Neutron-capture cross sections for heavy-mass fission fragments constrained with the β-Oslo method

10th Workshop on Nuclear Level Density and Gamma Strength

May 18 to 22, 2026

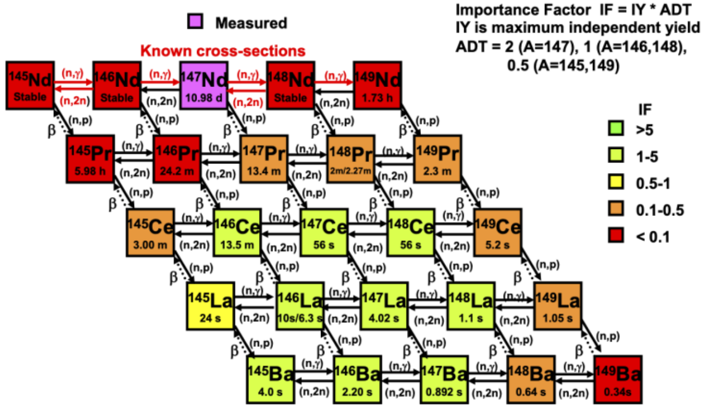
Dr. Adriana Sweet | PLS/NACS

Prepared by LLNL under Contract DE-AC52-07NA27344.

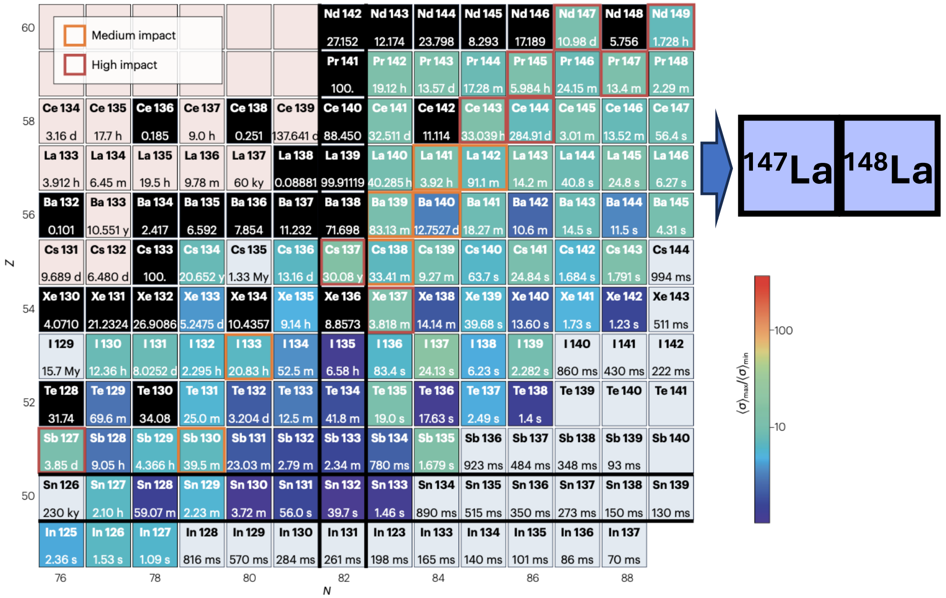
Shedding light on the structure of exotic nuclei: 9 nucleons from the last stable La

- Opportunity to study structure changes and their impact on nuclear level density and γ-ray strength function
- Nuclear level density and γ-ray strength function are key ingredients in neutron-induced reaction rates and improving network calculations
- Testing limits far from stability, may be the farthest yet!

Mass 147 fission products



Neutron reaction rates relevant to the i-process

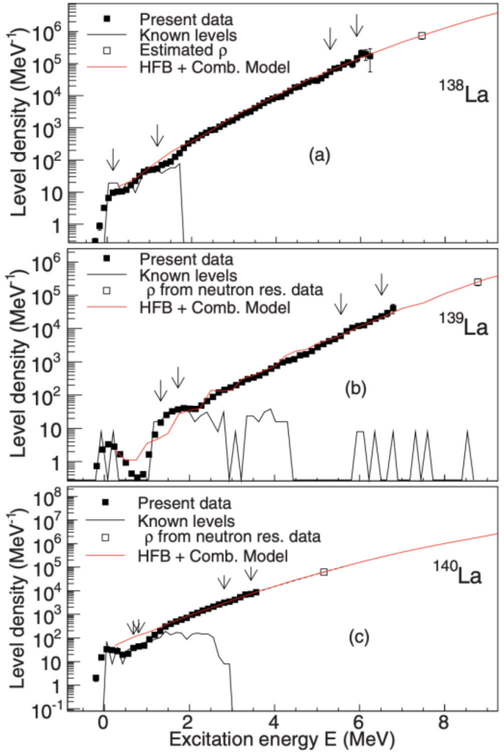


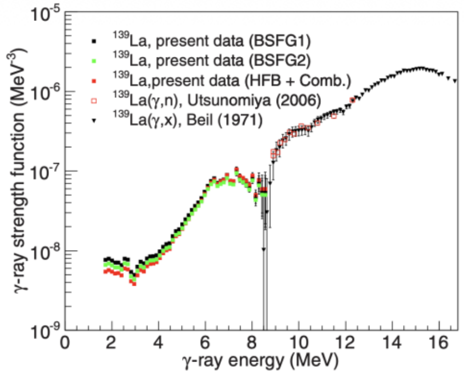
60							Nd 142 27.152	Nd 143 12.174	Nd 144 23.798	Nd 145 8.293	Nd 146 17.189	Nd 147 10.98 d	Nd 148 5.756	Nd 149 1.728 h
							Pr 141 100.	Pr 142 19.12 h	Pr 143 13.57 d	Pr 144 17.28 m	Pr 145 5.984 h	Pr 146 24.15 m	Pr 147 13.4 m	Pr 148 2.29 m
58	Ce 134 3.16 d	Ce 135 17.7 h	Ce 136 0.185	Ce 137 9.0 h	Ce 138 0.251	Ce 139 137.641 d	Ce 140 88.450	Ce 141 32.511 d	Ce 142 11.114	Ce 143 33.039 h	Ce 144 284.91 d	Ce 145 3.01 m	Ce 146 13.52 m	Ce 147 56.4 s
	La 133 3.912 h	La 134 6.45 m	La 135 19.5 h	La 136 9.78 m	La 137 60 ky	La 138 0.08881	La 139 99.91119	La 140 40.285 h	La 141 3.92 h	La 142 91.1 m	La 143 14.2 m	La 144 40.8 s	La 145 24.8 s	La 146 6.27 s
56	Ba 132 0.101	Ba 133 10.551 y	Ba 134 2.417	Ba 135 6.592	Ba 136 7.854	Ba 137 11.232	Ba 138 71.698	Ba 139 83.13 m	Ba 140 12.7527 d	Ba 141 18.27 m	Ba 142 10.6 m	Ba 143 14.5 s	Ba 144 11.5 s	Ba 145 4.31 s
	Cs 131 9.689 d	Cs 132 6.480 d	Cs 133 100.	Cs 134 20.652 y	Cs 135 1.33 My	Cs 136 13.16 d	Cs 137 30.08 y	Cs 138 33.41 m	Cs 139 9.27 m	Cs 140 63.7 s	Cs 141 24.84 s	Cs 142 1.684 s	Cs 143 1.791 s	Cs 144 994 ms
54	Xe 130 4.0710	Xe 131 21.2324	Xe 132 26.9086	Xe 133 5.2475 d	Xe 134 10.4357	Xe 135 9.14 h	Xe 136 8.8573	Xe 137 3.818 m	Xe 138 14.14 m	Xe 139 39.68 s	Xe 140 13.60 s	Xe 141 1.73 s	Xe 142 1.23 s	Xe 143 511 ms
	I 129 15.7 My	I 130 12.36 h	I 131 8.0252 d	I 132 2.295 h	I 133 20.83 h	I 134 52.5 m	I 135 6.58 h	I 136 83.4 s	I 137 24.13 s	I 138 6.23 s	I 139 2.282 s	I 140 860 ms	I 141 430 ms	I 142 222 ms
52	Te 128 31.74	Te 129 69.6 m	Te 130 34.08	Te 131 25.0 m	Te 132 3.204 d	Te 133 12.5 m	Te 134 41.8 m	Te 135 19.0 s	Te 136 17.63 s	Te 137 2.49 s	Te 138 1.4 s	Te 139	Te 140	Te 141
	Sb 127 3.85 d	Sb 128 9.05 h	Sb 129 4.366 h	Sb 130 39.5 m	Sb 131 23.03 m	Sb 132 2.79 m	Sb 133 2.34 m	Sb 134 780 ms	Sb 135 1.679 s	Sb 136 923 ms	Sb 137 484 ms	Sb 138 348 ms	Sb 139 93 ms	Sb 140
50	Sn 126 230 ky	Sn 127 2.10 h	Sn 128 59.07 m	Sn 129 2.23 m	Sn 130 3.72 m	Sn 131 56.0 s	Sn 132 39.7 s	Sn 133 1.46 s	Sn 134 890 ms	Sn 135 515 ms	Sn 136 350 ms	Sn 137 273 ms	Sn 138 150 ms	Sn 139 130 ms
	In 125 2.36 s	In 126 1.53 s	In 127 1.09 s	In 128 816 ms	In 129 570 ms	In 130 284 ms	In 131 261 ms	In 123 198 ms	In 133 165 ms	In 134 140 ms	In 135 101 ms	In 136 86 ms	In 137 70 ms	
	76		78		80		82		84		86		88	

