Nuclear data measurements of Ni and Cr thermal capture γ-rays

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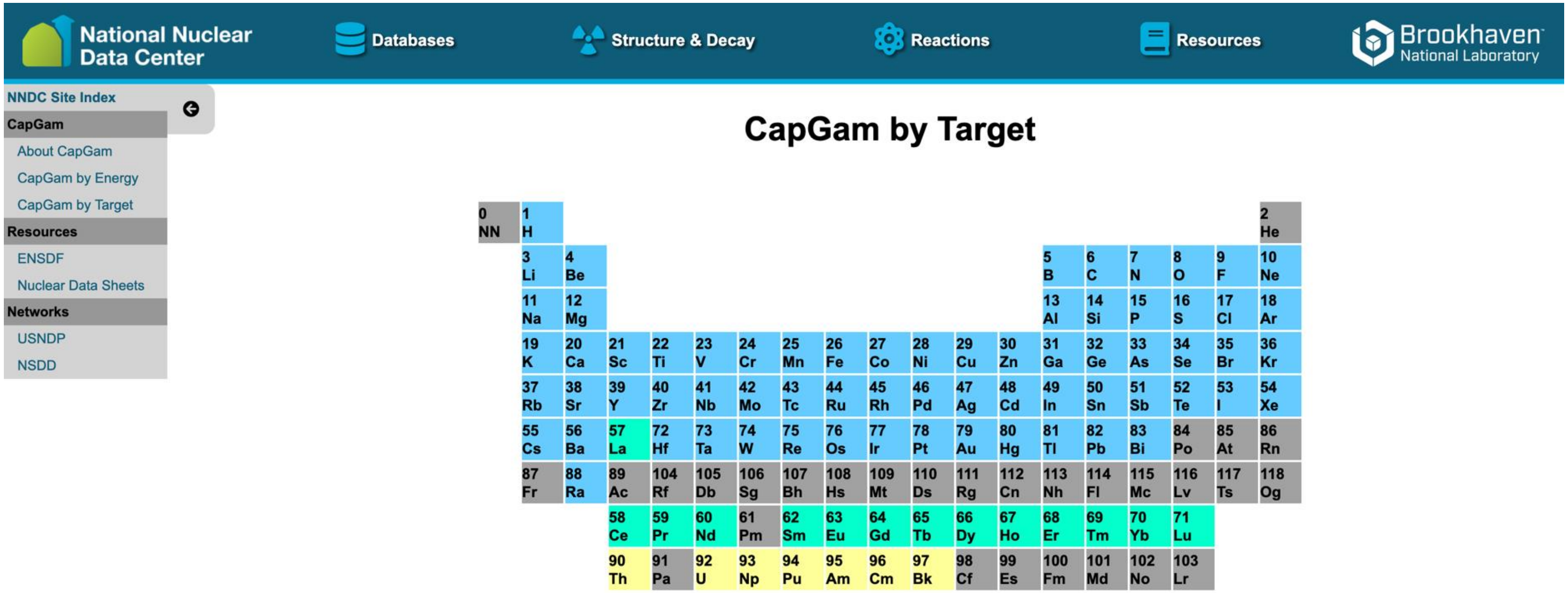
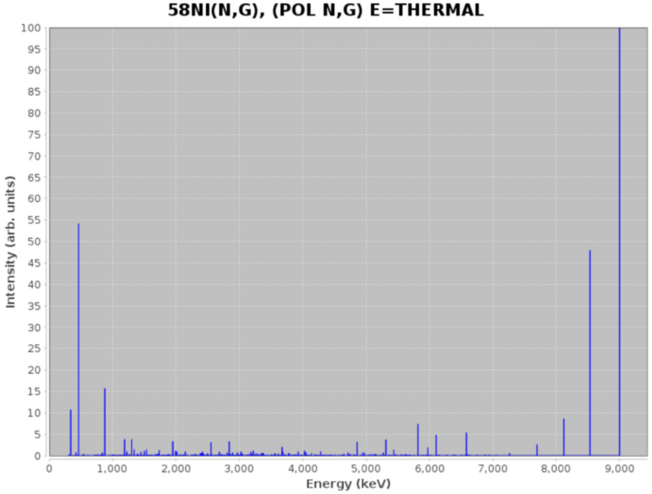
Brookhaven National Laboratory, USA

2026/1/7 – Nuclear Data Week, BNL

Thermal neutron capture γ-ray data





58NI(N,G), (POL N,G) E=THERMAL

59NI(N,G) E=THERMAL

60NI(N,G),(POL N,G) E=THERMAL

Type	E(γ)	ΔE(γ)	I(γ) / I(γ) (max)	Δ I(γ) / I(γ) (max)
Primary	8998.63	0.07	100.0	2.0365
Secondary	464.94	0.03	54.1	1.5556
Primary	8533.71	0.07	47.8	0.9982
Secondary	877.94	0.03	15.6	0.2667
Secondary	339.418	0.015	10.6	0.2845
Primary	8120.75	0.07	8.50	0.1888
Primary	5817.35	0.05	7.30	0.1425
Primary	6583.98	0.06	5.25	0.1044
Primary	6105.38	0.06	4.71	0.0955
Secondary	1188.77	0.03	3.69	0.0656
Secondary	1301.44	0.03	3.68	0.0654
Primary	5312.95	0.04	3.62	0.0677
Secondary	1949.92	0.03	3.25	0.0819
Secondary	2842.10	0.04	3.23	0.0574

