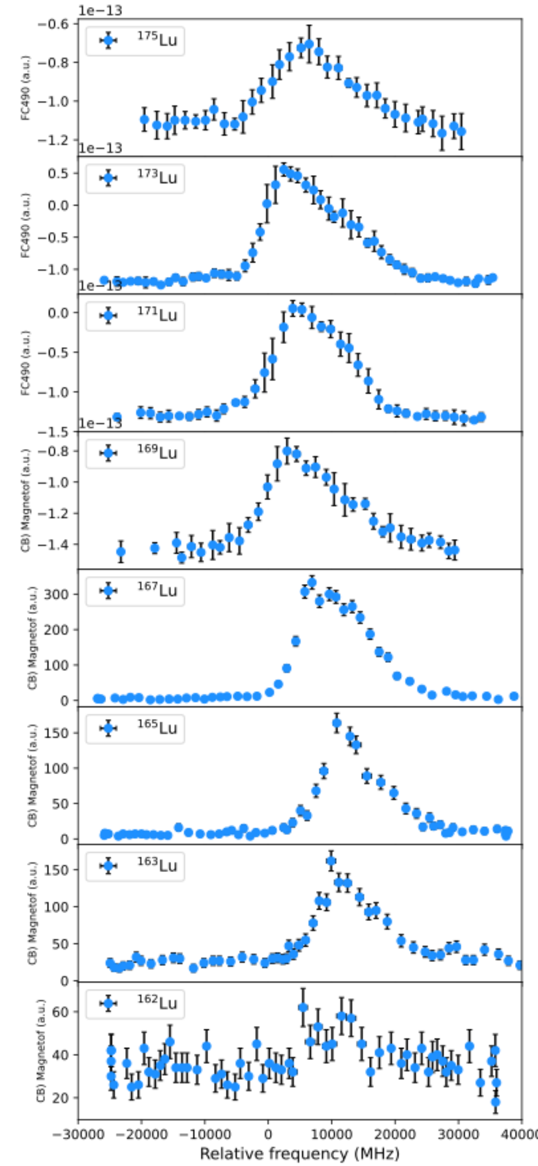


^{160g}Lu	?	36.1 s	2,200	2	I, μ, Q, $\delta\langle r^2\rangle$
^{160m}Lu	?	40.0 s			I, μ, Q, $\delta\langle r^2\rangle$
^{159}Lu	?	12.1 s	340	1	I, μ, Q, $\delta\langle r^2\rangle$
^{158}Lu	$(2)^-$	10.6 s	140	1	I, μ, Q, $\delta\langle r^2\rangle$
^{157g}Lu	$(1/2^+, 3/2^+)$	7.6 s	8	3	I, μ, Q, $\delta\langle r^2\rangle$
^{157m}Lu	$(11/2^-)$	4.8 s			I, μ, Q, $\delta\langle r^2\rangle$
^{156g}Lu	$(2)^-$	494 ms	0.04	5	$\delta\langle r^2\rangle$
^{156m}Lu	$(9^+, 10^+)$	198 ms			I, μ, Q, $\delta\langle r^2\rangle$

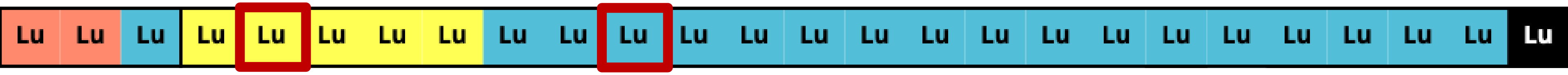
Results from LOI278

- In-source laser spectroscopy of Lu-175, 173, 171, 169, 167, 165, 163, 162
- LIST-mode
- PI-LIST mode in process of optimization when target broke





Laser-assisted decay spectroscopy



- Addendum (after LS3): Laser-assisted decay spectroscopy of ^{154,156,160}Lu with IDS

- Neutron-deficient Lu have rich structure of isomeric states
  - Level structure of ^{154}Lu, ^{156}Lu and ^{160}Lu still an open question

- Exploit selectivity of PI-LIST
- Perform laser-assisted decay spectroscopy on neutron-deficient Lu isotopes
  - ISOLDE Decay Station (IDS)
  - Understand level structure and alpha decay

