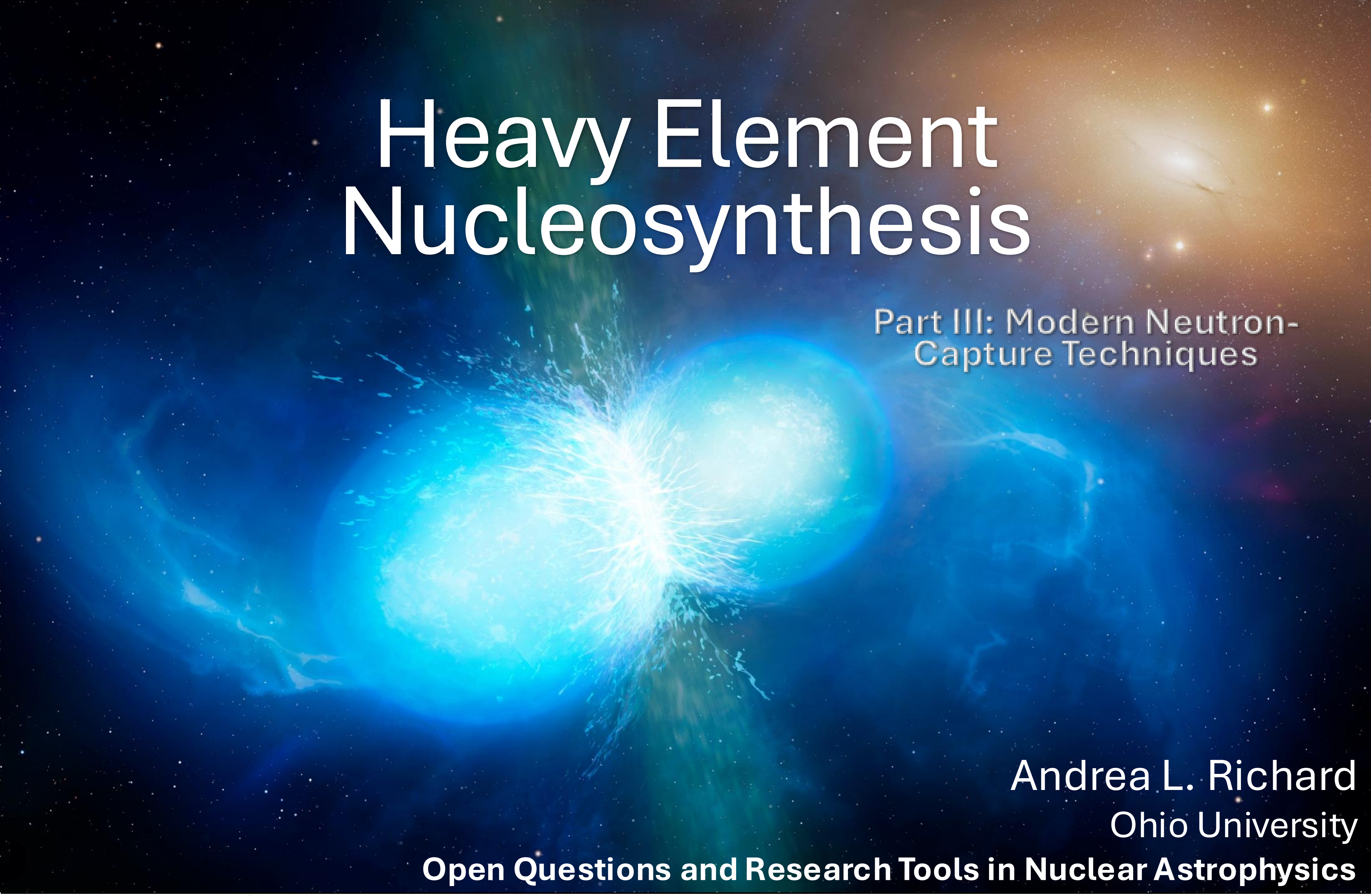


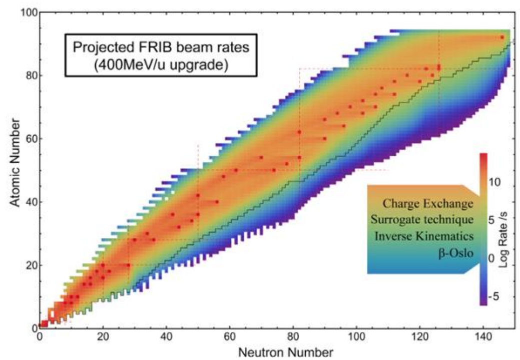
Heavy Element Nucleosynthesis

Part III: Modern Neutron-Capture Techniques

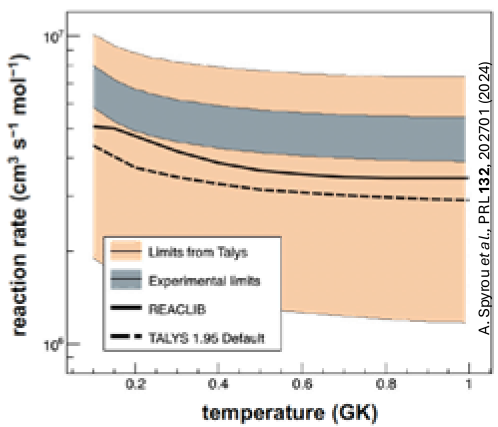
Andrea L. Richard
Ohio University

Open Questions and Research Tools in Nuclear Astrophysics

What's the Plan?



A.C. Larsen *et al.* PPNP **107** 69 (2019)



- Overview of Heavy Element Nucleosynthesis and Introduction of Nuclear Data
- Nuclear Data Uncertainties and Experiments
- Deep Dive into Indirect Neutron Capture and Wrap-up

How do we measure neutron-capture reactions?

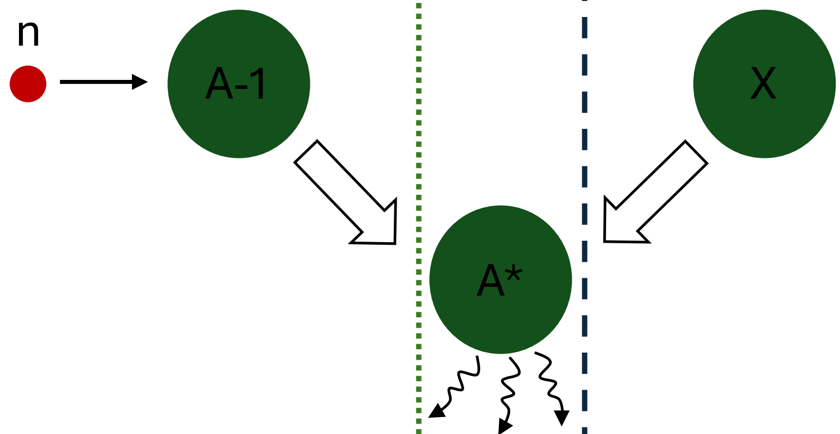
Direct Measurement

- Only feasible for stable or long-lived nuclei
- For i/n/r-process, desired targets are too short-lived
- No feasible neutron target…
- Not possible for rare isotopes