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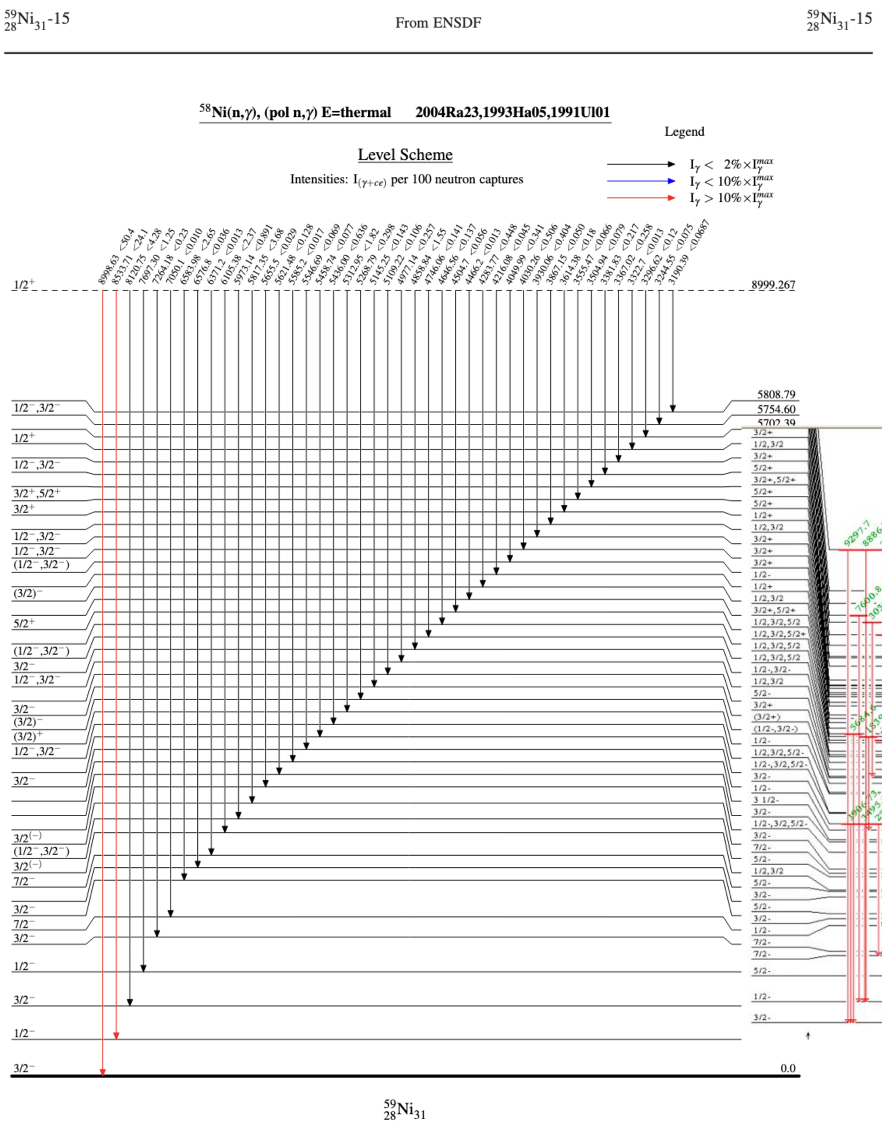
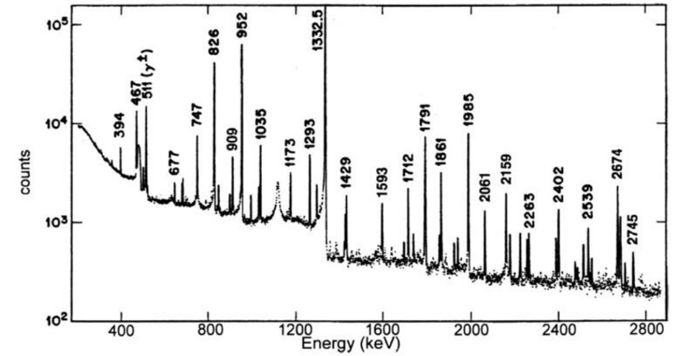
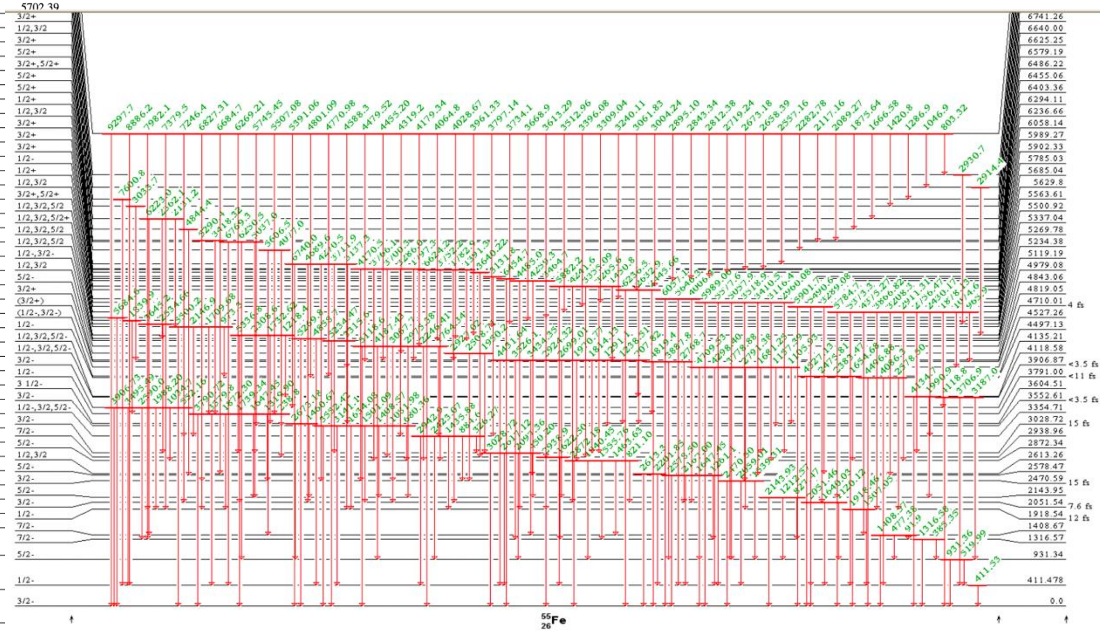
$(n_{thermal},\gamma)$ spectroscopy for ENSDF

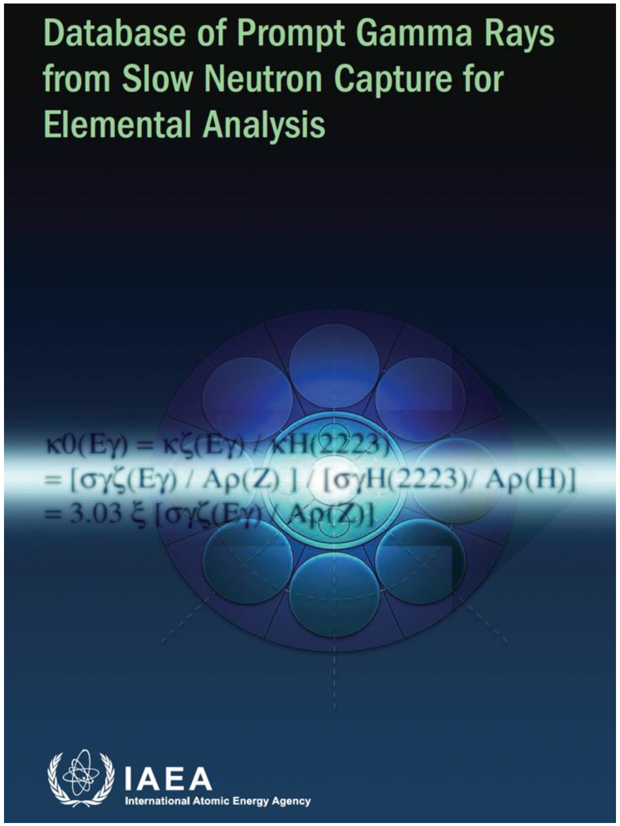




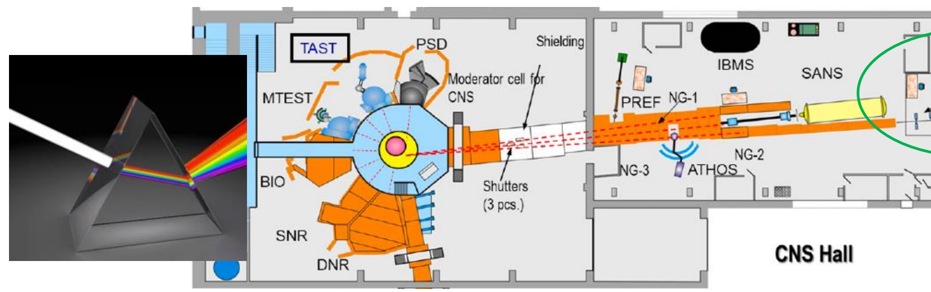


Thermal neutron capture γ-ray data

Prompt Gamma Activation Analysis (PGAA)



- Non-destructive assay to determine isotopic composition of materials
- Based on thermal/cold (n,γ)