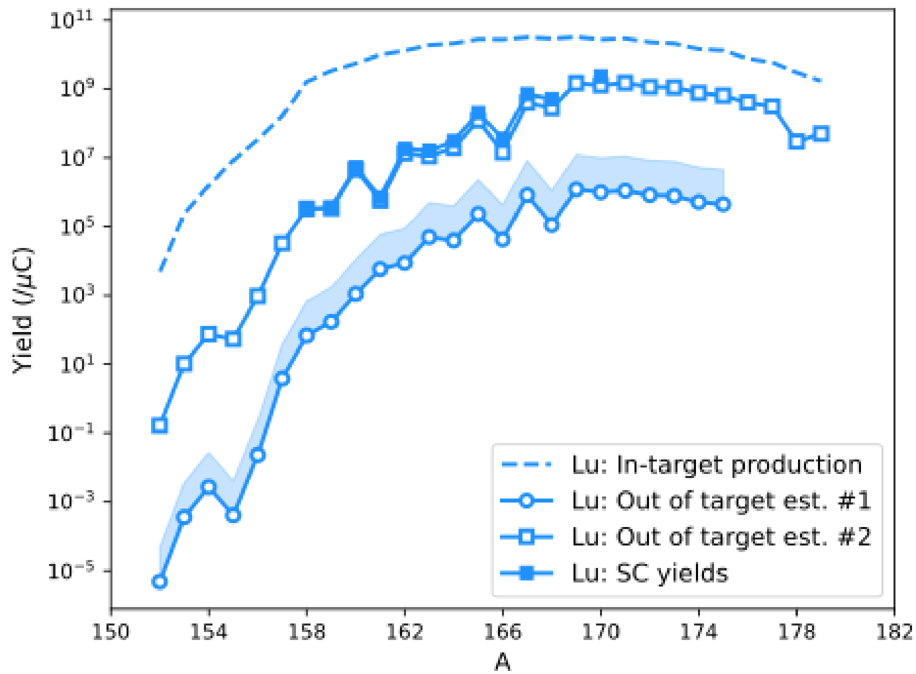
ISOLDE Decay Station

Nuclide	Energy [keV]	J^π	$T_{1/2}$ or Width Abund. [mole fract.]	$T_{1/2}$ [s]	Decay Modes BR [%]
$^{154}_{71}$Lu$_{83}$	0	(2-)			
$^{154}_{71}$Lu$_{83}$	X	(9+)	1.12 s *8*	1.12 *8*	ec β+ ≈ 100

Nuclide	Energy [keV]	J^π	$T_{1/2}$ or Width Abund. [mole fract.]	$T_{1/2}$ [s]	Decay Modes BR [%]
$^{156}_{71}$Lu$_{85}$	0	(2)-	494 ms *12*	0.494 *12*	α ≈ 95 ec β+ ≈ 5
$^{156m}_{71}$Lu$_{85}$	0+X	9+	198 ms *2*	0.198 *2*	α 100

Nuclide	Energy [keV]	J^π	$T_{1/2}$ or Width Abund. [mole fract.]	$T_{1/2}$ [s]	Decay Modes BR [%]
$^{160}_{71}$Lu$_{89}$	0.0		36.1 s *3*	36.1 *3*	ec β+ 100 α ≤ 1 x 10^{-4}
$^{160m}_{71}$Lu$_{89}$	0.0+X		40 s *1*	40 *1*	ec β+ ≤ 100 α ?