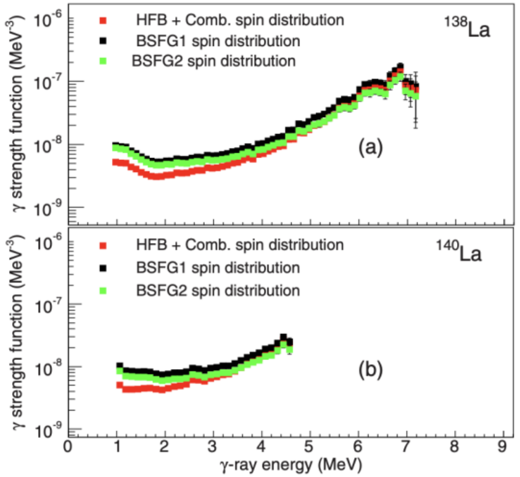
M.A. Stoyer, private communication reaction networks for A=147
M. Wiedeking, et al., Nat Rev Phy B7B, 696-712 (2025)

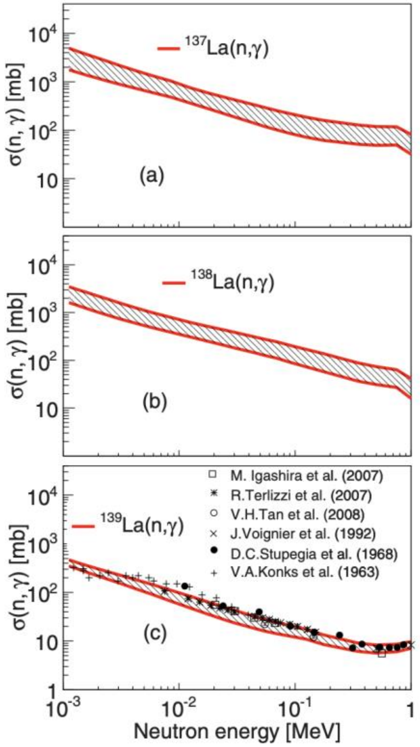
La isotopes were measured here in Oslo!

- There's a scarcity in spectroscopic information! Most exotic studied: ^{149}La
- It's worse for β-decay information!
- Kheswa et al., identified a low-energy upbend in ^{138}La and a plateau behavior for ^{139,140}La
- Spectroscopic studies propose an octupolar to prolate deformation at N≥92





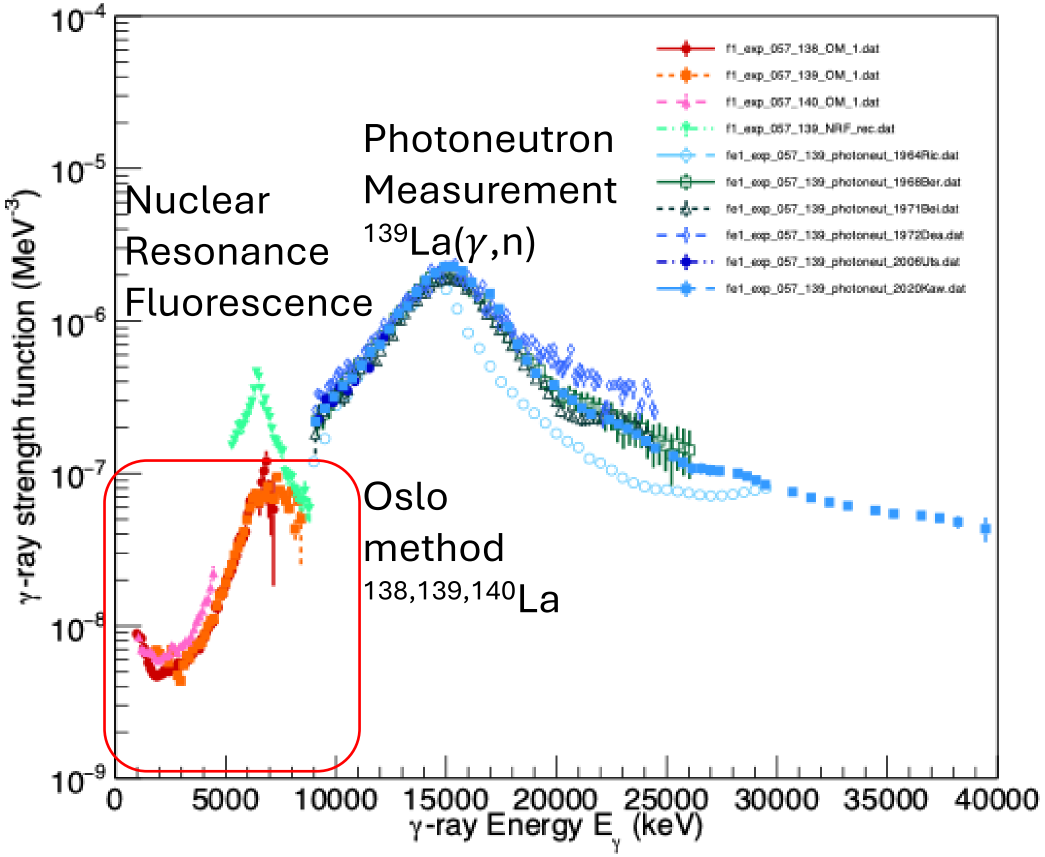




B.V. Kheswa et al., Phys. Rev. C **95**, 045805 (2017)
A. Jaries et al., Phys. Rev. Lett. **134**, 042501 (2025)

What do we know so far about the photon strength function for La isotopes?

Experimental γ-ray strength data for La

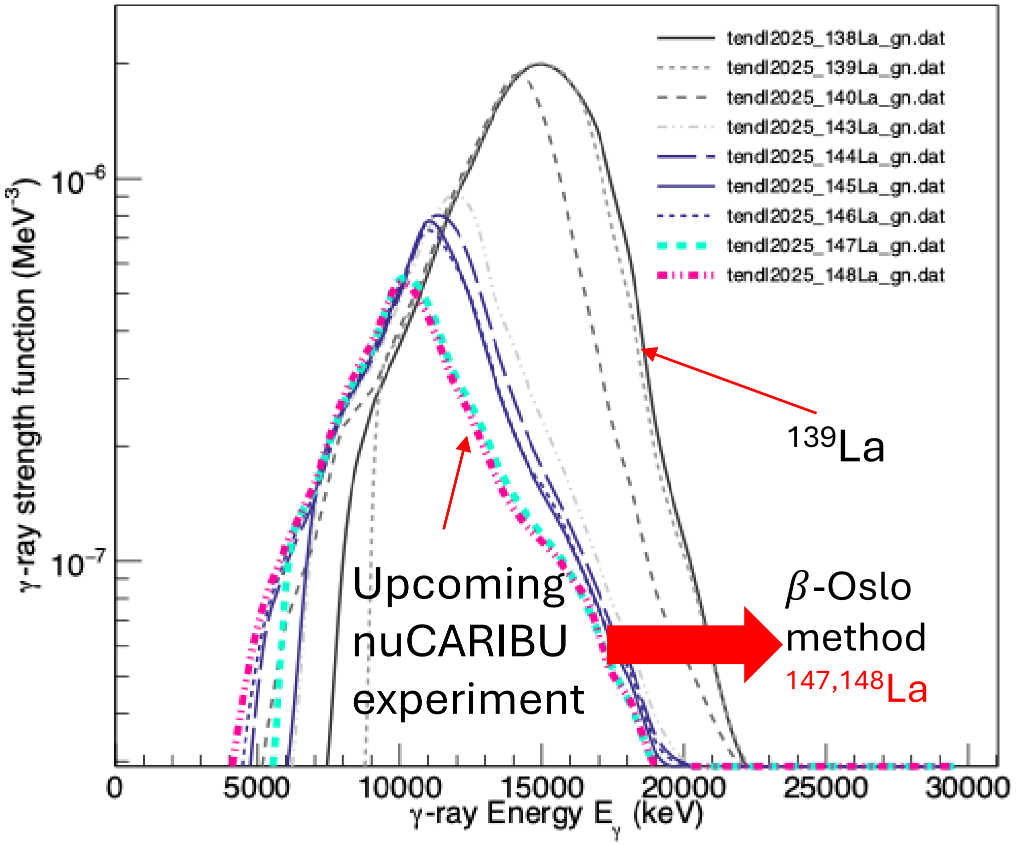


Nuclear Resonance Fluorescence

Photoneutron Measurement ^{139}La(γ,n)

Oslo method ^{138,139,140}La

TENDL 2025 (γ, n) cross section for La



^{139}La

Upcoming nuCARIBU experiment

β-Oslo method ^{147,148}La

B. V. Kheswa et al., Phys. Rev. C 95, 045805 (2017); A. Makinaga et al., Phys. Rev. C 82, 024314 (2010); L.B.Rice, L.N.Bolen, W.D.Whitehead, Phys. Rev. 134, B557, (1964); R.Bergere, R.Beil, A.Veyssiere, Nucl. Phys. A121, 463, (1968); H.Beil, R.Bergere, P.Carlos, A.Lepretre, A.Veyssiere, A. Parlag, Nucl. Phys. A172, 426, (1971); T.K.Deague, R.J.J.Stewart, Nucl.Phys. A191, 305, (1972); H.Utsunomiya,A.Makinaga,S.Goko,T.Kaihori,H.Akimune, et al., J,PR/C, 74, 025806, (2006); T.Kawano, Y.S.Cho, P.Dimitriou, et al., J,NDS,163,109,(2020); TENDL-2025