Indirect Measurement

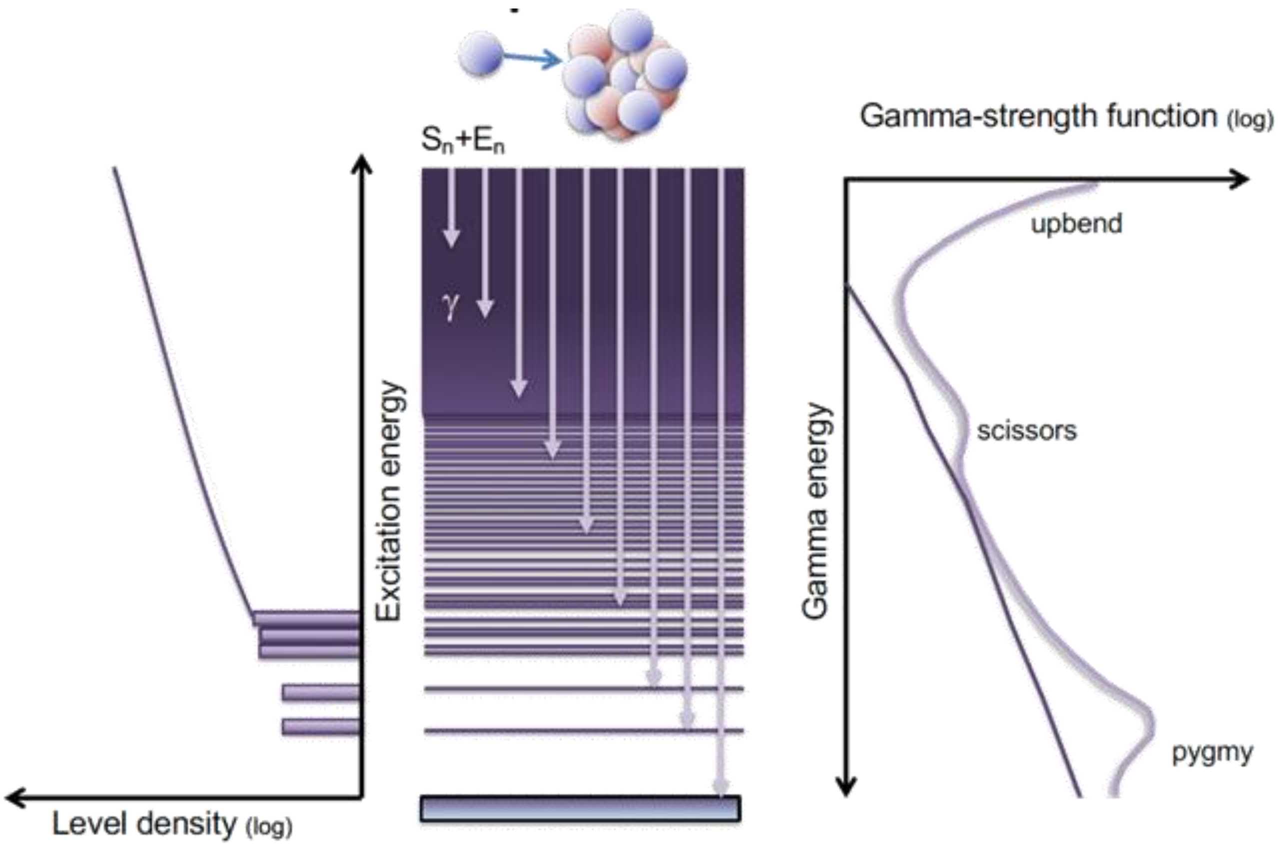
- Access same nucleus through different pathway
- Can utilize short half-lives

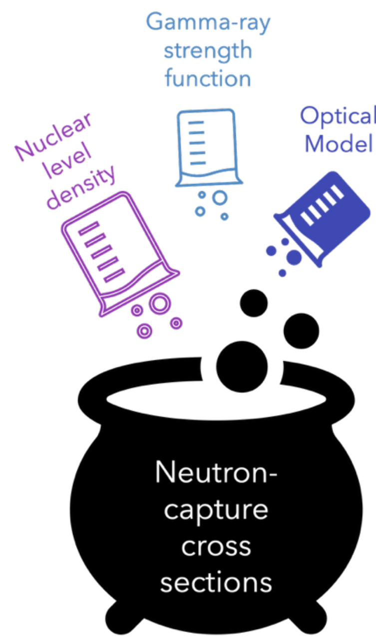
Some Examples:
Oslo Method
β-Oslo Method
Surrogate Method
Inverse Oslo Method
γ-ray strength method
Particle Evaporation Method



A. Spyrou *et al.*, PRL **113**, 232502 (2014)
J. Escher *et al.*, PRL **121**, 052501 (2018)
A. Ratkiewicz *et al.*, PRL **122**, 052502 (2019)
H. Utsunomiya *et al.*, PRC **82**, 064610 (2010)
M. Guttormsen *et al.*, NIMA **255**, 518 (1987)
M. Guttormsen *et al.*, NIMA **374**, 371 (1996)
A. Schiller *et al.*, NIMA **447**, 498 (2000)
A.C. Larsen *et al.*, PRC **83**, 034315 (2011)
V. Ingeberg *et al.*, EPJA **56**, 68 (2020)
V. Ingeberg *et al.*, PRC **106**, 054315 (2022)
A. Voinov, *et al.*, PRC **99**, 054609 (2019).

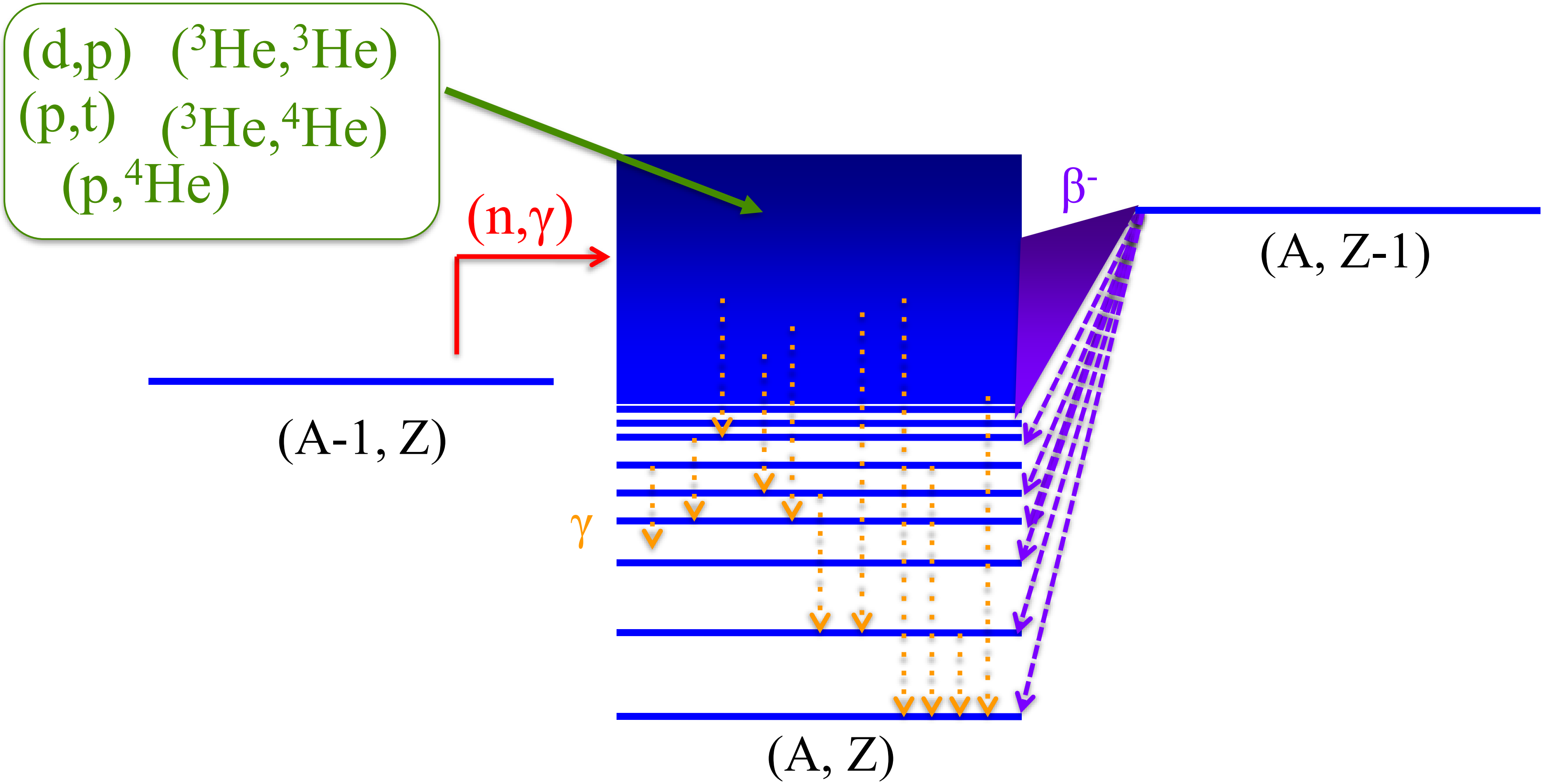
(Wolfenstein) Hauser Feshbach Theory





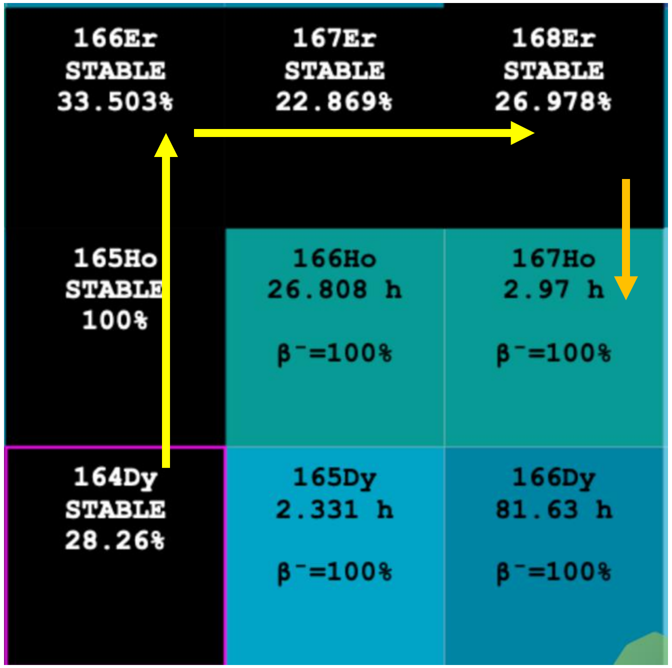
W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952)
Slide modified from Ann-Cecilie Larsen