Yield estimates

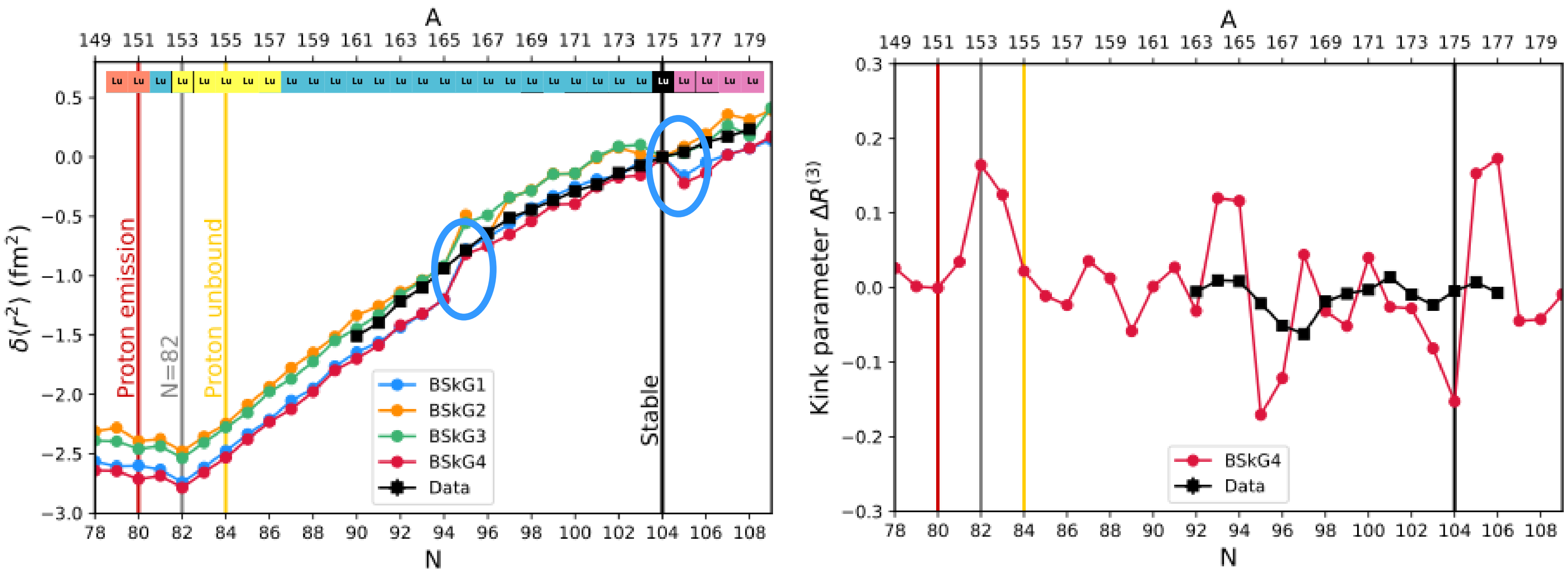


- Success of yield estimate #1 in predicting Tm yields
  - Same Ta-foil LIST target
  - Yields measured prior to target degrading
- Use yield estimate #1 to estimate shift request

INTC-P-730		CRIS/RILIS	

Realistic estimates but no guarantees.
- Ta-foil + LIST target
  - Please do not overheat the target too early due to risk of sintering!