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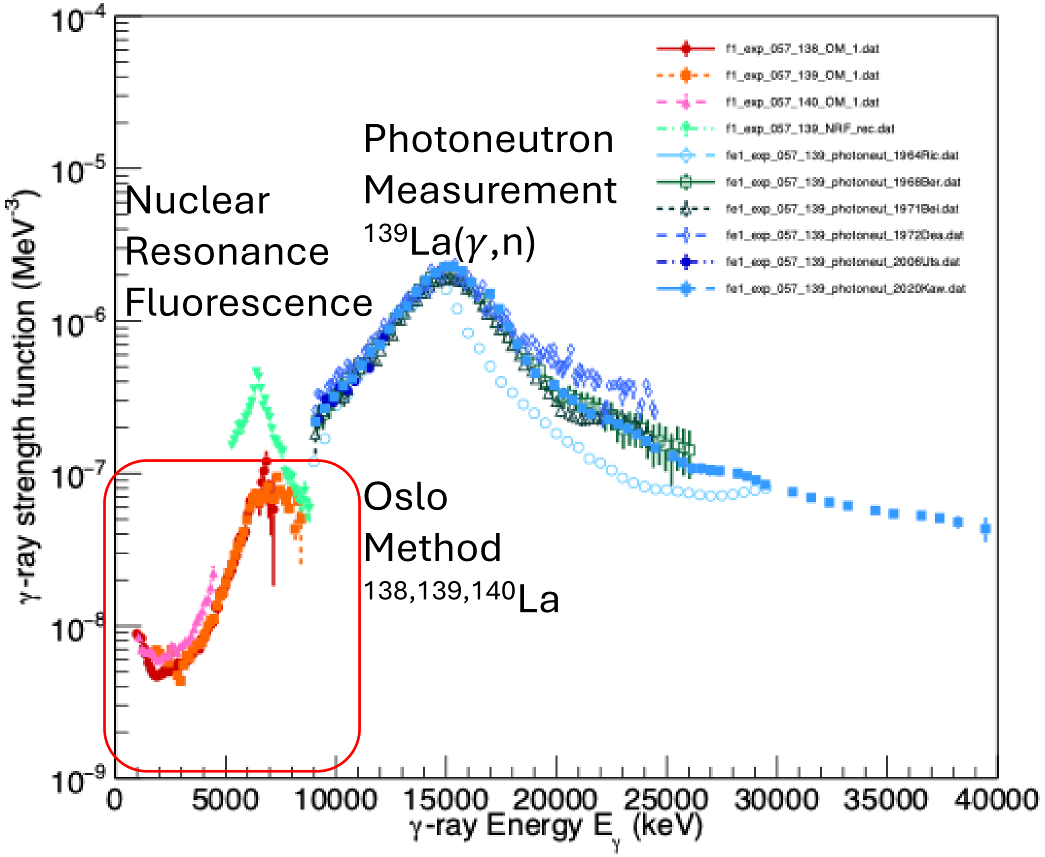

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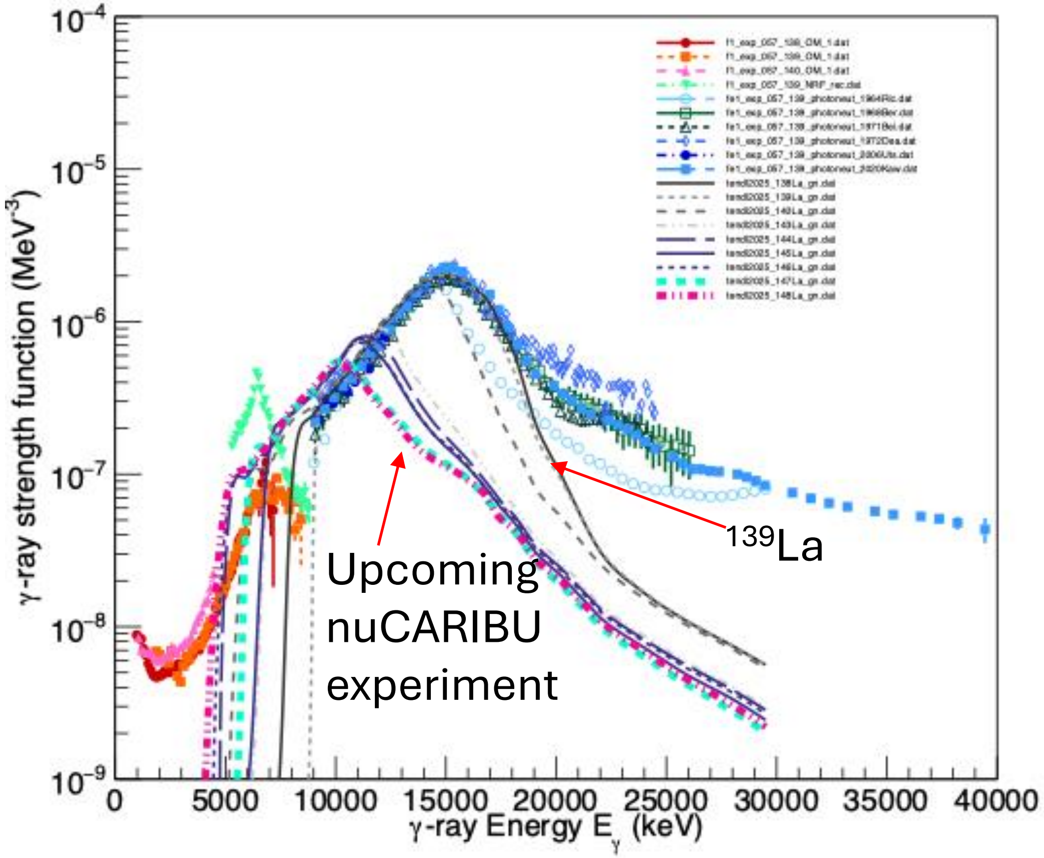

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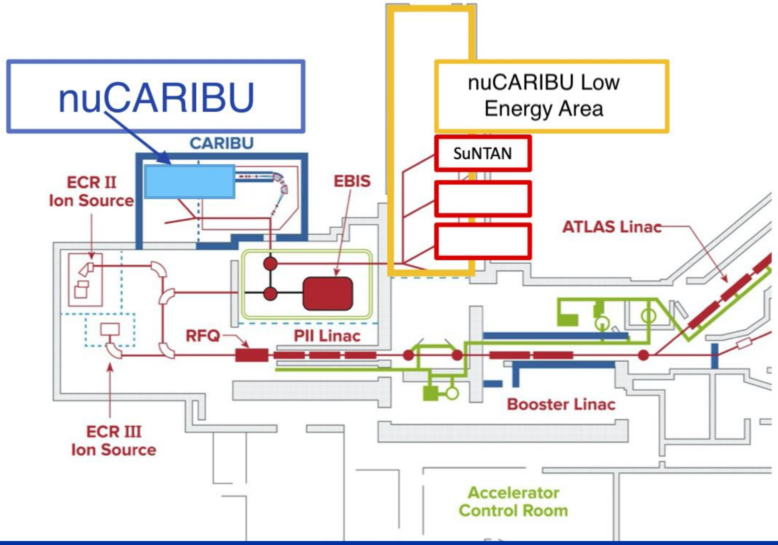
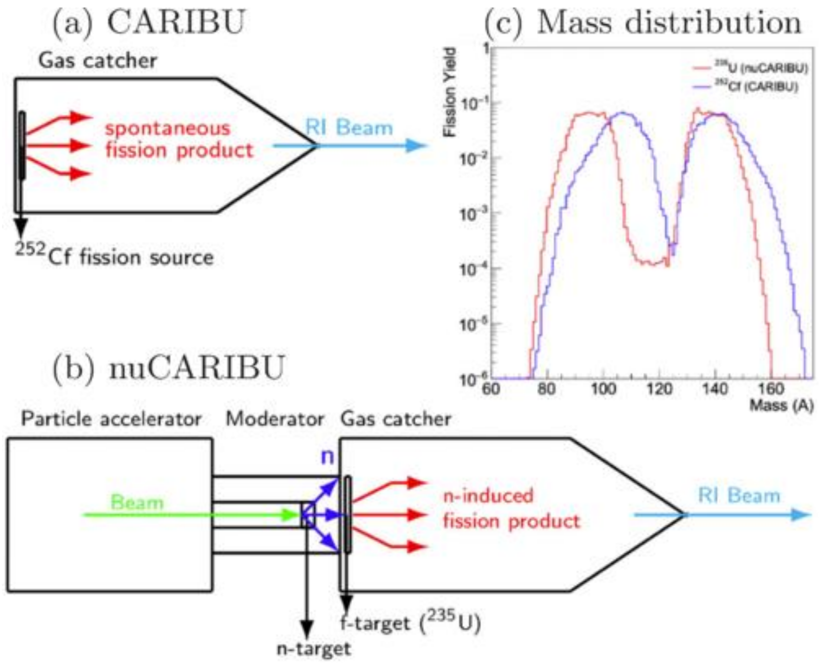
What’s new at ATLAS/nuCARIBU facility?