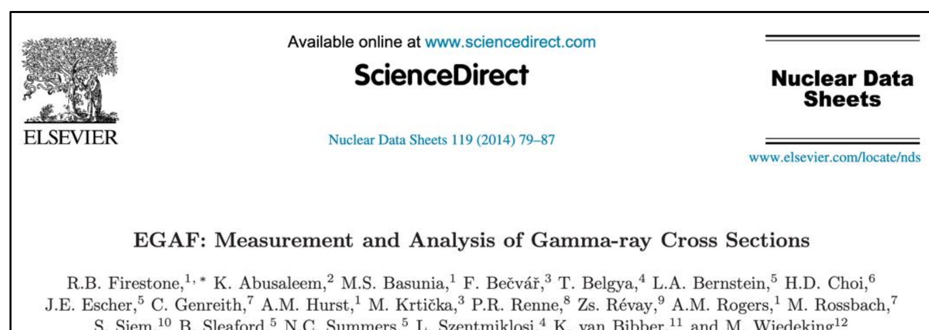


IAEA-coordinated project at Budapest Research Reactor (2000-2007)

$$\Sigma\, \sigma_{\gamma \rightarrow gs} = \sigma(n,\gamma)$$
$$\Sigma\, \sigma_{\gamma,prim} = \sigma(n,\gamma)$$

Understanding individual γ intensities (partial cross sections) allows us to cross check $\sigma(n,\gamma)$

Evaluated Gamma-ray Activation File (EGAF)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EGAF: Measurement and Analysis of Gamma-ray Cross Sections

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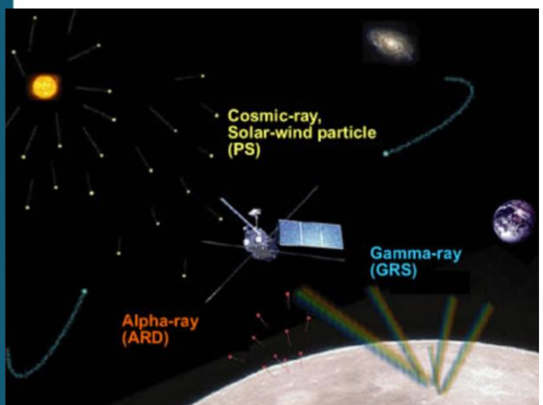
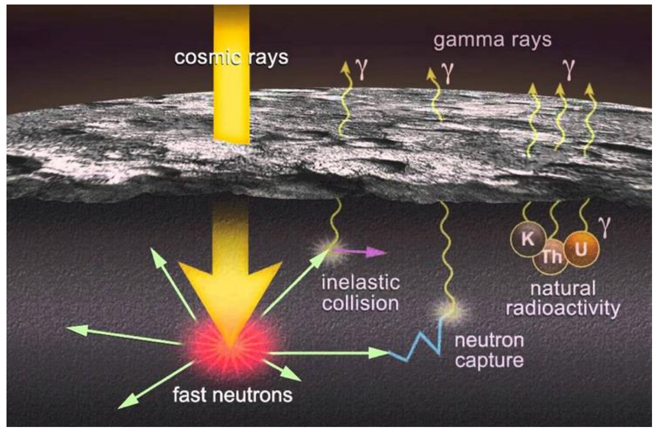
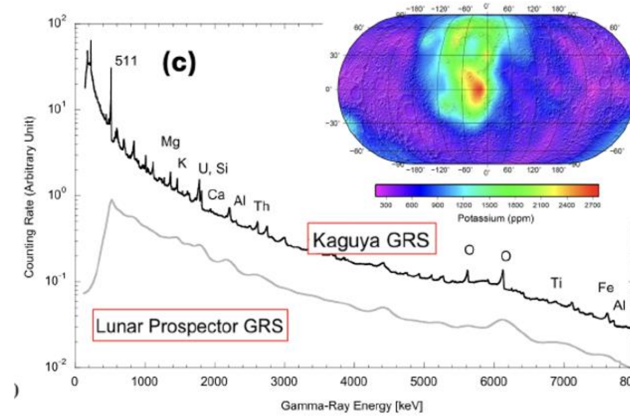
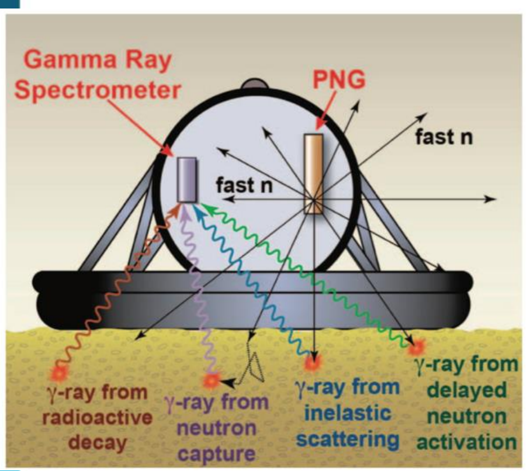
Nuclear application with ($n_{thermal}$,γ)
- planetary science, oil logging -









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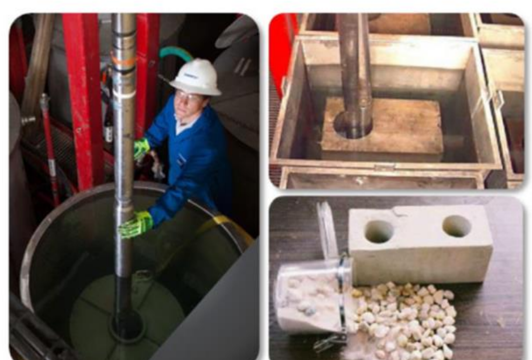


Overview of the Gamma Rays Induced by Neutrons (GRIN) Project

Author: BROWN, David (Brookhaven National Laboratory)

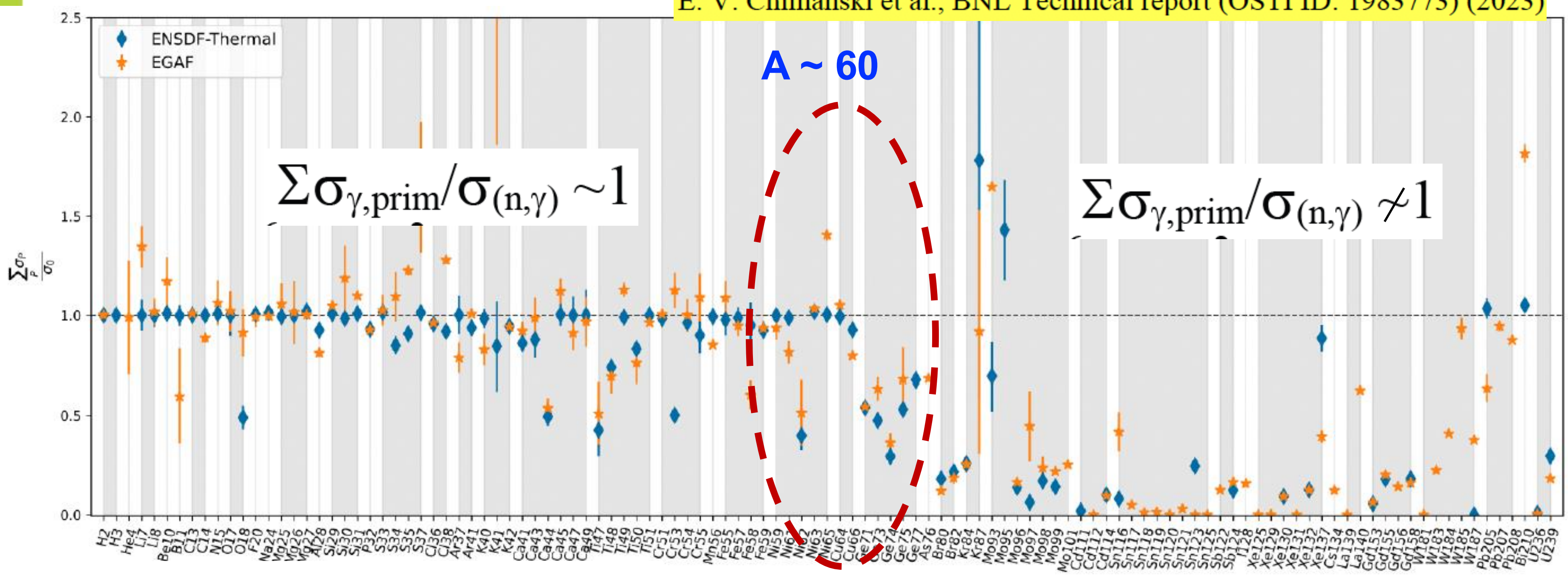
Co-authors: HURST, Aaron (LBNL); LEWIS, Amanda; BECK, Bret (LLNL); MATTOON, Caleb (LLNL); MORSE, Chris (BNL); MCCUTCHAN, Elizabeth (BNL); CHIMANSKI, Emanuel (BNL); GERT, Godfree (LLNL); NOBRE, Gustavo (BNL); OTA, Shuya (BNL)