Indirect Techniques are used to constrain (n,γ) rates

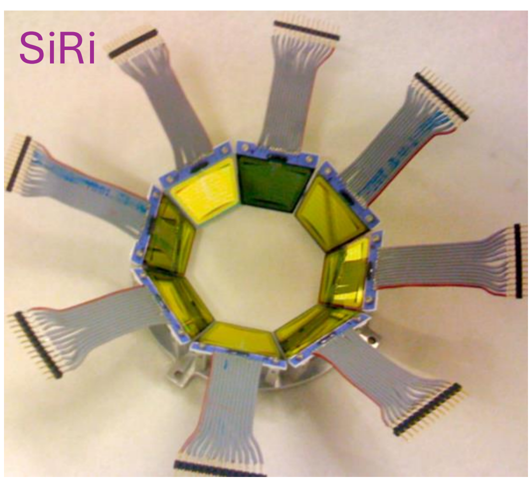


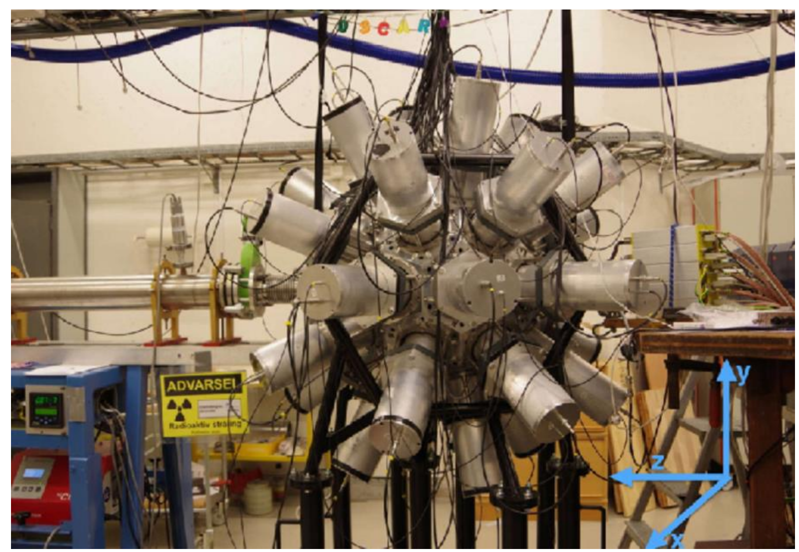
β-Oslo Method, Inverse-Oslo, and the Surrogate Reaction Method

The Oslo Method for (n,γ) Reactions



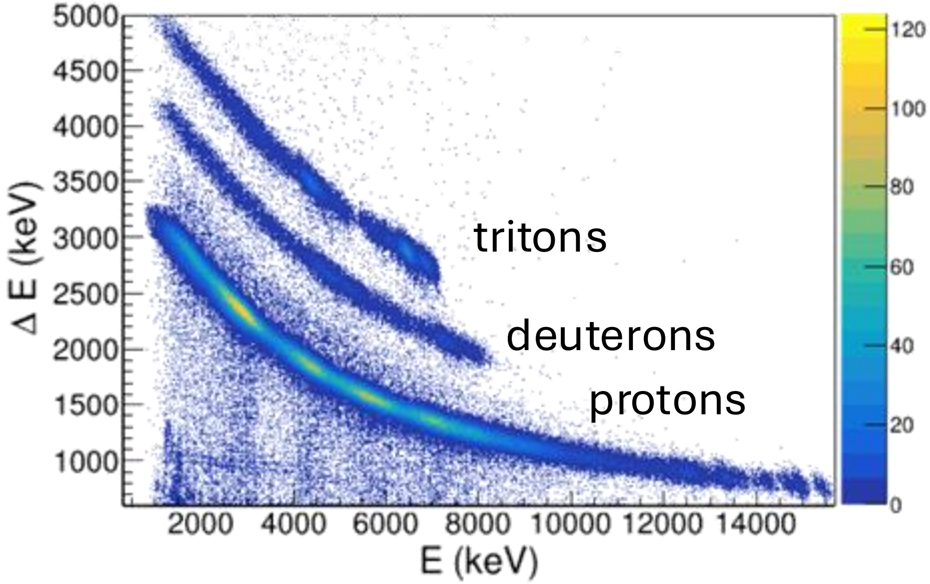
- ^{164}Dy(α,pγ)^{167}Ho to constrain ^{166}Ho(n,γ)^{167}Ho
- Oslo Cyclotron Lab
  - 26 MeV α beam
  - 1.73 mg/cm^2 ^{164}Dy target
  - Proton detection in SiRi
    - 64 Si ΔE-E particle telescopes
  - Gamma detection in OSCAR
    - 30 large volume LaBr$_3$ (Ce) detectors