- DOE nuclear physics national user facility
- Neutron induced fissions on ^{235}U
- Neutrons generated by ^{7}Li(p,n)^{7}Be
- Shift fission fragment spectrum with gains in $A<100$ & $120<A<150$
- First low-energy radioactive beam extracted last summer & scheduling experiments in progress





^{147,148}Ba beam experiment expected to run by end of year 🤞

nuCARIBU facility schematic by Guy Savard
J. Song G. Savard, J. Greene, and J. A. Nolen, Phys. Rev. C. **109**, 024605 (2024)

Experimental setup at nuCARIBU

- **SuN** — the summing NaI(Tl) detector — a high efficiency γ-ray calorimeter
    - 16 in by 16 in cyclinder with a 1.8 in diameter bore hole
    - 8-fold segmented NaI(Tl) barrel
    - 3 photomultiplier per crystal= 24 PMTs
- **SuNTAN** — SuN+Tape Station for Active Nuclei — prevents build up of activity from decay daughter
    - “9-track” tape, i.e, 0.5 in wide by 35 μm thick mylar tape
    - Al box
    - Stepper motor
- **SuNSPOT** — SuN Scintillating Plastic Optical Transport— a new β-particle detector fitted inside SuN
    - 20 cm x 3 mm x 9 mm octagonal barrel
    - 1 mm multi-clad wavelength shifting optical fibers
    - Coupled to two photomultiplier tubes

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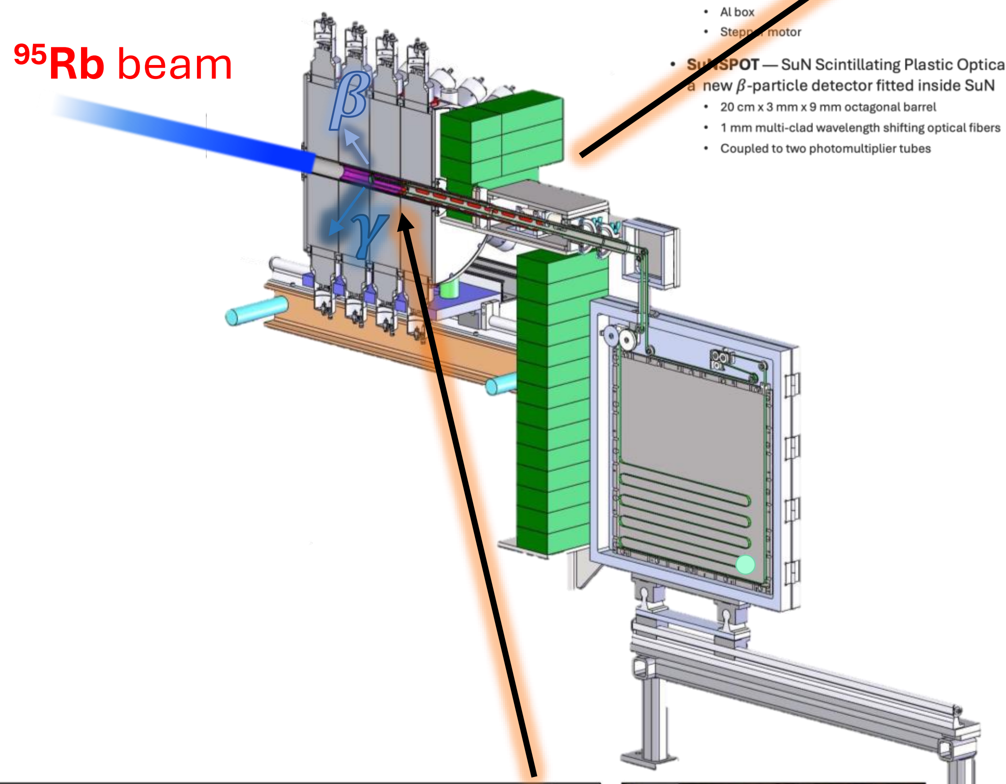
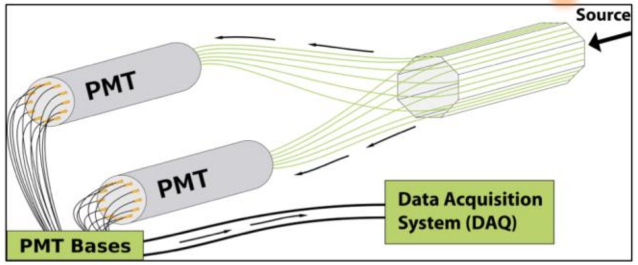
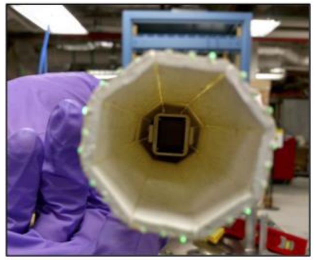
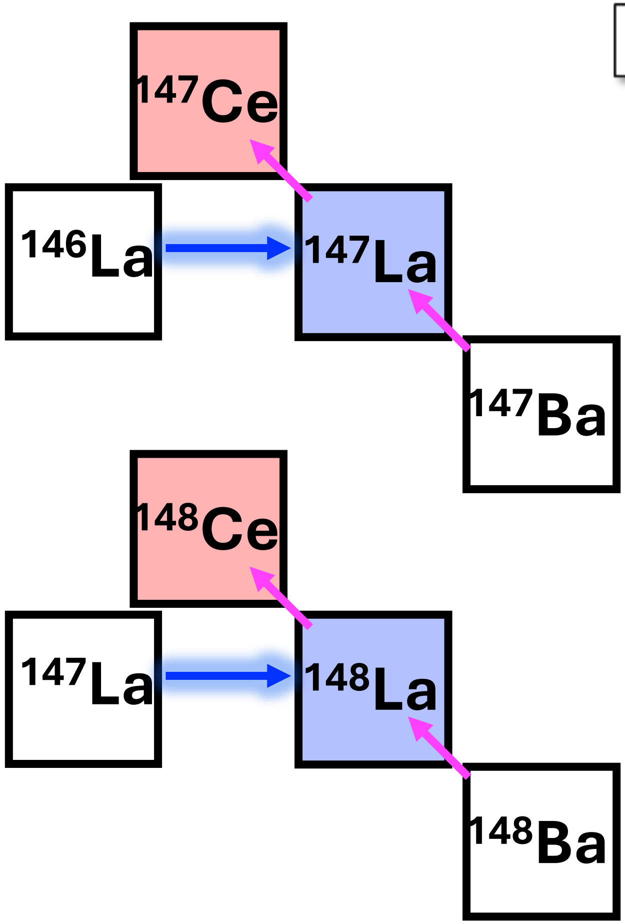


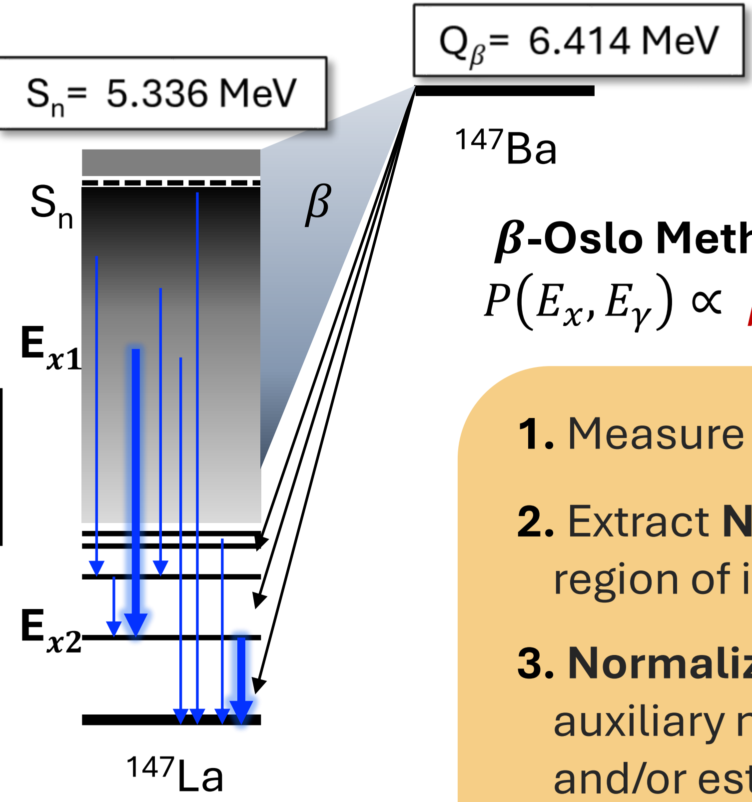




A. Simon, S. J. Quinn, A. S., et al., Nucl. Instr. Meth A 703 16 (2013)
C. M. Harris, et al., Nucl. Instr. Meth A 1084 (2026)
E. K. Ronning, et al., Nucl. Instr. Meth A 1082 (2026)

Indirect technique for determining (n,γ) cross section: β-Oslo method

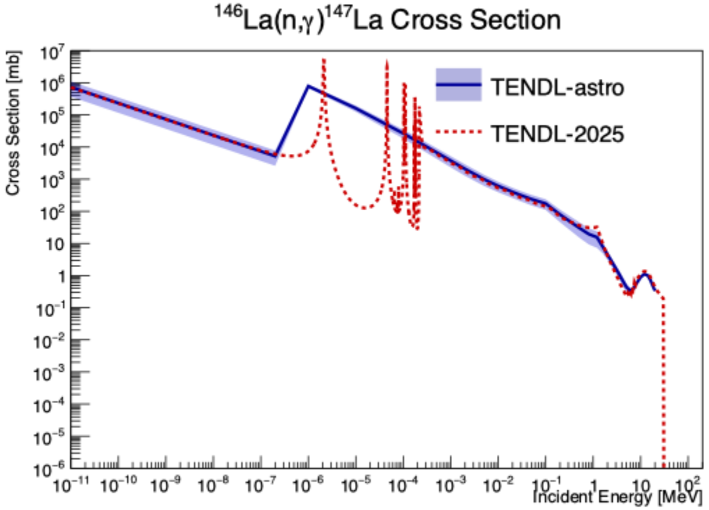


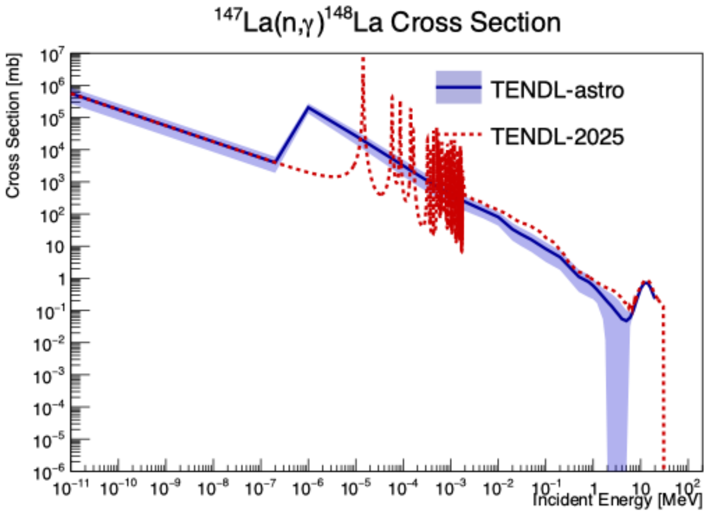


β-Oslo Method assumes:

$$P(E_x, E_\gamma) \propto \rho(E_x - E_\gamma)\,\mathcal{T}(E_\gamma)$$

1. Measure E_x & E_γ
2. Extract **NLD** & **γSF** from region of interest (ROI)
3. **Normalize** using auxiliary nuclear data and/or estimates
4. Constrain the σ(n,γ)