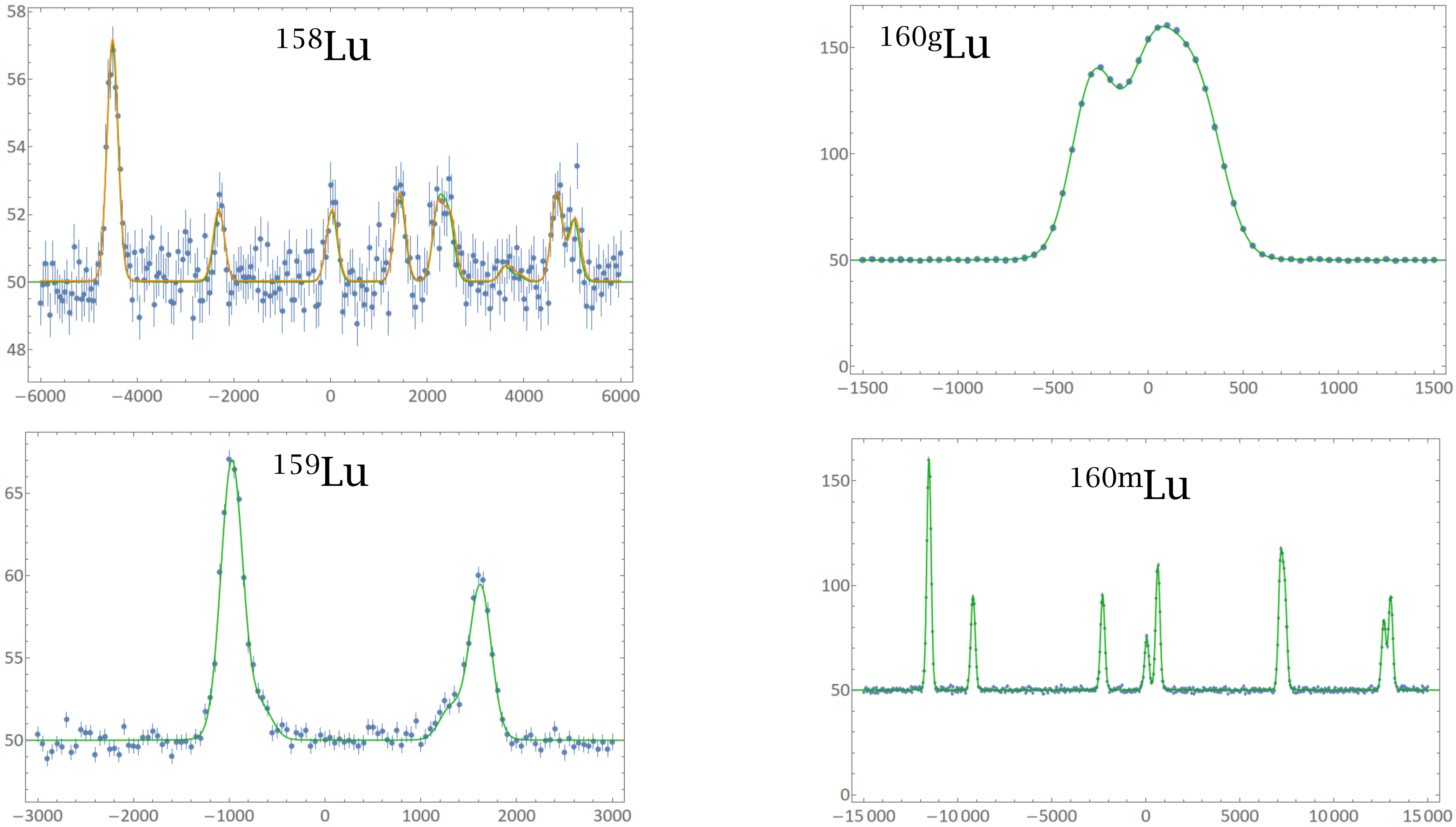
Kink parameter $\Delta R^{(3)}$



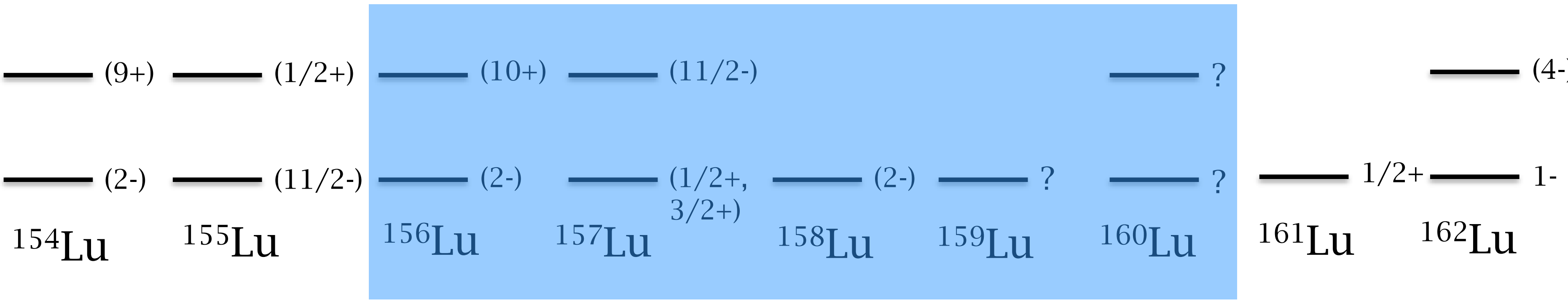
$$\Delta R^{(3)} = \frac{1}{2}\left(\delta\langle r^2\rangle^{A-2} + \delta\langle r^2\rangle^{A+2} - 2\delta\langle r^2\rangle^{A}\right)$$

- Small effects of charge radii 'kinks' or 'jumps' can be seen in experimental data
- Much more pronounced in theoretical predictions

Simulated HFS spectra



- HFS spectra expected with measurement time requested
- PI-LIST mode assumes factor of 20 loss cf. yield estimates


(9+)
(2-)
154Lu
(1/2+)
(11/2-)
155Lu
(10+)
(2-)
156Lu
(11/2-)
(1/2+,
3/2+)
157Lu
(2-)
158Lu
?
159Lu
?
?
160Lu
1/2+
161Lu
(4-)
1-
162Lu

^{149}Lu

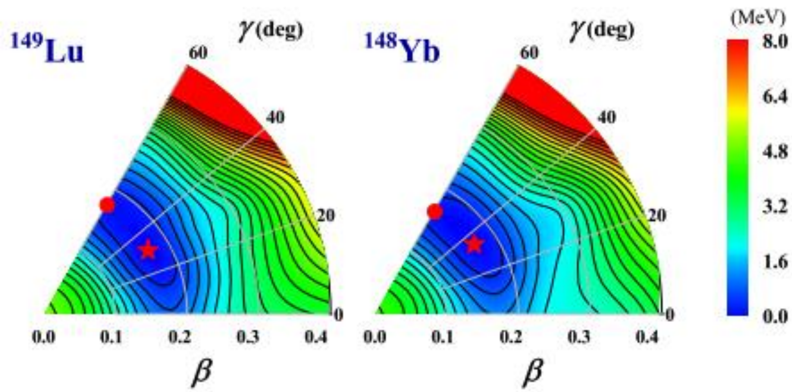


Fig. 1. Potential energy surfaces for ^{149}Lu and ^{148}Yb in the β-γ plane from the TRHBc theory. The energy separation between each contour line is 0.4 MeV. All energies are normalized with respect to the energy of absolute minimum (triaxial ground state) indicated by a red star. The ground-state deformation predicted by the DRHBc theory is denoted by a red closed circle.

- Triaxially deformed relativistic Hartree-Bogoliubov theory in continuum (TRHBc)
  - $\beta = 0.17$ and $\gamma = 31^{\circ}$
  - Slightly extended half-life achieved after considering triaxial deformation degrees of freedom

Q. Lu, K.Y. Zhang, S.S. Zhang, Physics Letters B 856, 138922 (2024)