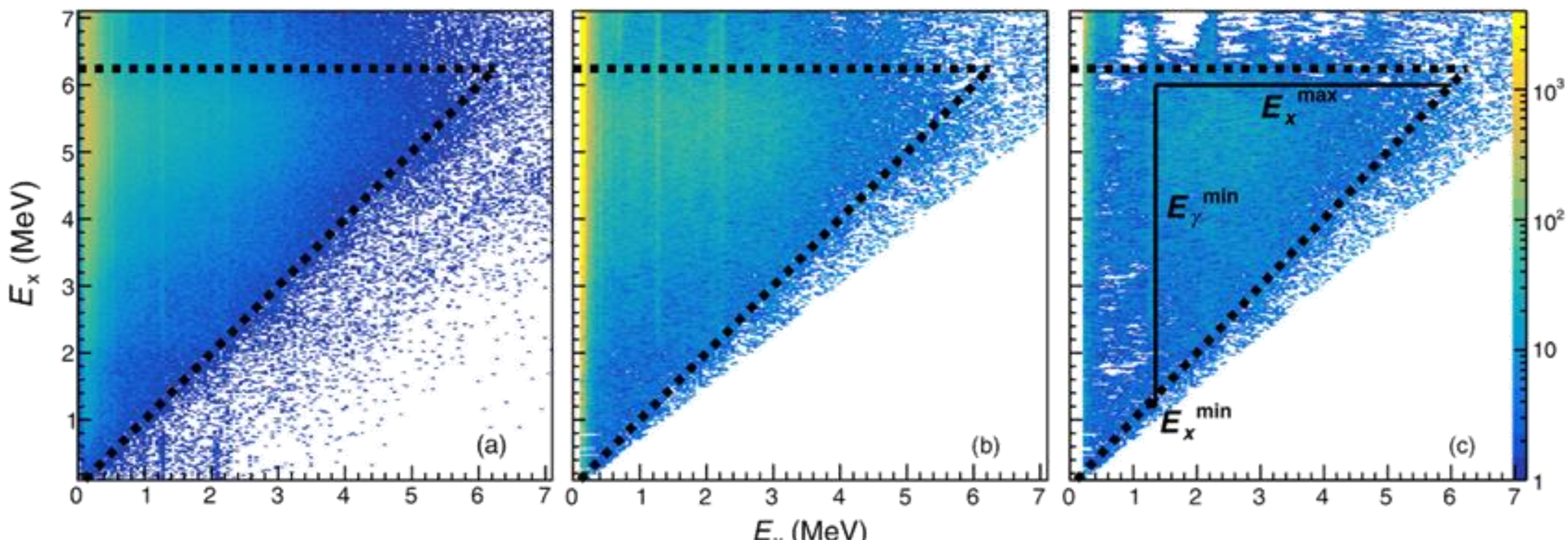


http://dx.doi.org/10.1016/j.nima.2020.164678

Establishing particle-gamma coincidences



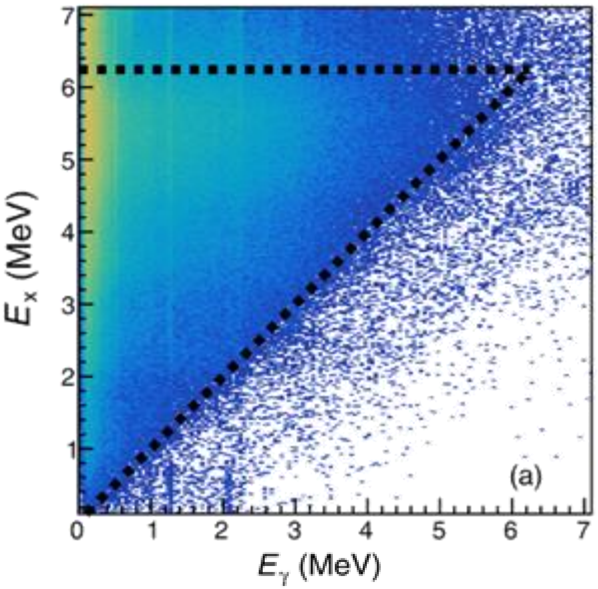
- Identify particles
- Calibrate γ-ray spectra
- Particle-gamma coincidences



F. Pogliano *et al.*, PRC **107**, 034605 (2023)

Traditional Oslo Analysis Outline

F. Pogliano *et al.*, PRC **107**, 034605 (2023)

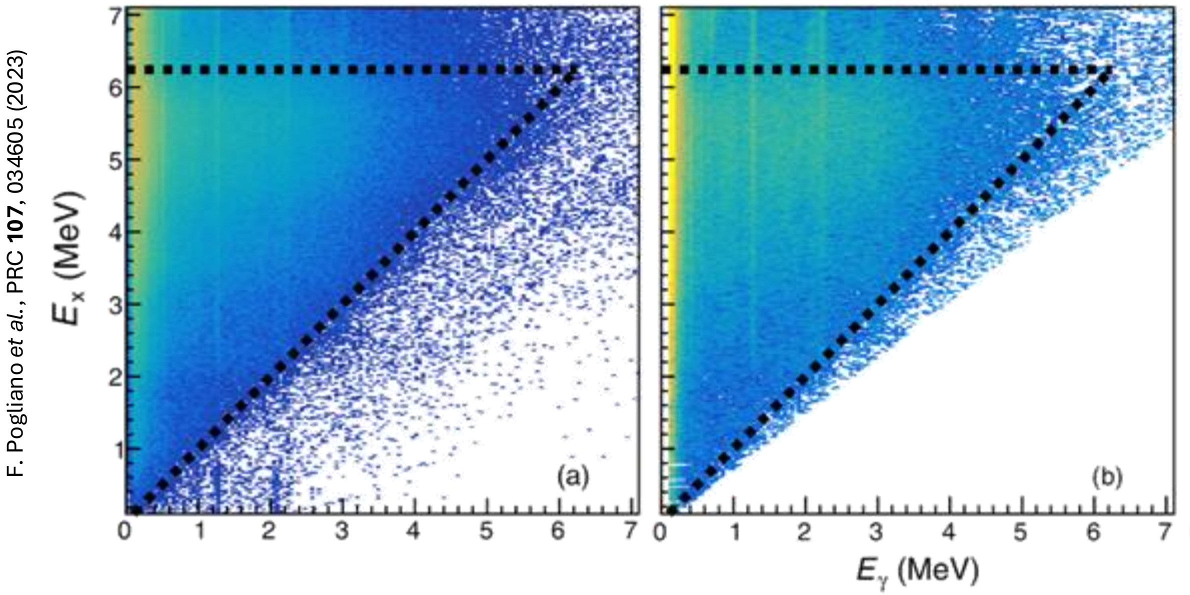


Raw Matrix

- Purely experimental data OSCAR and SiRi
- p-γ coincidences
- Investigate transitions, build level schemes, angular distributions

Guttormsen *et al.*, NIMA **374**, 371 (1996)
Guttormsen *et al.*, NIMA **255**, 518 (1987)
Schiller *et al.*, NIMA **447**, 498 (2000)

Traditional Oslo Analysis Outline

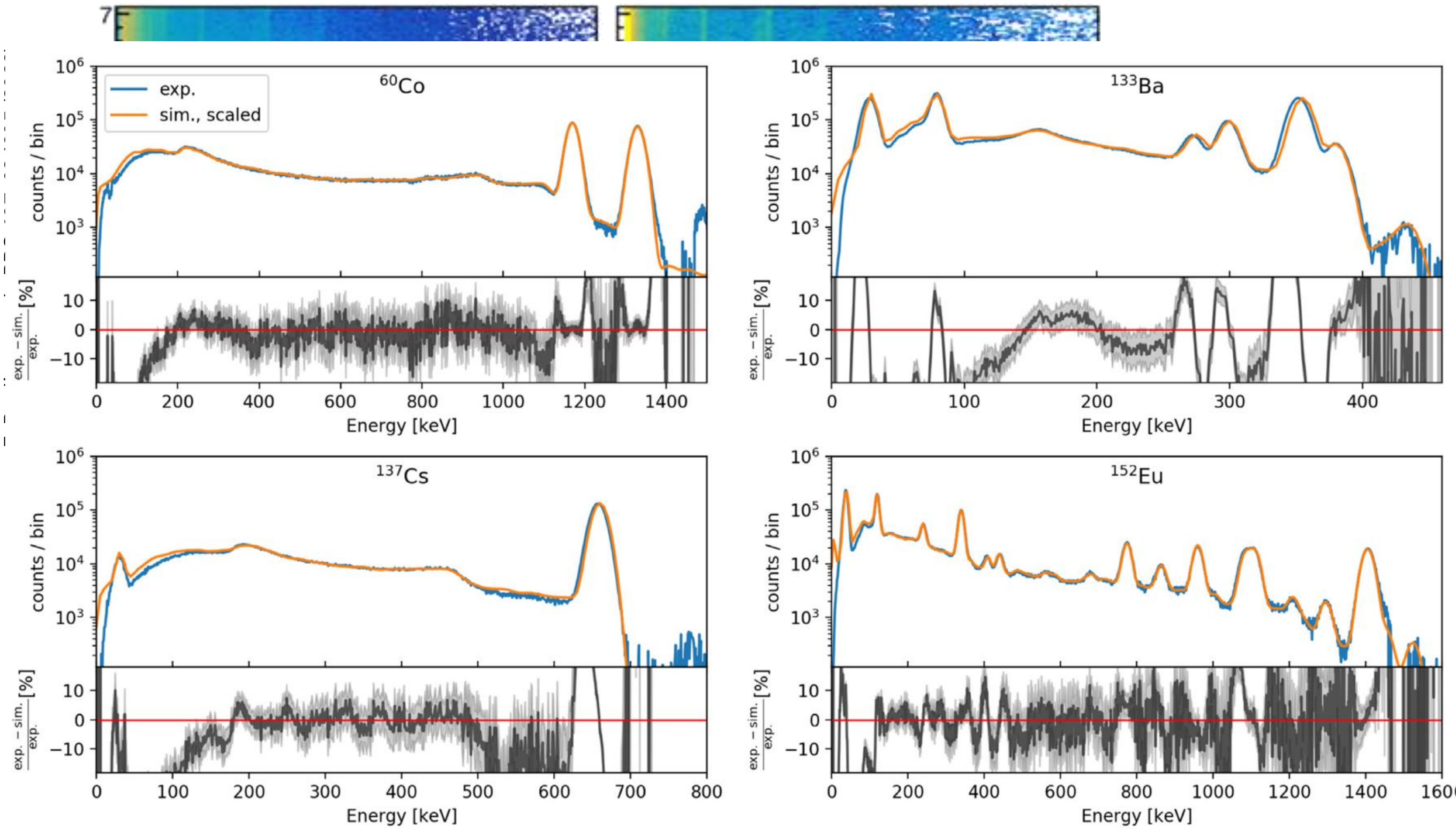


Unfolded Matrix

- Need to account for the interaction of γ-rays in the detector
- Generate response function for OSCAR in GEANT4