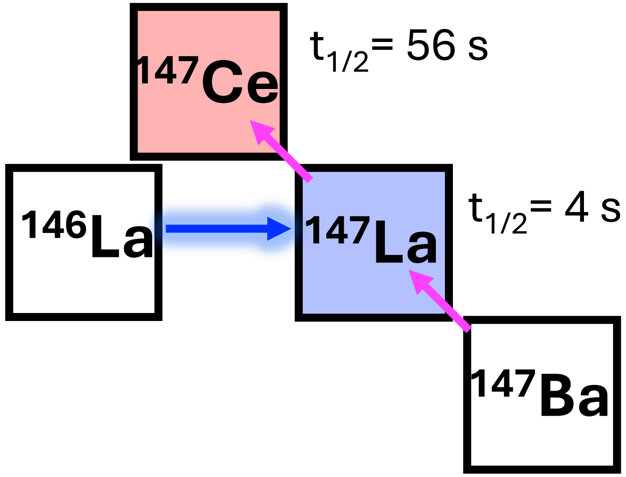

^{146}La(n,γ)^{147}La Cross Section


^{147}La(n,γ)^{148}La Cross Section

(First gen.) M. Guttormsen et al., NIM A **255**, 518 (1987)
(Unfolding) M. Guttormsen et al., NIM A **374**, 371 (1996)
(Extract NLD&PSF) Schiller et al., NIM A **447**, 498 (2000)
(bOM) Spyrou et al., Phys. Rev. Lett. **113**, 232502 (2014)

ENDF https://nds.iaea.org/exfor/endf.htm
TENDL-astro https://www.astro.ulb.ac.be/tendl-astro.html;
Rochman et al., Nuc. Phys A 1053, 122951 (2025)

Radioactive beams of ^{147}Ba and ^{148}Ba

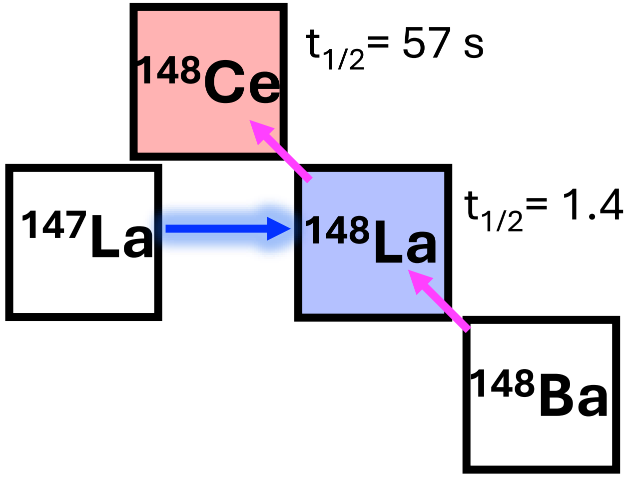


^{147}Ce $t_{1/2}$= 56 s

^{146}La

^{147}La $t_{1/2}$= 4 s

^{147}Ba $t_{1/2}$= 0.894 s

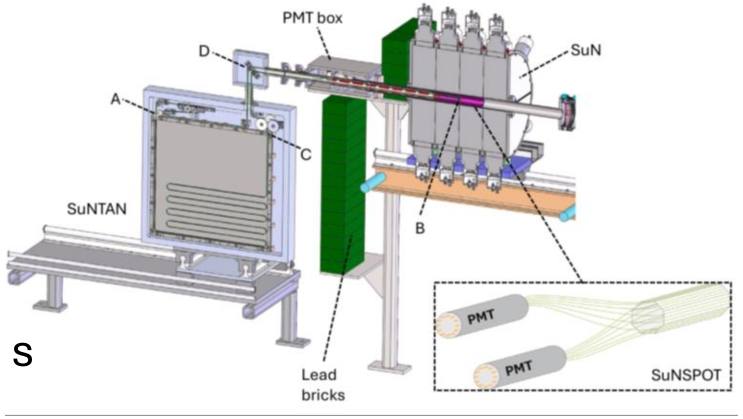


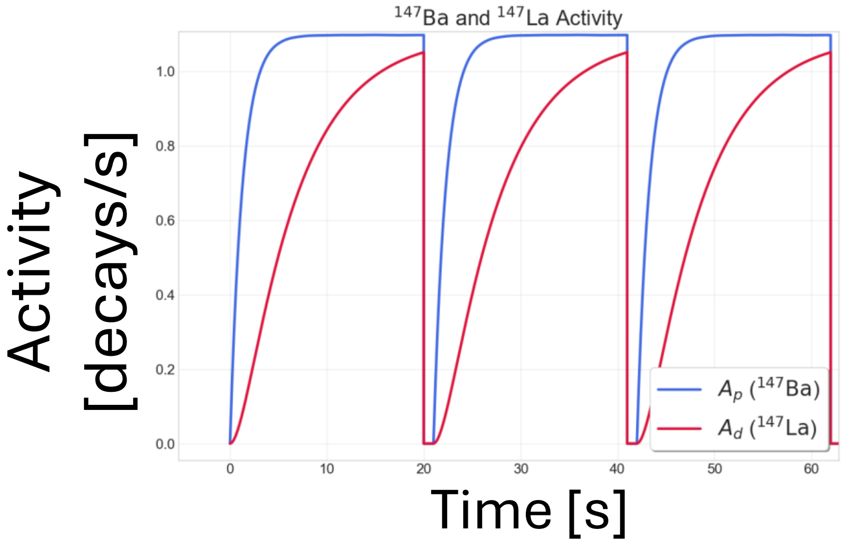
^{148}Ce $t_{1/2}$= 57 s

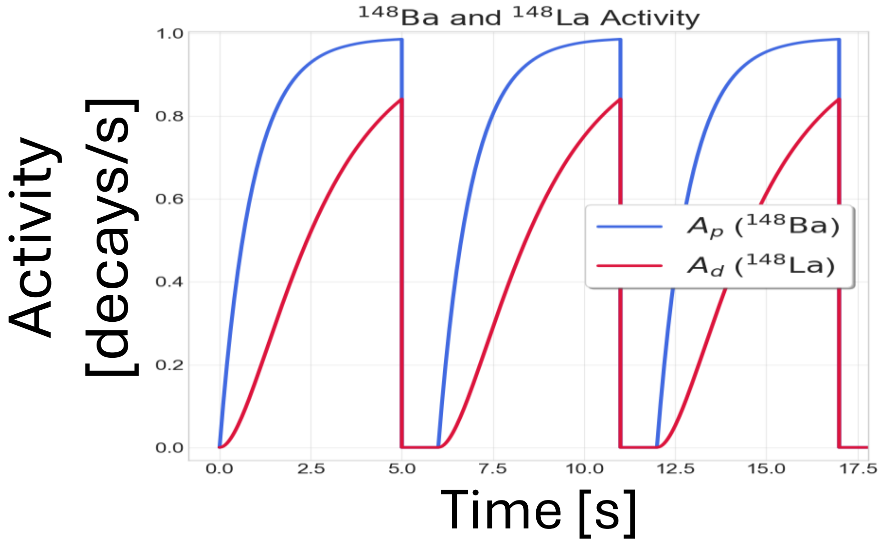
^{147}La

^{148}La $t_{1/2}$= 1.411 s

^{148}Ba $t_{1/2}$= 0.619 s







UC Berkeley,
Undergraduate
Nathan Alejandria

Key steps of the β-Oslo method

- Measure $\gamma - \beta$ coincidence with TAS detector
- Develop decay specific detector response function
- Unfold the raw measurement
- Isolate the first γ ray emitted from each excited state

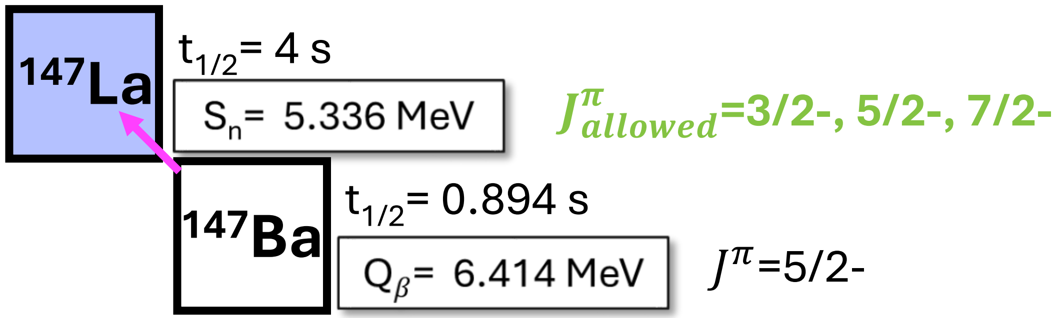
First generation γ rays

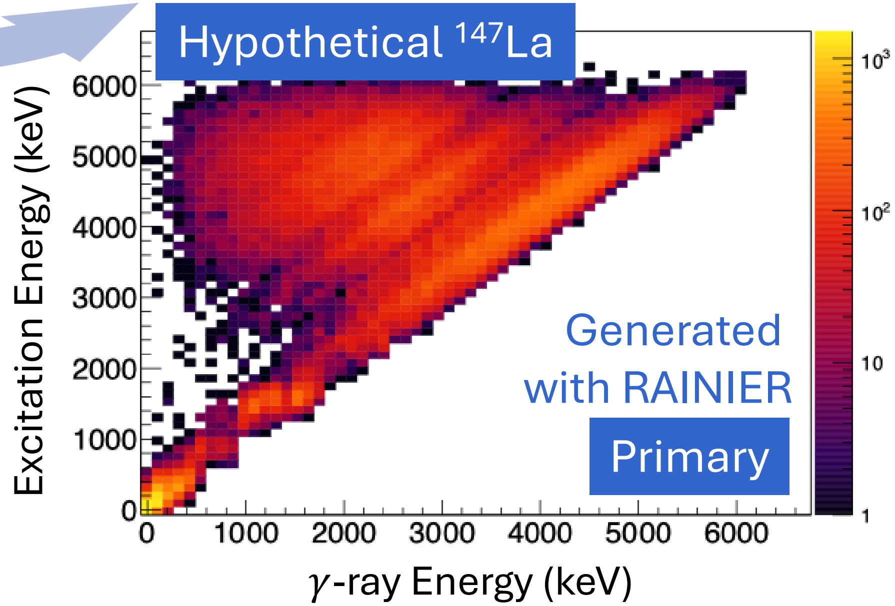
Nuclear level density (NLD) and γ-ray strength function (γSF)