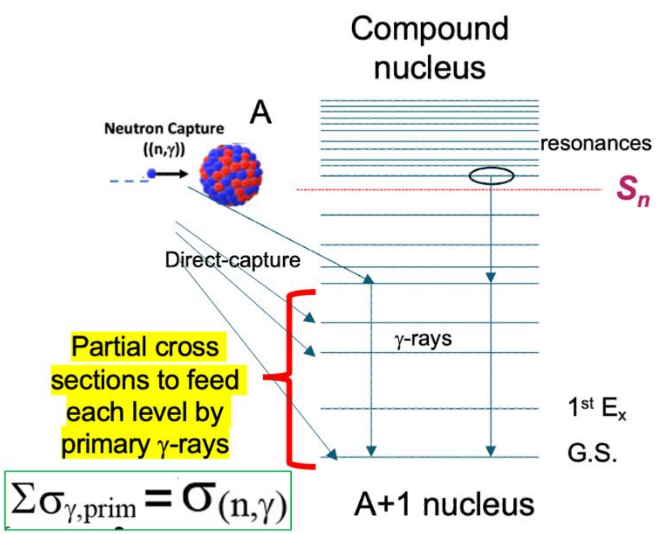
Presenter: BROWN, David (Brookhaven National Laboratory)

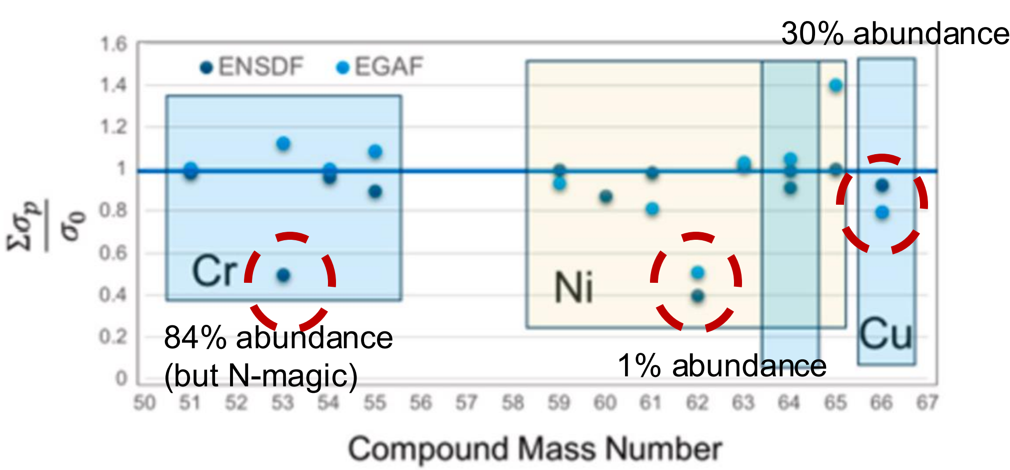
NA-22 (2021-2024)

Missing Primary γ-rays from GRIN 😁

E. V. Chimanski et al., BNL Technical report (OSTI ID: 1983773) (2023)







FAIR (2023-2026 funded by DOE) at UMass Lowell Research Reactor

DE-SC0024373: M. Jandel & S. Ota

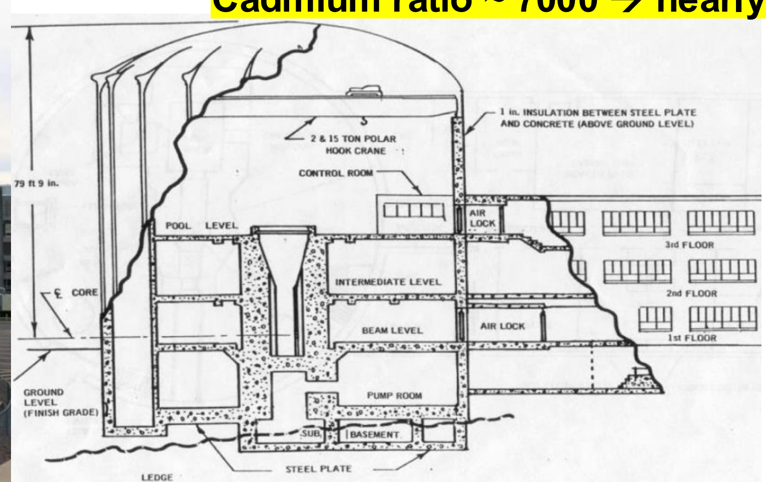
Goals

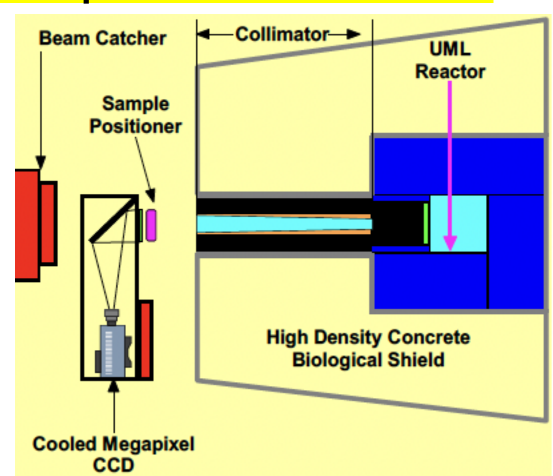
- Enhance thermal neutron capture gammas on Cr, Ni, and Cu (A~60)
- Develop experimental setup and tools (detectors, DAQ, analysis codes, etc.)
- Offer UML graduate students training on experiments and ENSDF evaluations

UML RESEARCH REACTOR

- 1 MW – in core flux 2×10^{13} n/cm^2/s
- Pool of 75,000 gallons of demineralized water
- Various irradiation capabilities available
- https://www.uml.edu/research/radlab/

$10^{5\text{-}6}$ n/cm^2 at 1 MW (max) Thermal neutron flux on target
Cadmium ratio ~ 7000 → nearly no epithermal/fast neutrons