Guttormsen *et al.*, NIMA **374**, 371 (1996)
Guttormsen *et al.*, NIMA **255**, 518 (1987)
Schiller *et al.*, NIMA **447**, 498 (2000)

Traditional Oslo Analysis Outline

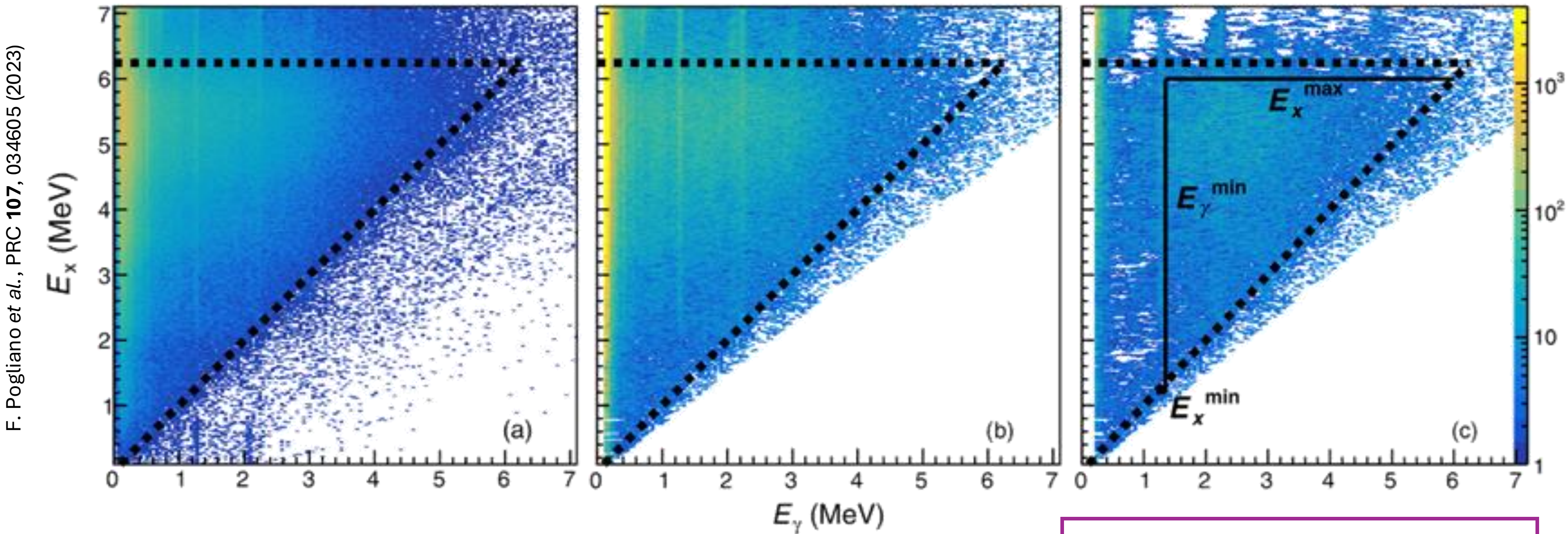


function for OSCAR in GEANT4

Validate simulation with source data, and simulate response of detector to γ-rays up to 20 MeV

Guttormsen *et al.*, NIMA **374**, 371 (1996)
Guttormsen *et al.*, NIMA **255**, 518 (1987)
Schiller *et al.*, NIMA **447**, 498 (2000)

Traditional Oslo Analysis Outline



$$P(E_\gamma, E_x) \propto \rho(E_x - E_\gamma) \cdot T(E_\gamma)$$

$$\gamma SF(E_\gamma) = \frac{1}{2\pi} \frac{T(E_\gamma)}{E_\gamma^3}$$

First Generation Matrix

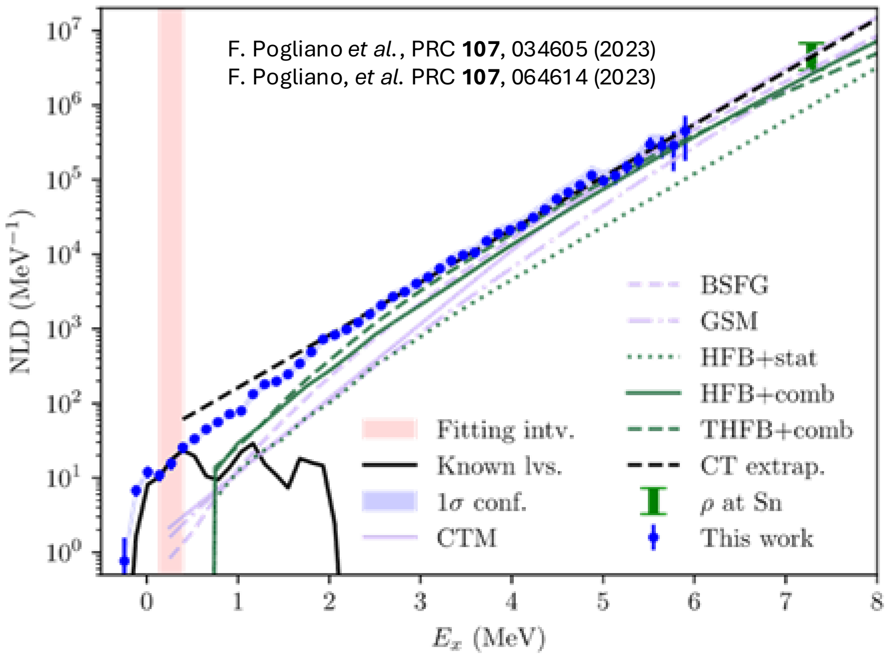
- Isolate the first γ-ray to be emitted from each excited state
- Iterative subtraction of the γ-rays emitted from lower excited states
- Becomes the probability matrix needed to extract NLD and γSF

Guttormsen *et al.*, NIMA **374**, 371 (1996)
Guttormsen *et al.*, NIMA **255**, 518 (1987)
Schiller *et al.*, NIMA **447**, 498 (2000)

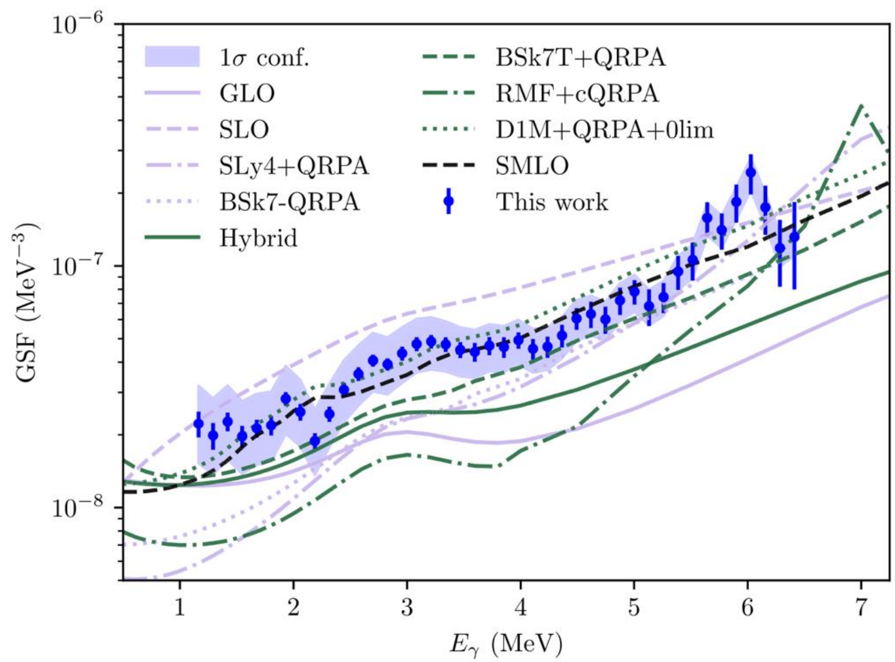
Obtaining the ^{166}Ho(n,γ)^{167}Ho cross section

- Remember, this is an indirect technique, so we don't immediately get the (n,γ) rate!
- We get the "ingredients" and put them in HF codes