First generation γ rays represent the probability to decay from an initial E_i to final E_f by emitting a γ with energy E_γ

- Anchor NLD to **discrete levels at low energy** & to **estimate total level density at the neutron separation energy**
- Adjust for **β-decay populated states**
- Scale γSF to estimated **average total radiative width**

Normalize NLD and γSF





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(RAINIER) L.E.Kirsch, L.A.Bernstein. NIM A. 892 (2018)

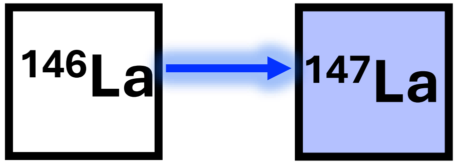
β decay, advantages and drawbacks

\+ Generally, β decay populates states well above the neutron separation energy for exotic nuclei

\- Range of spins populated by β decay can be very limiting

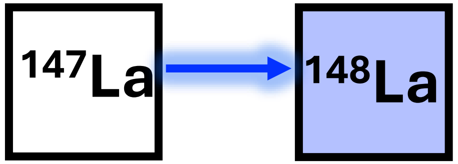
\- β-delayed neutrons limit analysis region, narrow excitation energy range and higher γ-ray energy threshold

s-wave neutron capture



Ground state
J^{π}=2-

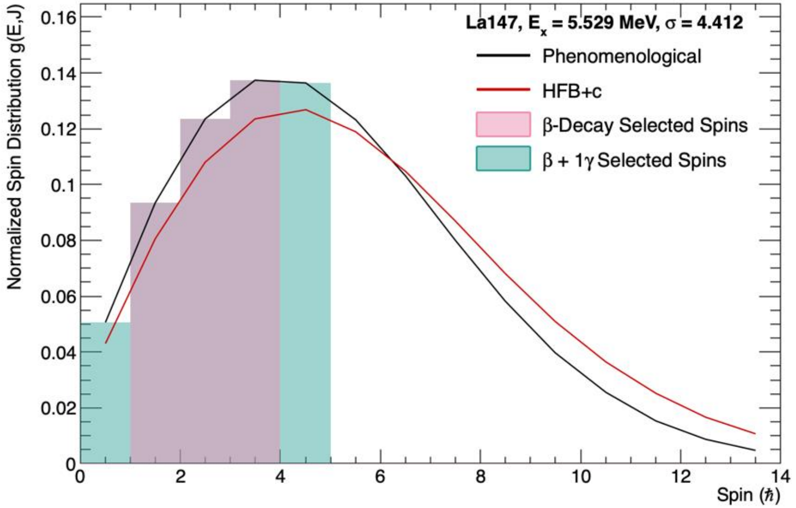
Capture state
J^{π}=3/2-, 5/2-

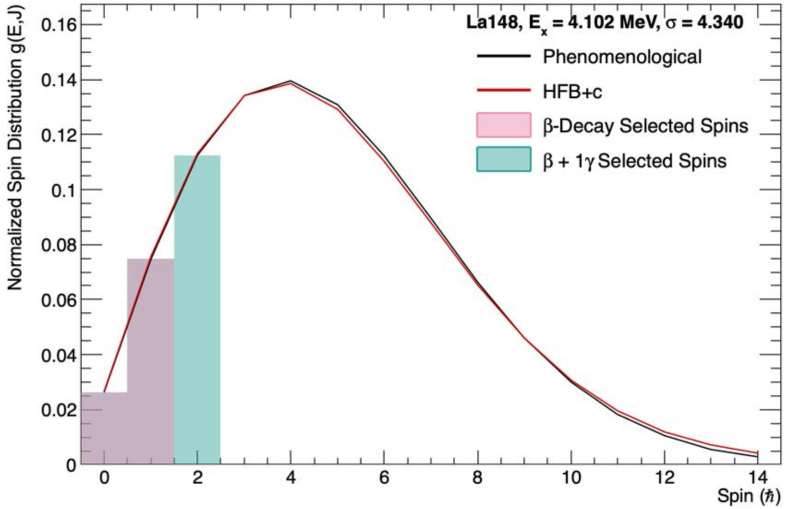


Ground state
J^{π}=5/2+

Capture state
J^{π}=2+, 3+

β decay



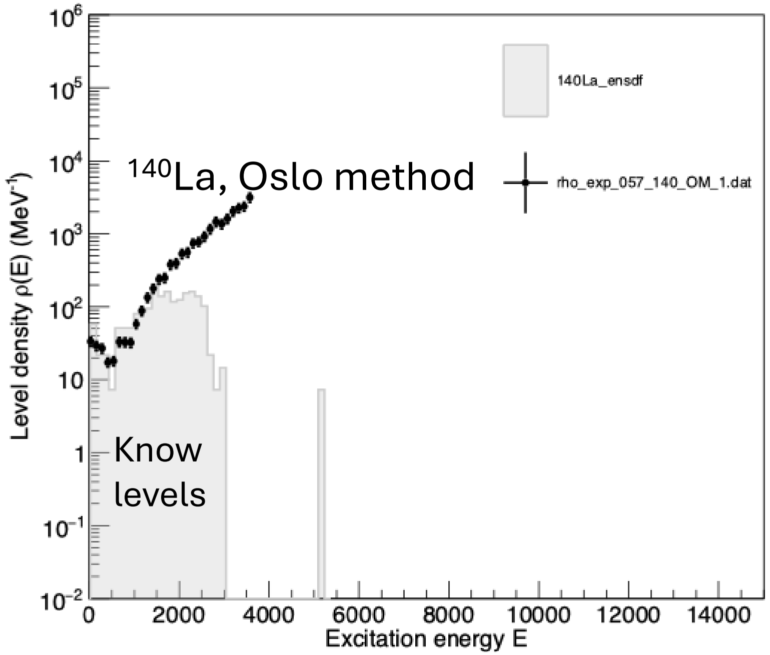


Challenges ahead for extracting the nuclear level density

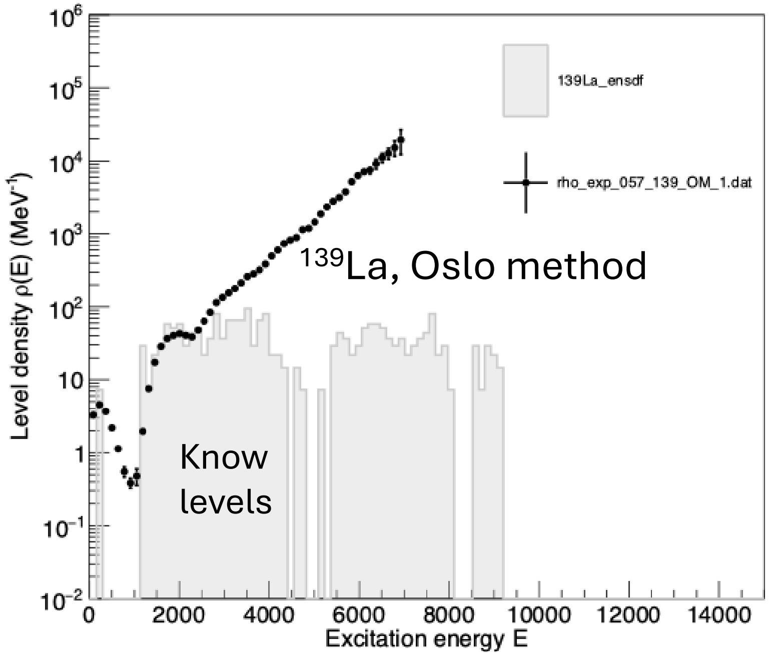
Decay	Q-value (MeV)	S_n (MeV)	$\rho(S_n)$ (1/MeV), CT estimate
^{147}Ba→^{147}La	6.414	5.336	1.06E+05
^{148}Ba→^{148}La	5.164	4.102	5.9E+04

- ^{147,148}La, known levels plateau at ~0.5 MeV
- β decay data is also sparse
    - ^{147}La: I_β is know up to 1.757 MeV
    - ^{147}La: I_β is know up to 0.471 MeV