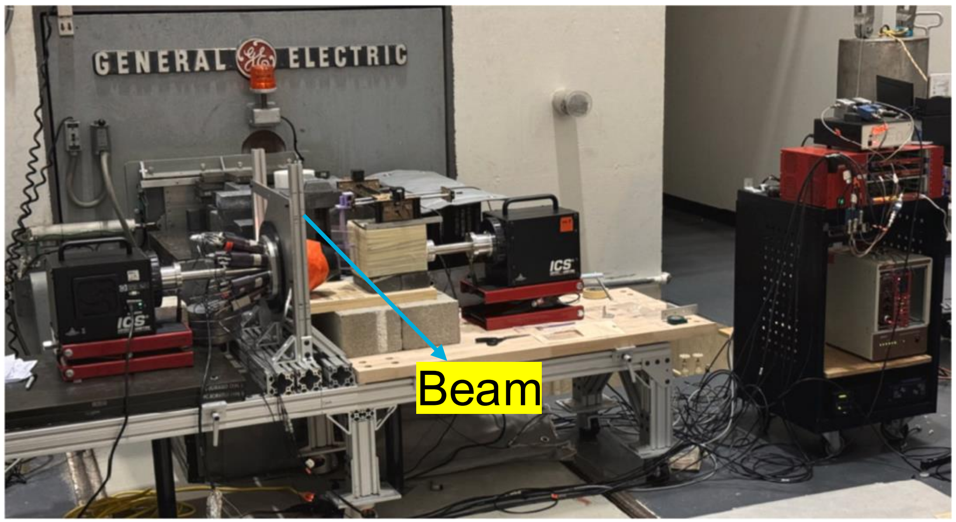


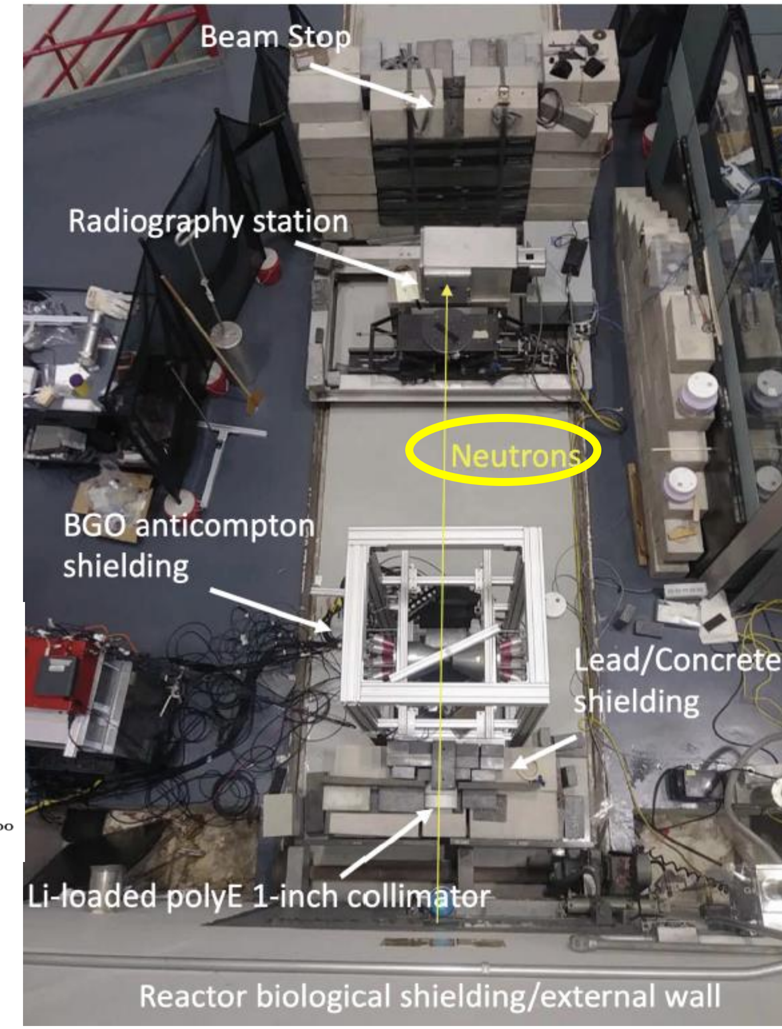
FAIRRAY HPGe array

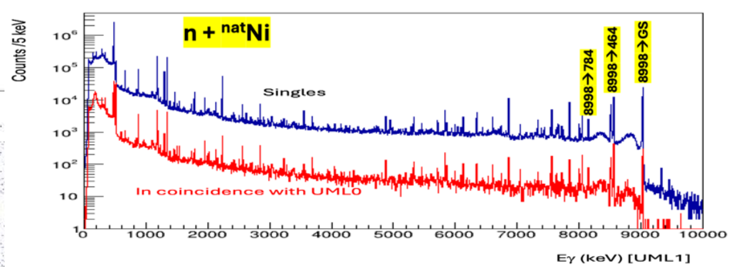
Two ORTEC HPGe (mechanically-cooled); two more HPGe are arriving soon.

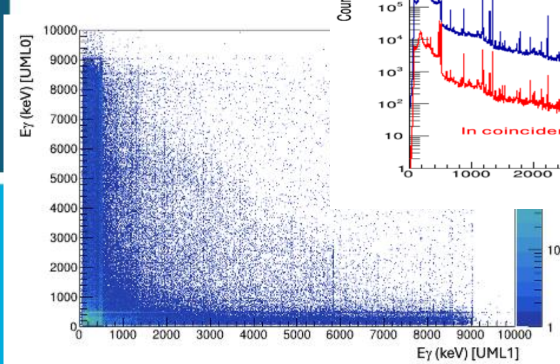
- ε_{rel} = 30% each.
- One with BGO (11 cm from target)
- The other with Pb shielding (6 cm from target)