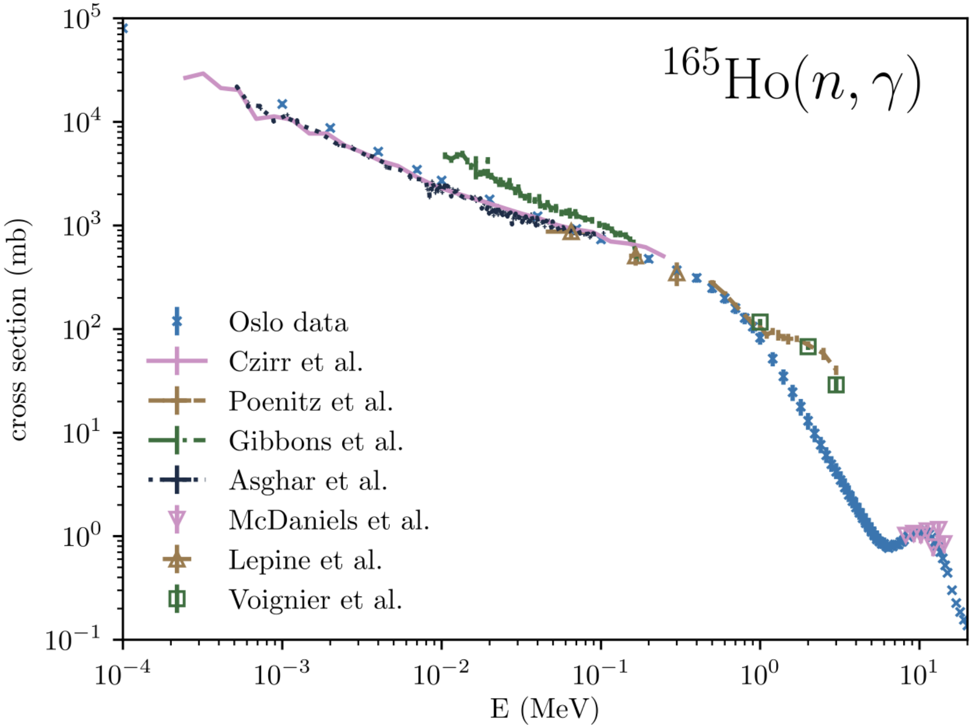
Nuclear Level Density

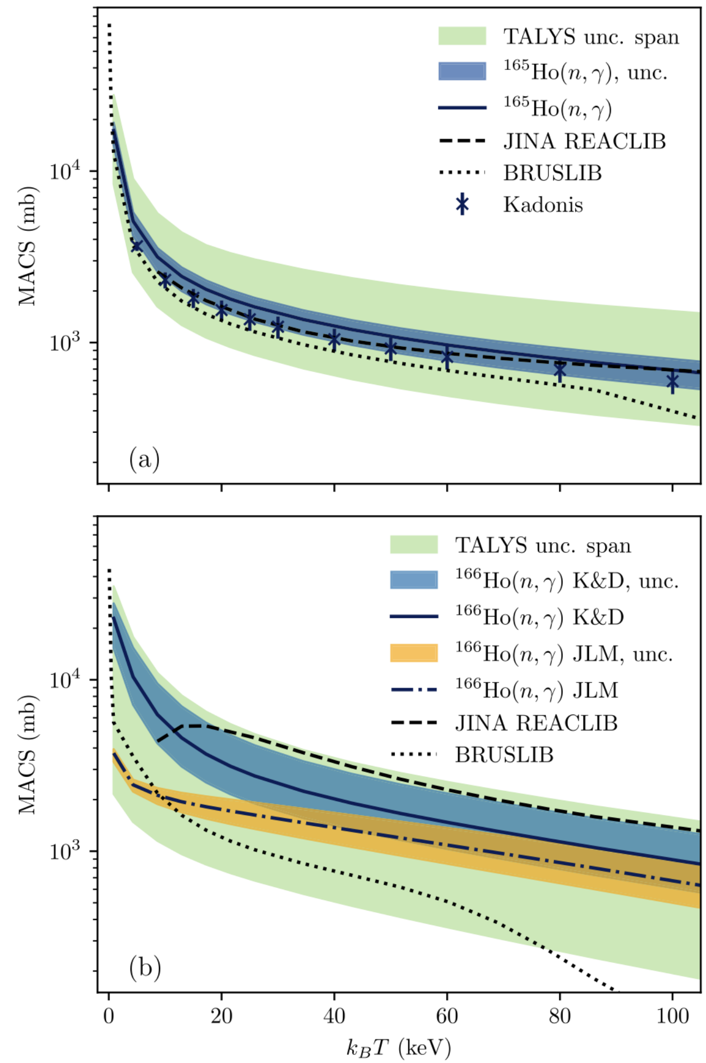


Gamma Strength Function



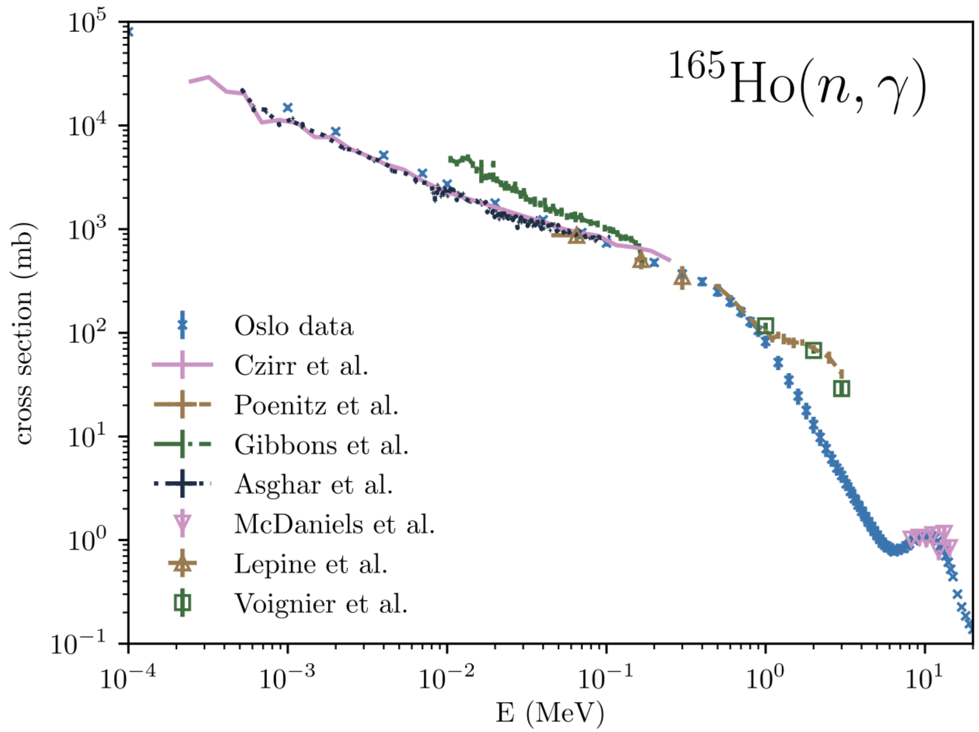
Obtaining the ^{165,166}Ho(n,γ)^{166,167}Ho cross section