Even-A La



Odd-A La



B. V. Kheswa et al., Phys. Rev. C 95, 045805 (2017)

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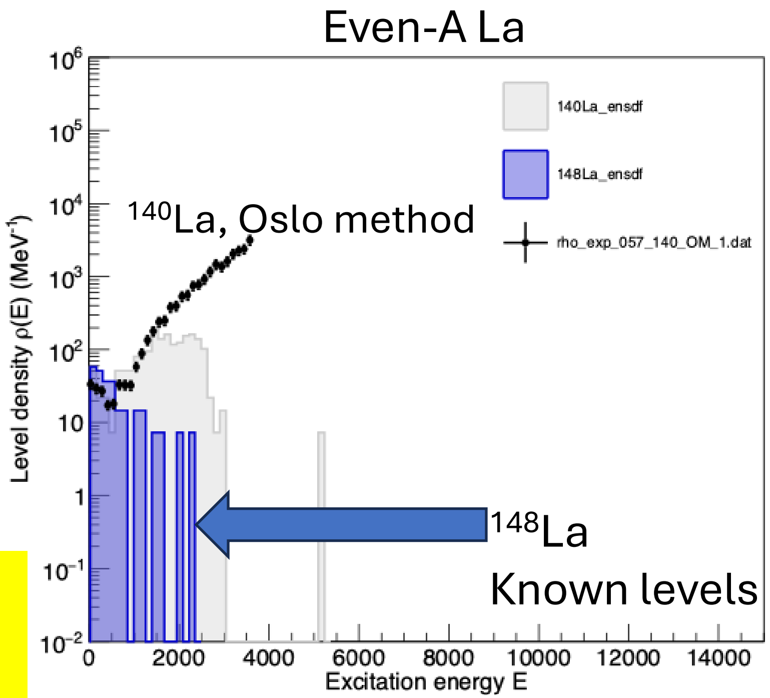
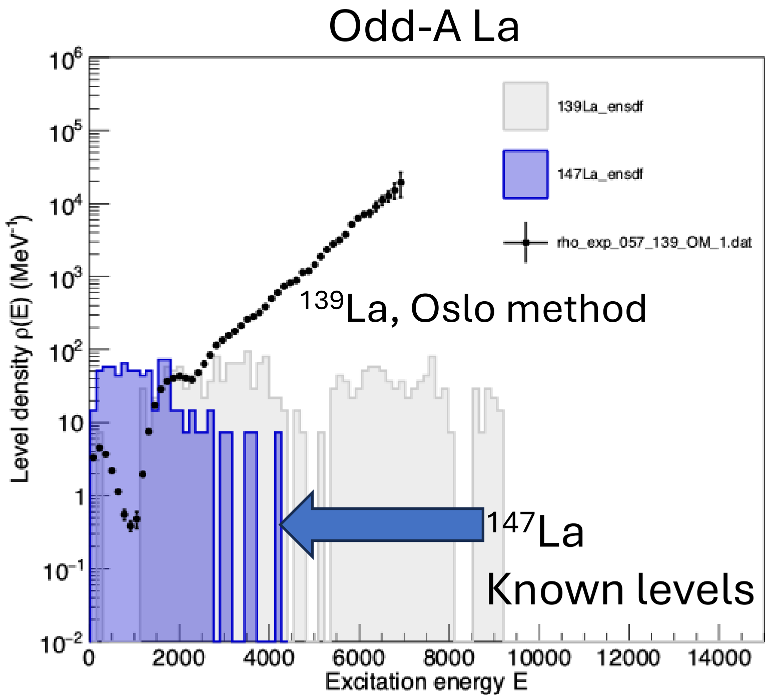
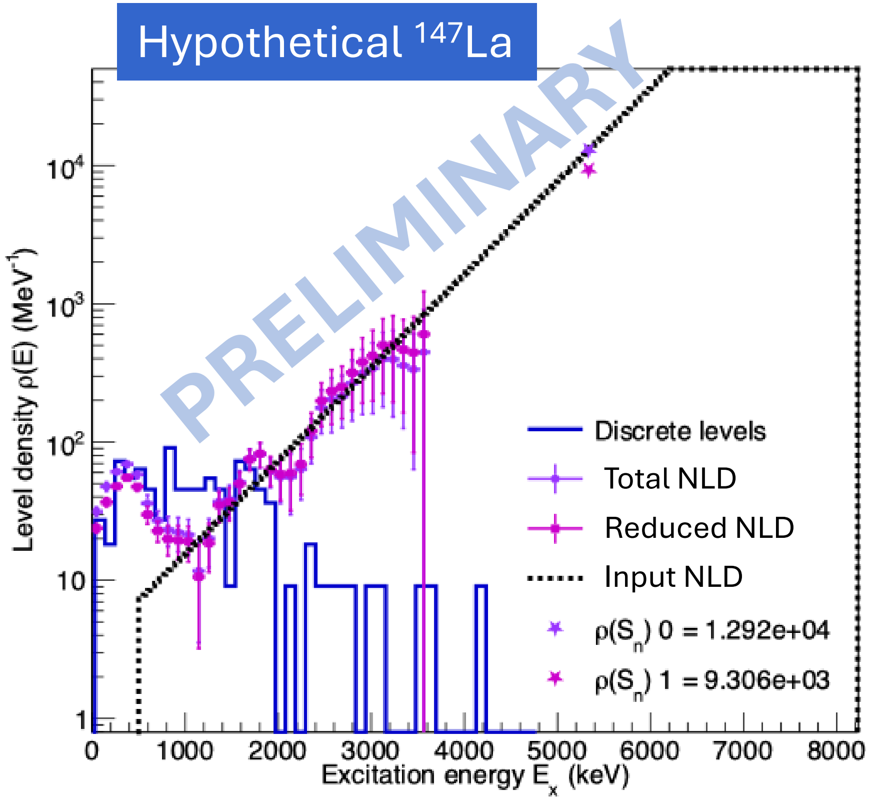


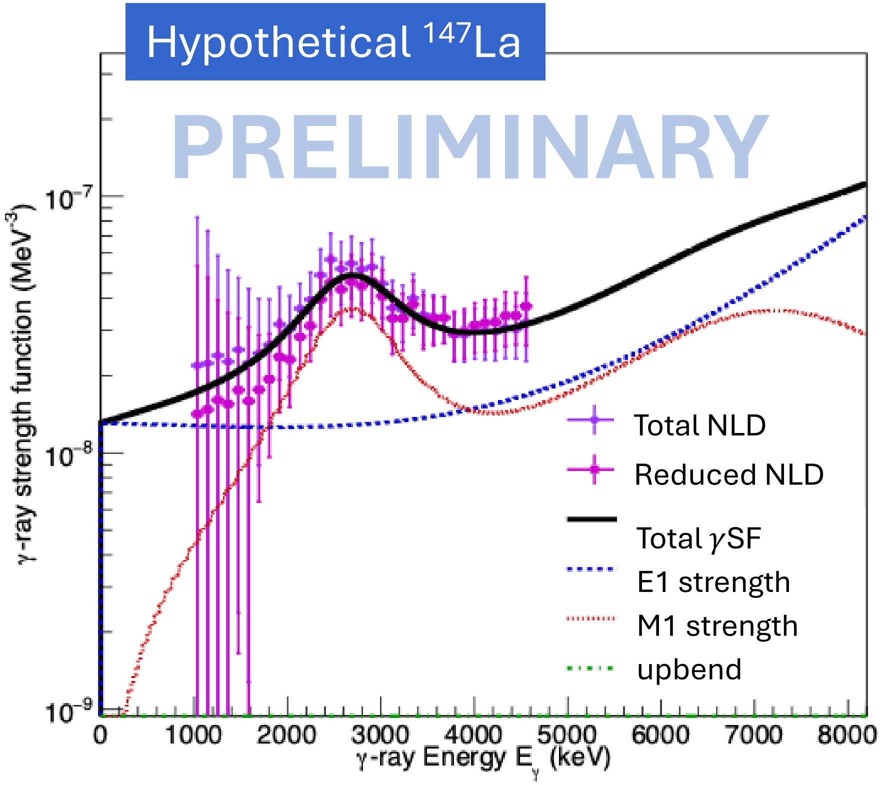


An opportunity here to contribute much needed energy level scheme and β-decay branching ratio data!

B. V. Kheswa et al., Phys. Rev. C 95, 045805 (2017)

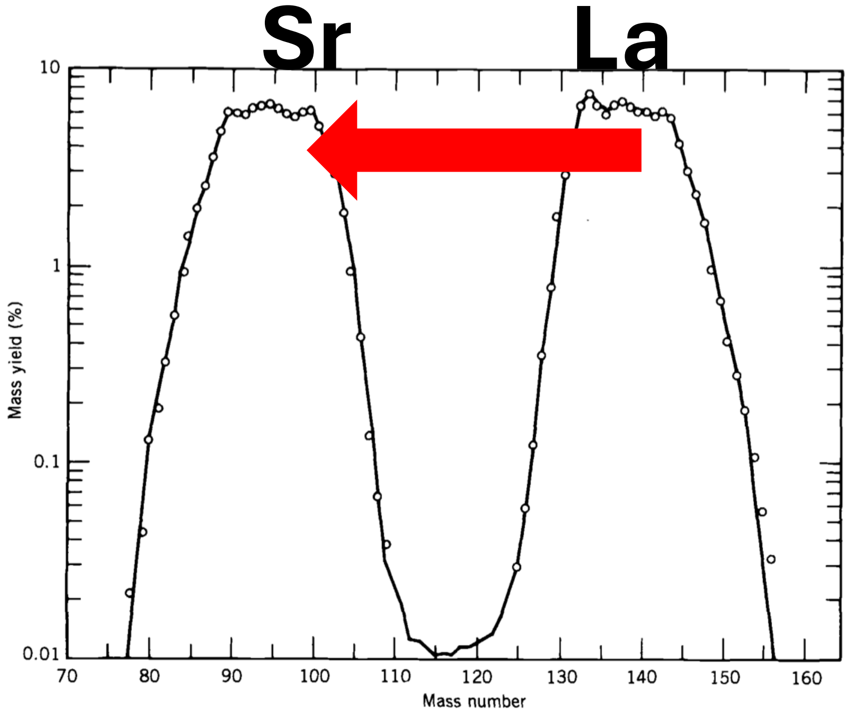
Experiment preparation using synthetic data generated with RAINIER


Hypothetical ^{147}La


Hypothetical ^{147}La

Model combinations and restricted spin-ranges will be used to quantify systematic unertainty.