See M. Jandel et al. Nucl. Phys. A (2025) for detail





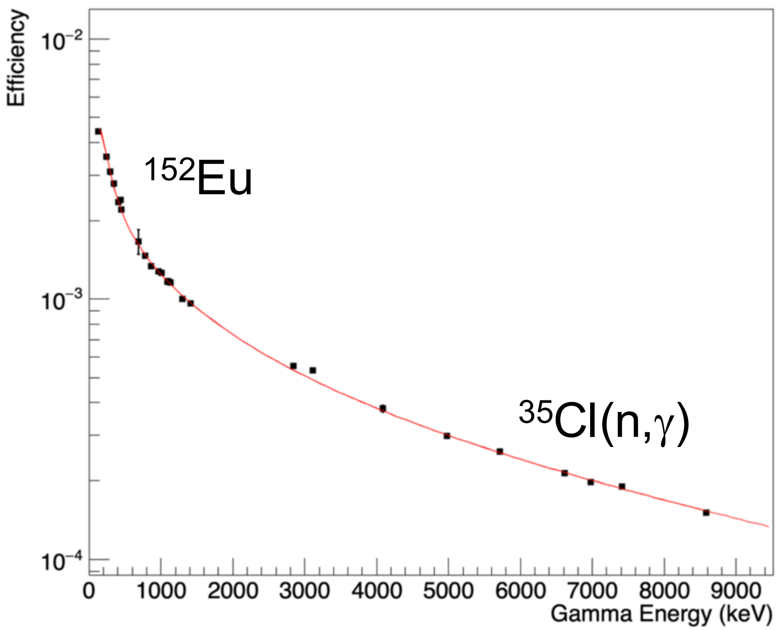




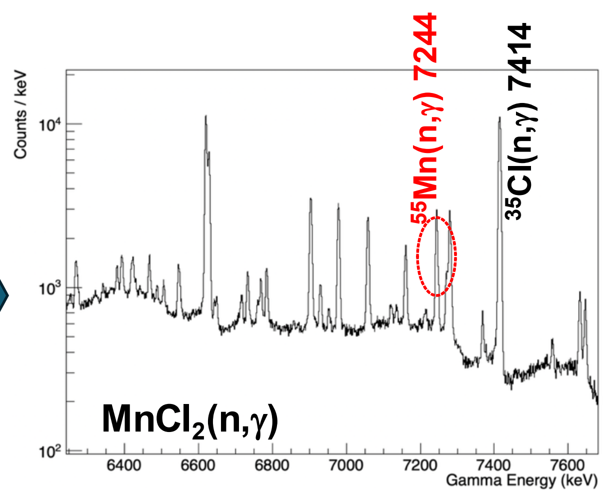
Analysis strategy

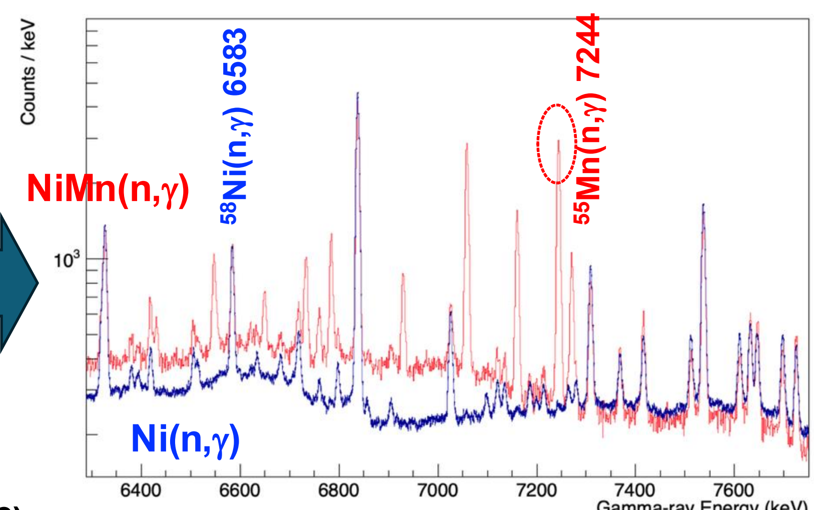
^{152}Eu standard source + ^{35}Cl(n,γ)

Source	E_γ (keV)	$\sigma_{\gamma,c}$ (b)
^{36}Cl:^{35}Cl(n, γ)	292.2	0.0893(10)
^{36}Cl:^{35}Cl(n, γ)	436.2	0.3093(20)
^{36}Cl:^{35}Cl(n, γ)	1131.3	0.6262(33)
^{36}Cl:^{35}Cl(n, γ)	2845.5	0.3495(26)
^{36}Cl:^{35}Cl(n, γ)	2975.2	0.3765(43)
^{36}Cl:^{35}Cl(n, γ)	3116.0	0.2975(26)
^{36}Cl:^{35}Cl(n, γ)	4082.7	0.2629(49)
^{36}Cl:^{35}Cl(n, γ)	4979.8	1.2320(99)
^{36}Cl:^{35}Cl(n, γ)	5715.2	1.818(16)
^{36}Cl:^{35}Cl(n, γ)	6619.6	2.530(23)
^{36}Cl:^{35}Cl(n, γ)	6977.8	0.7412(99)
^{36}Cl:^{35}Cl(n, γ)	7414.0	3.291(46)
^{36}Cl:^{35}Cl(n, γ)	8578.6	0.883(13)



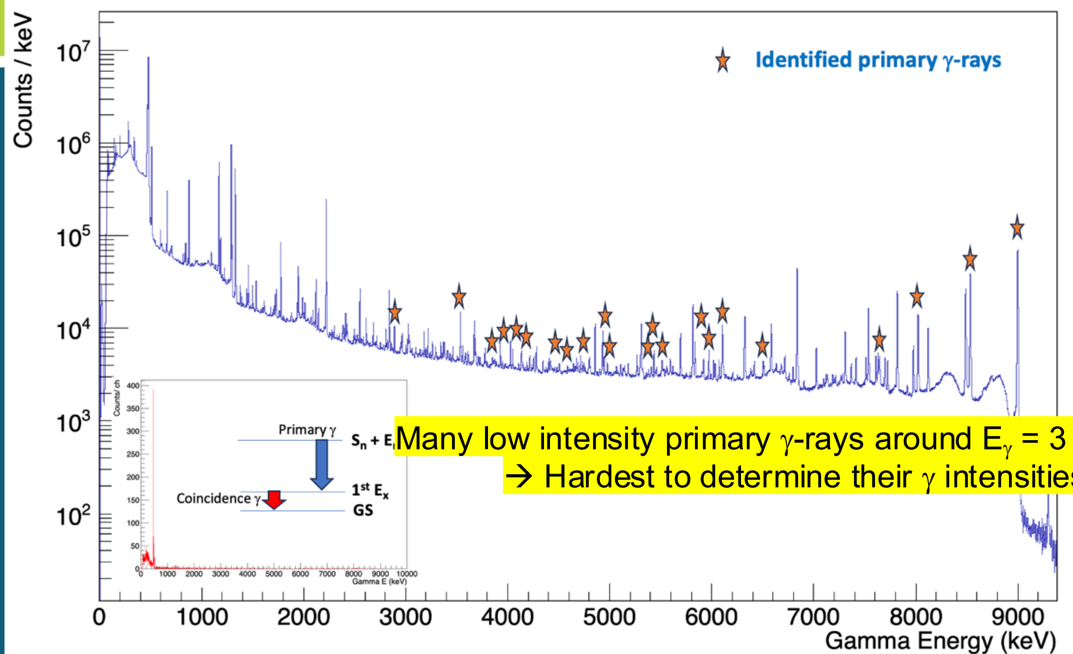
Normalizing the Mn cross sections measured with the same setup cancel out DAQ livetime, efficiency, etc.



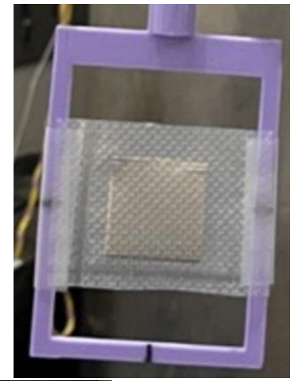


$\Delta\sigma_{(n,\gamma)}$ < 3% (Howe, PhD thesis, 2026)

$^{nat}Ni(n,\gamma)$ γ-ray spectrum and determining γ-ray intensities

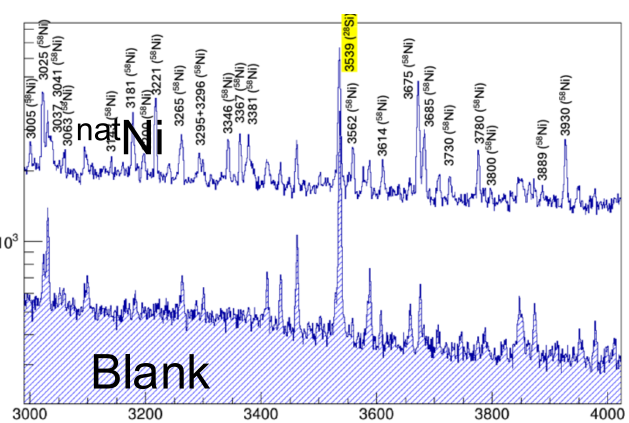


Many low intensity primary γ-rays around E_γ = 3 – 6 MeV
→ Hardest to determine their γ intensities

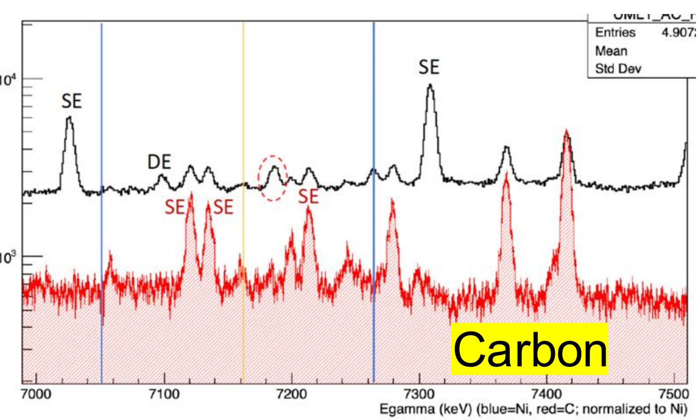


^{nat}Ni
(2 mm thick)
(2 x 2 cm^2)