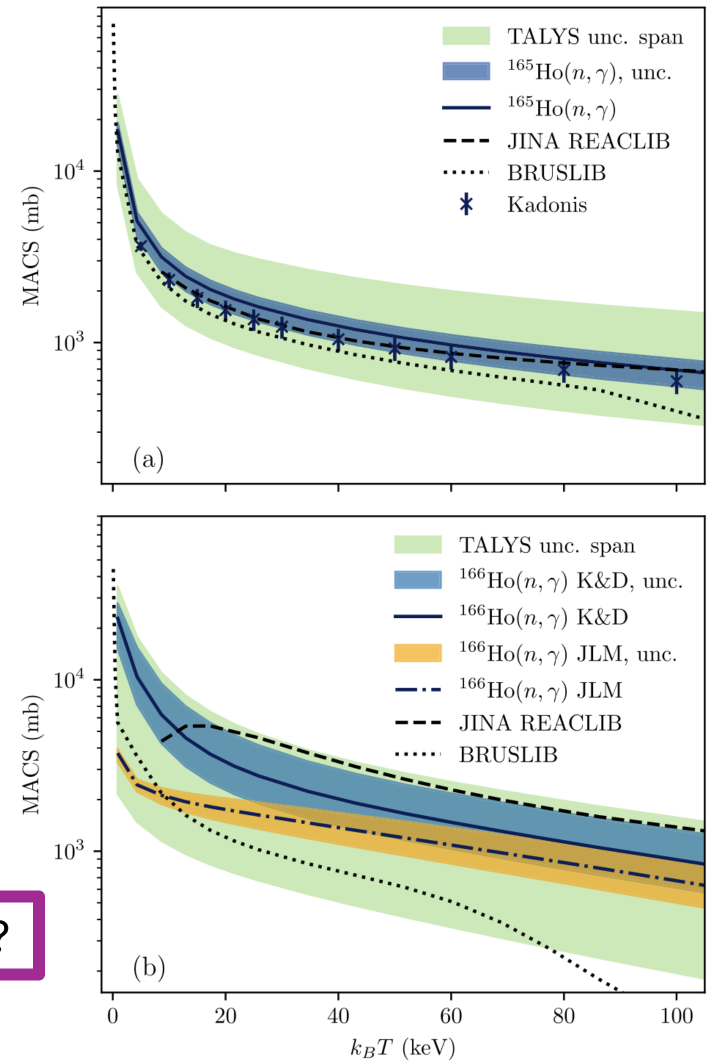




F. Pogliano *et al.*, PRC **107**, 034605 (2023)
F. Pogliano, *et al.* PRC **107**, 064614 (2023)

Obtaining the ^{165,166}Ho(n,γ)^{166,167}Ho cross section



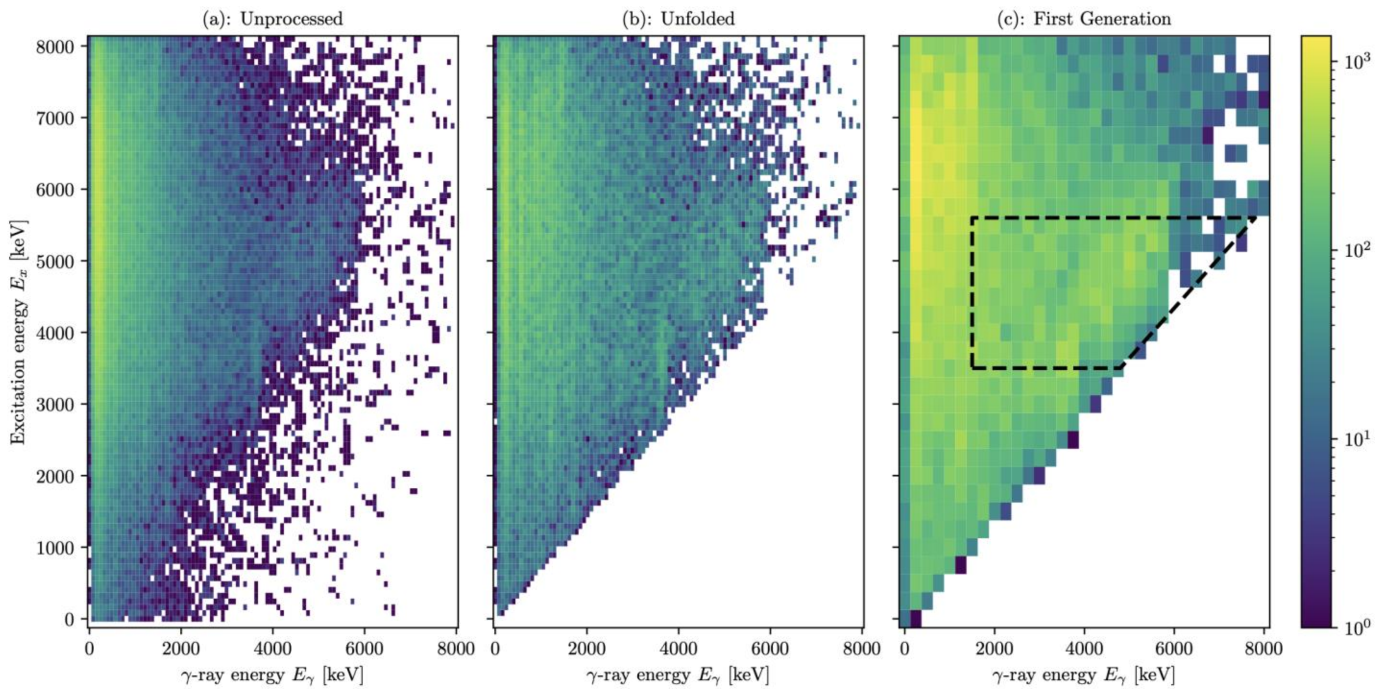


Can we do it in Inverse Kinematics with RIBs?

F. Pogliano *et al.*, PRC **107**, 034605 (2023)
F. Pogliano, *et al.* PRC **107**, 064614 (2023)

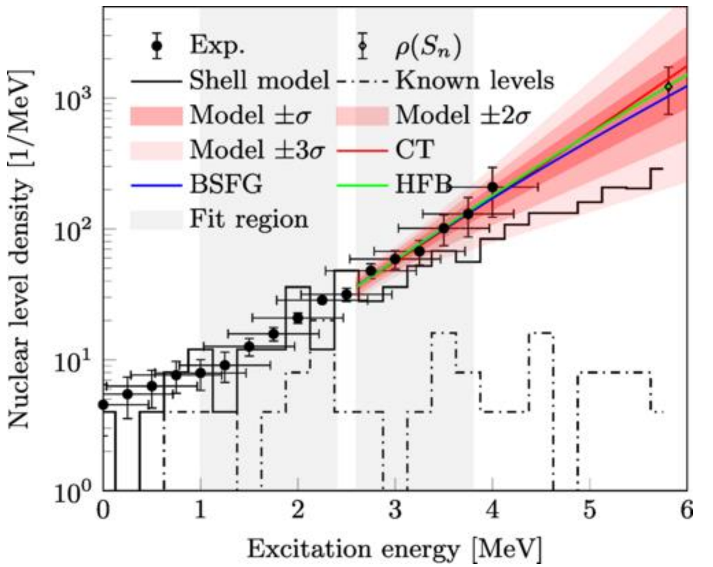
^{66}Ni(n,γ)^{67}Ni for the *i*-process

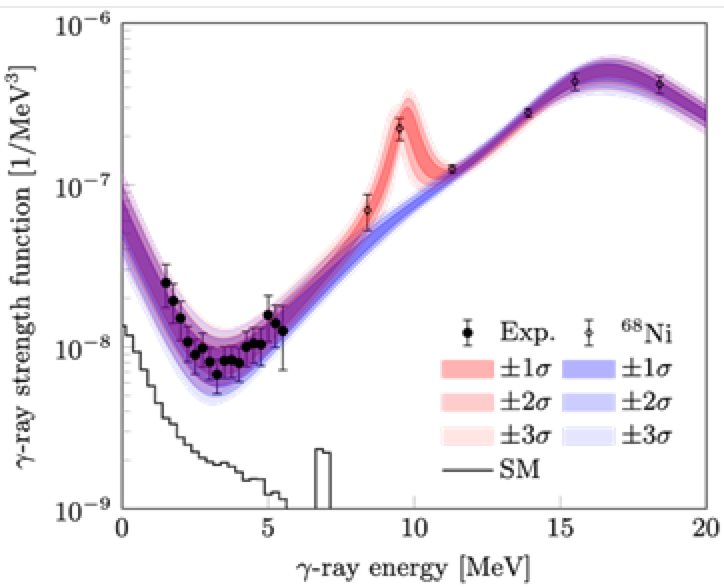
- ^{66}Ni beam at 4.5 MeV/u impinged CD_2 target (670 μg/cm^2)
- ISOLDE at CERN
- Protons detected in C-REX array (segmented silicon)
- Gammas detected in Miniball (HPGe and $LaBr_3$)