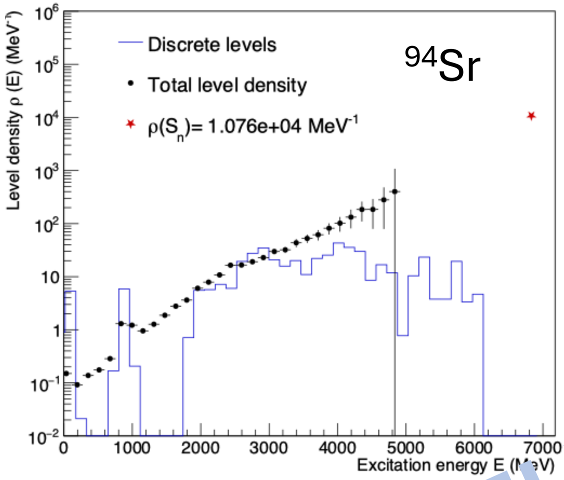
Switching gears

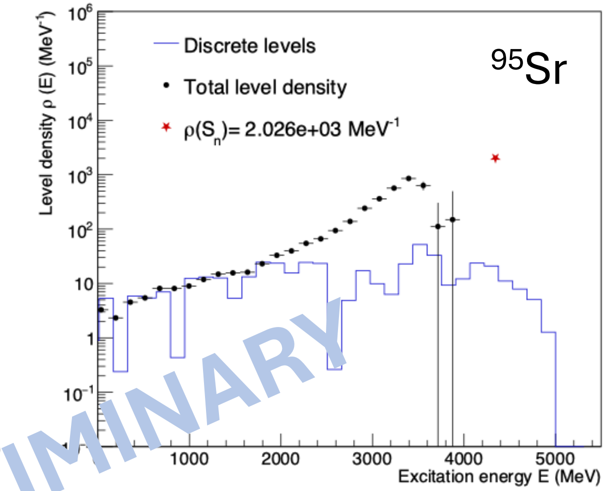


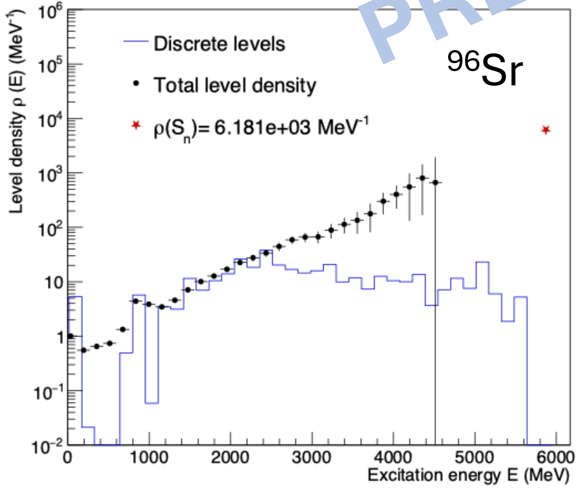
Krane, K.S. (1988) Introductory Nuclear Physics. Wiley John & Sons, New York.

PRELIMINARY

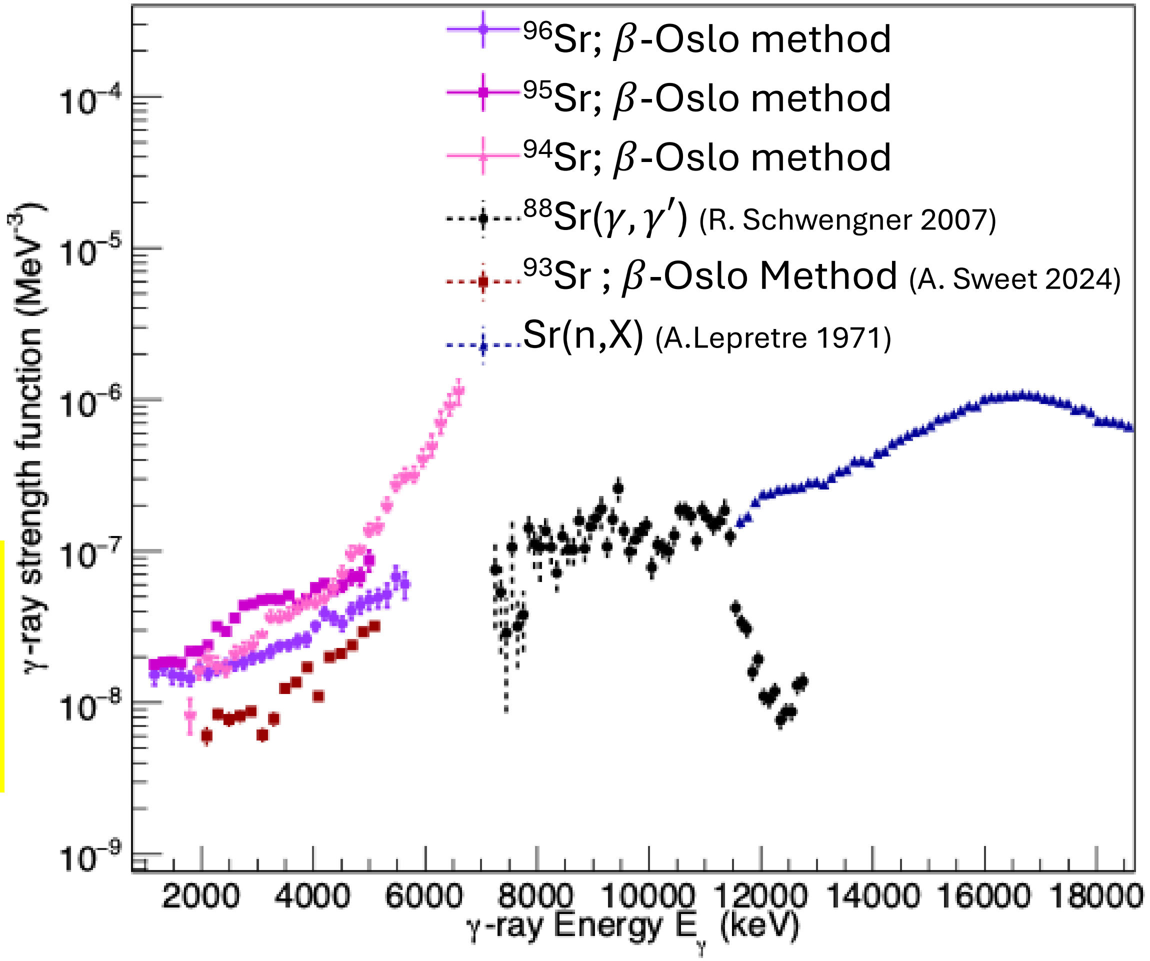
Back to the lighter side of the fission fragment curve







For exotic nuclei, the β-Oslo method and surrogate reaction method will be compared for the first time!



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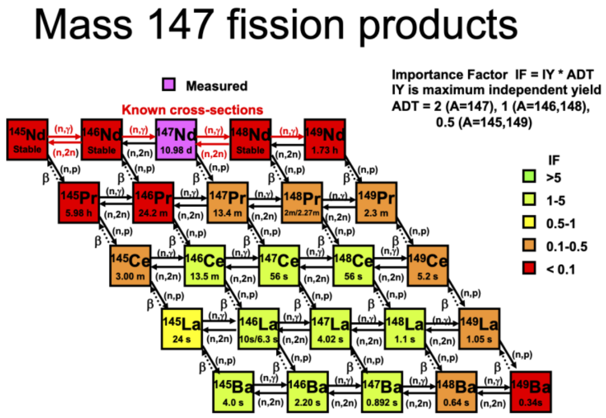
See Prof. Andrea Richard’s talk tomorrow!

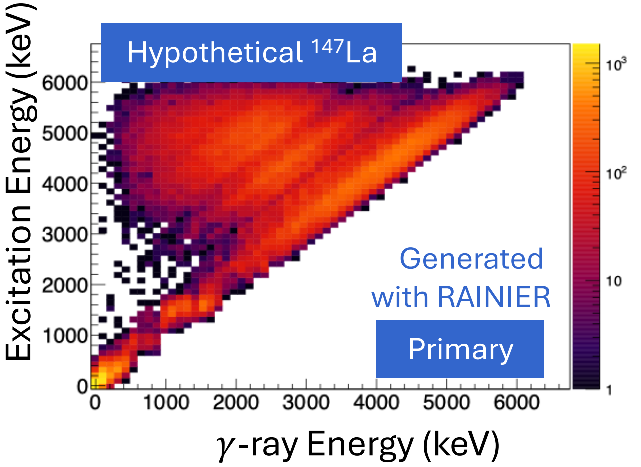
Summary and Outlook

- La isotopes are needed to improve reaction network calculations.
- La isotopes are an interesting case due to possible octupole correlations.
  - A decrease in E1 strength enhancement with increasing N
  - Chance to investigate near expected structure change at N = 92
- Spectroscopy data is sparse! An opportunity to contribute much needed β-decay data.



Next Steps:

- Experiment preparations for ^{147,148}La β-Oslo measurements are underway using synthetic data generated with RAINIER.
  - Investigating the variance in model combination
  - Impact of restricted spin-range
  - Can the Shape method complement the β-Oslo method analysis in these cases?
- Evaluation of alternative methods to normalize the NLD and γSF for Sr isotpes, i.e., *Shape Method* [M. Wiedeking *et al.*, PRC **104** (2021), D. Mücher et al., PRC **107** (2023)].
- Refine systematic uncertainties of experimental Sr cross section results to compare to TENDL-2025 recommendations.
- Benchmark with Surrogate Reaction Method for **^{93}Sr(n,γ)^{94}Sr** and **^{95}Sr(n,γ)^{96}Sr.**



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