Blank target



Eγ (keV)



Carbon

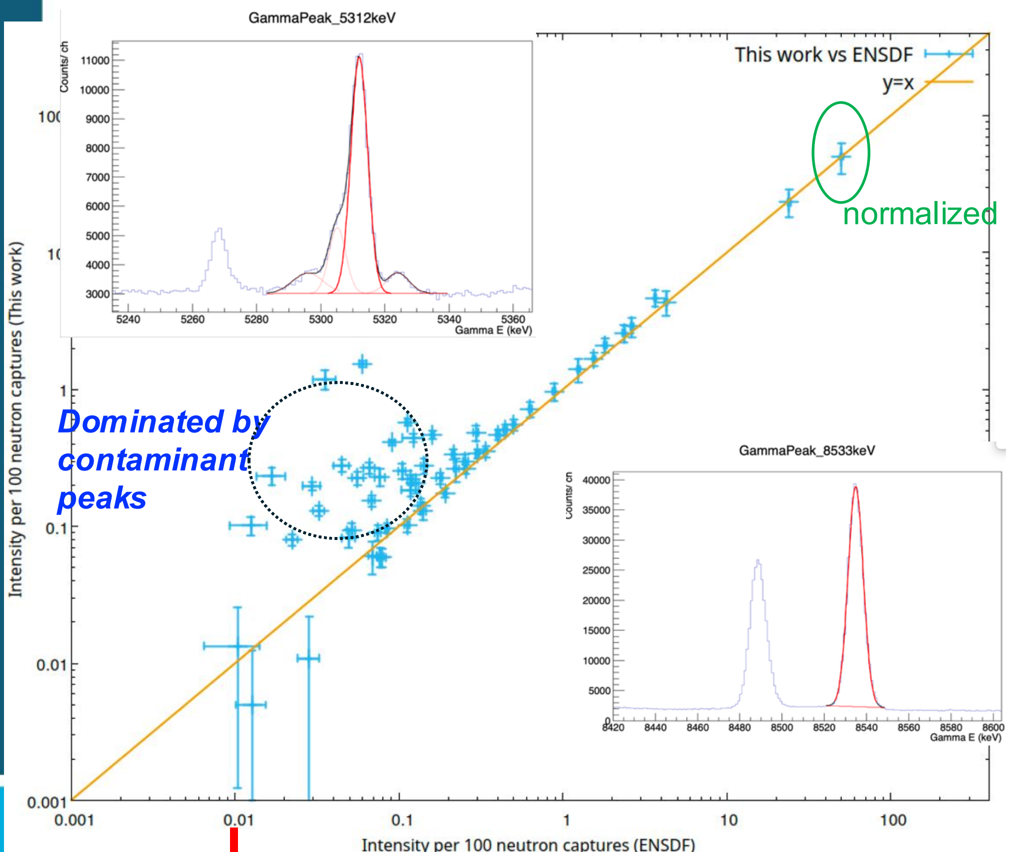
σ Ratio to ENSDF (^{59}Ni CN): positive results

$$\Sigma\sigma_{\gamma,prim}/\sigma_{(n,\gamma)} \sim 1$$

For both ENSDF & EGAF

Results from 55 hrs of beam irradiation

(^{58}Ni(n,γ); the isotope accounts for ~68% of ^{nat}Ni isotopes)



Lower limit by previous experiment
(Raman (2004); 2-3 γ per 10^4 capture

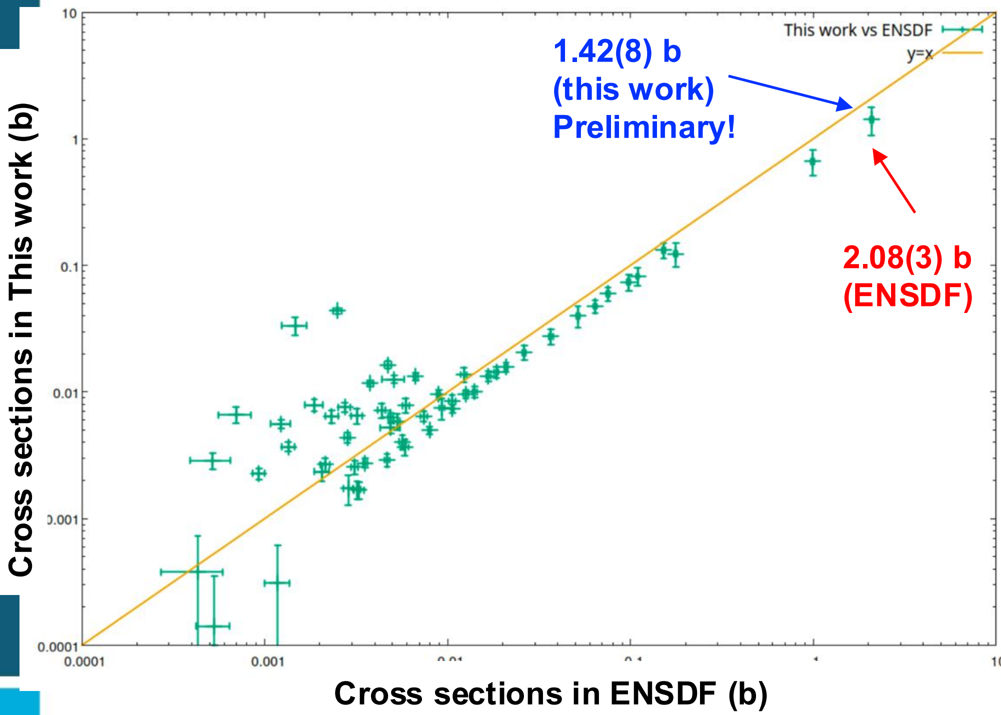
- Normalized the measured intensities to ENSDF (strongest γ)
- Agreements are well within 20%
- Some low intensity γ-rays are overlapped by contaminant peaks
- Lower limit we could detect is as much as previous experiments

σ Ratio to ENSDF (^{59}Ni CN): other results

$\Sigma\sigma_{\gamma,prim}/\sigma_{(n,\gamma)} \sim 1$ For both ENSDF & EGAF

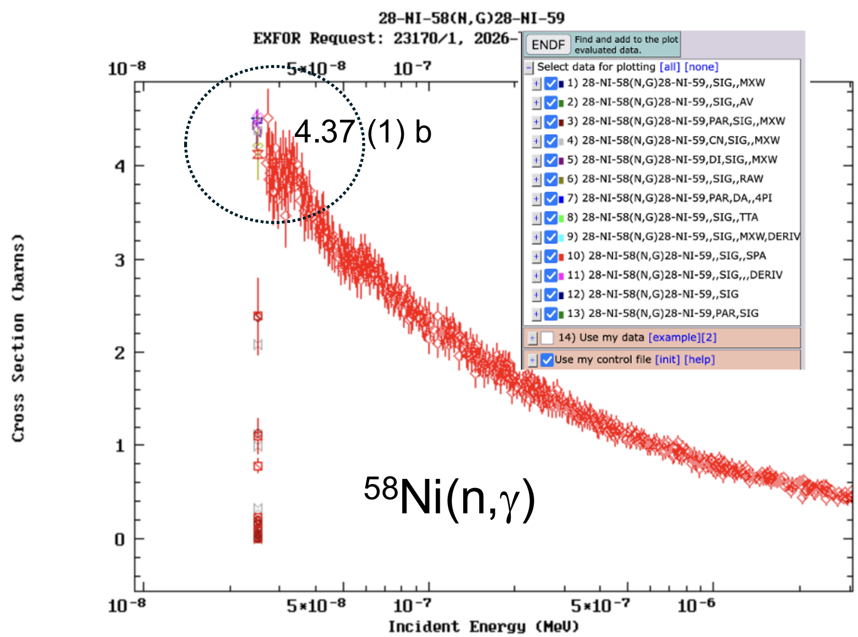
Results from 55 hrs of beam irradiation

(^{58}Ni(n,γ); the isotope accounts for ~68% of ^{nat}Ni isotopes)



$\Sigma\sigma_{\gamma,prim}$ ENSDF → 4.16 (6) b

$\Sigma\sigma_{\gamma,prim}$ This work → 2.83 (16) b



Normalization is not working well yet – or ENSDF intensities are not accurate?

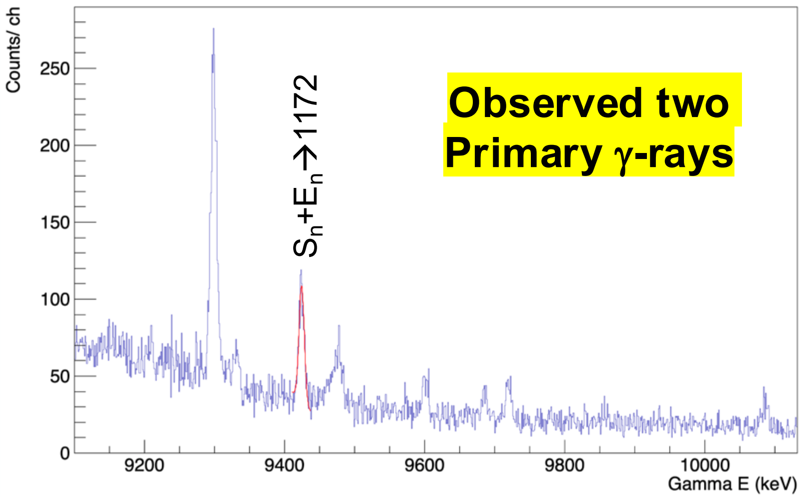
Ratio to ENSDF intensities (^{62}Ni CN)

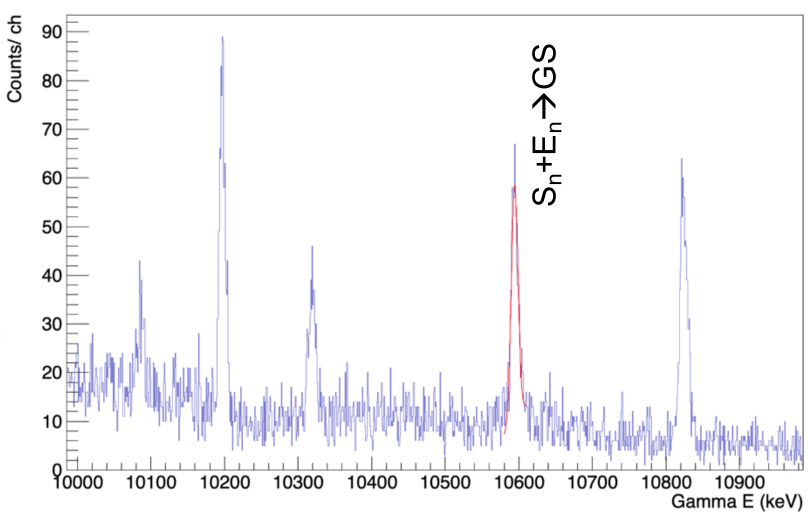
$\Sigma\sigma_{\gamma,prim}/\sigma_{(n,\gamma)} \sim$ **0.4**

For both ENSDF & EGAF

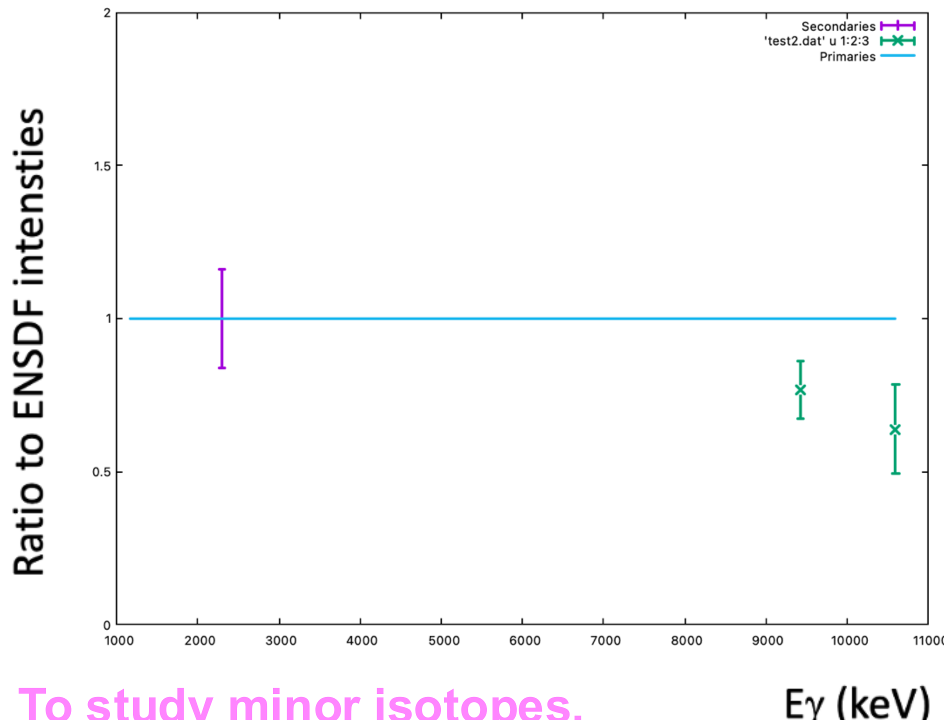
Results from 55 hrs of beam irradiation

(^{61}Ni(n,γ); the isotope accounts for ~1% of ^{nat}Ni isotopes)





Only 3 γ-rays were identified in the present data.
Many low E γ-rays were swallowed in Compton
This work and ENSDF intensities are not consistent with each other (preliminary!)



To study minor isotopes,
We need to reduce BG or enriched target

Summary & Acknowledgement

- Insufficiently known thermal neutron capture γ-ray data for A>60 isotopes
  - We started the systematic measurements for Cu, Ni, and Cr at UML reactor
  - Beyond FAIR (2023-2026), in future, we will expand into heavier elements

- Our preliminary results show some success
  - Major Ni isotopes are consistent with ENSDF within 20%
  - ^{61}Ni and Cr analysis are ongoing.
  - Achieving the same sensitivity to former experiments (2-3 γs / 10^4 captures)
  - New two HPGe will enhance the sensitivity.

- Normalizing the measured γ-ray intensities to cross sections may still have issues
  - Relying on Mn cross sections ($\Delta\sigma$ <3%) by (A. Howe's thesis 2026))
  - Revisit details – maybe the thermal spectrum is slightly different?

ACKNOWLEDGMENTS

- UML Reactor Staff: Leo Bobek, Tom Regan, Kseno Konomi, Tim Rogers
- UML Undergrads: Michael McGlynn (now in UK), Michael Wooldridge, Tabor Morin
- UML Grad students: Alex Howe (RA), Daniel Fernandez , Aaron Fishbein
- Stan Valenta, Milan Krticka (Charles University, Czech Republic) – DICEBOX, data analysis
- UML Nuclear Structure Group: P. Bender, P. Chowdhury, K. Lister
- E. Ricard-McCutchan, A. Sonzogni, Brookhaven National Lab.

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Thank you for your attention!!