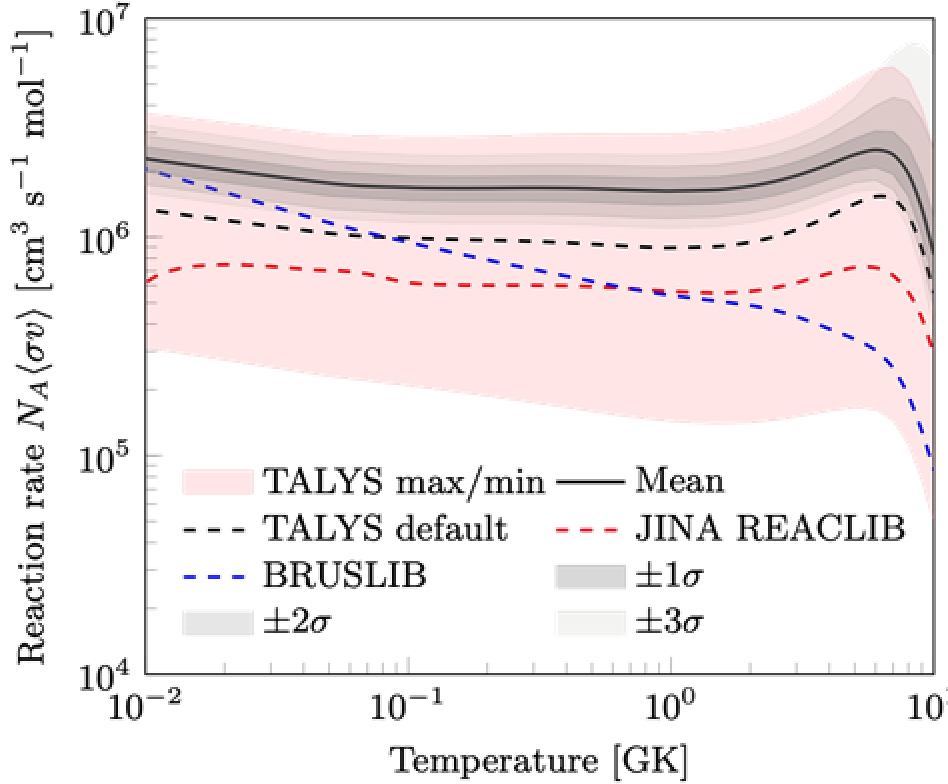


V. Ingeberg, *et al*. PRC **111**, 015803 (2025).

$^{66}Ni(n,\gamma)^{67}Ni$ for the *i*-process

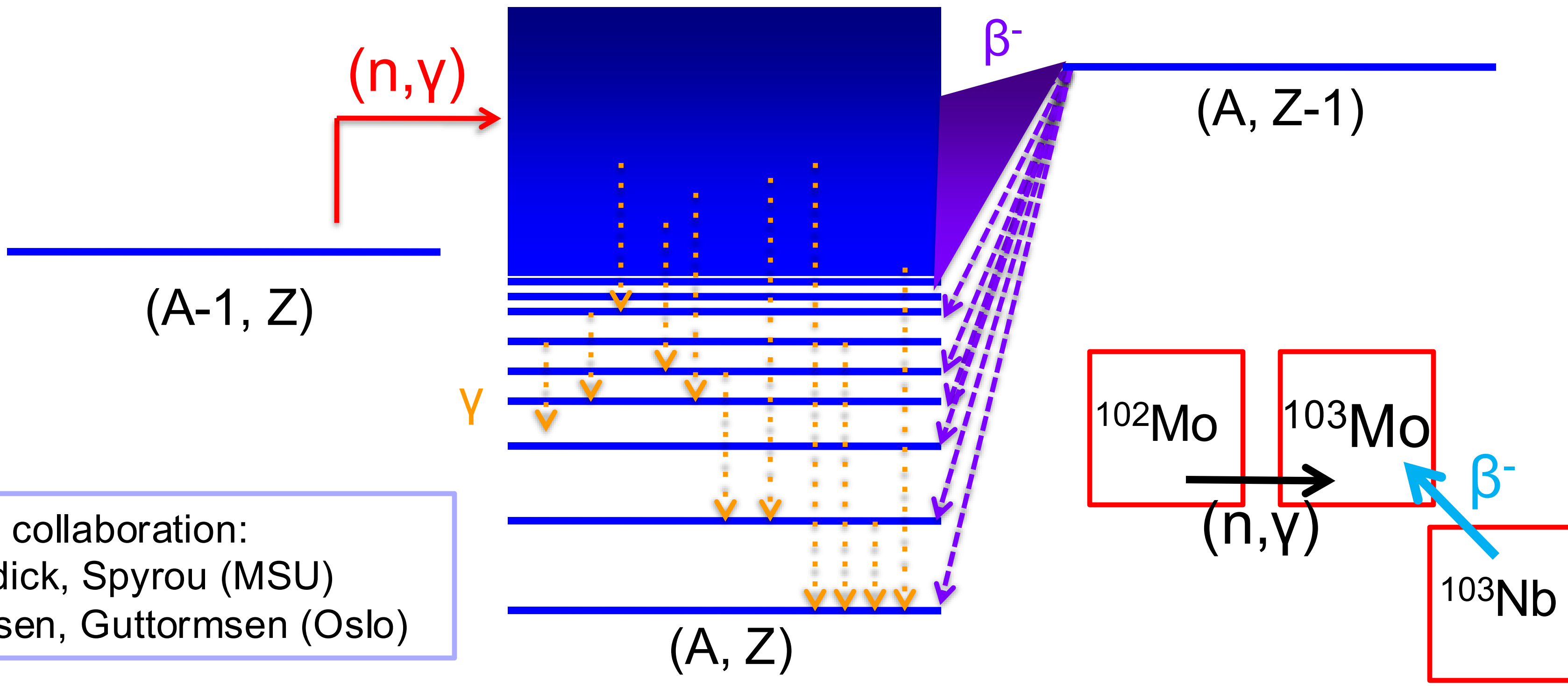






V. Ingeberg, *et al*. PRC **111**, 015803 (2025).

Indirect Studies using the β-Oslo Method



β-Oslo collaboration:
- Liddick, Spyrou (MSU)
- Larsen, Guttormsen (Oslo)

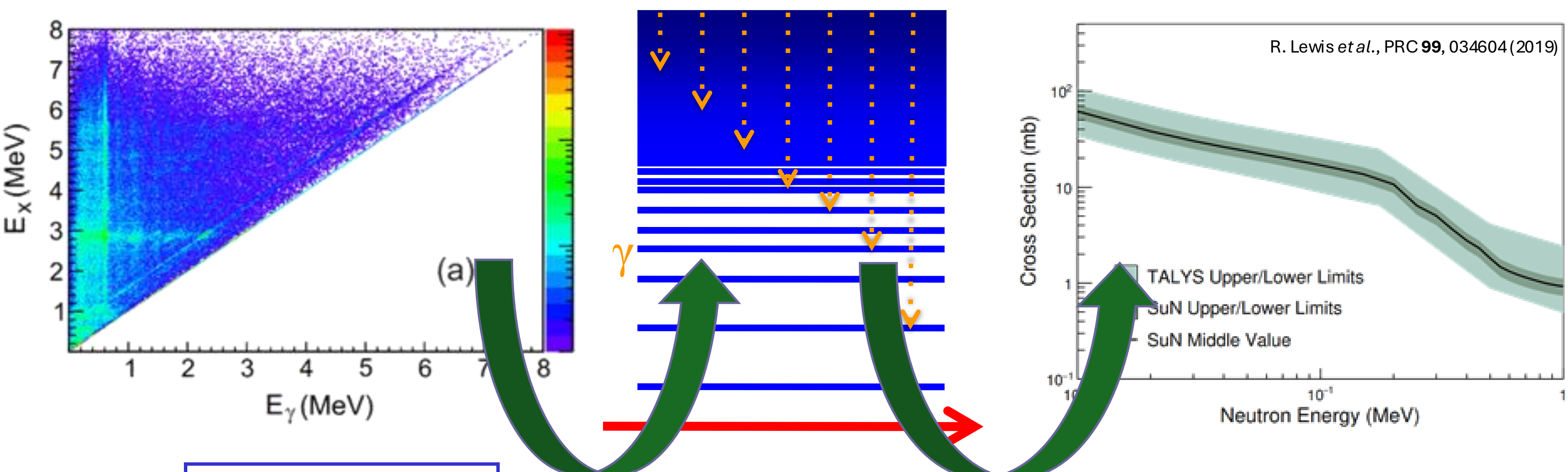
- Populate the compound nucleus via β-decay
- Study nuclei far from stability
- Feasible with low beam intensities

•Need:
- ✓ Radioactive Beam
- ✓ Segmented γ-ray calorimeter

A. Spyrou *et al.* PRL **113**, 232502 (2014)

The β-Oslo Method to constrain (n,γ) reactions

- Use β-decay to populate the compound nucleus of interest
- Measure <u>excitation energy</u> and <u>γ-ray energy</u>
- Extract **level density** and **γ-ray strength function** (external normalizations)
  - Three normalization points:
    - Low-lying levels (from NNDC)
    - Level density at neutron-separation energy (from previous data or from theory)
    - Average radiative width or giant dipole resonance (GDR) data
- Calculate “semi-experimental” (n,γ) cross section



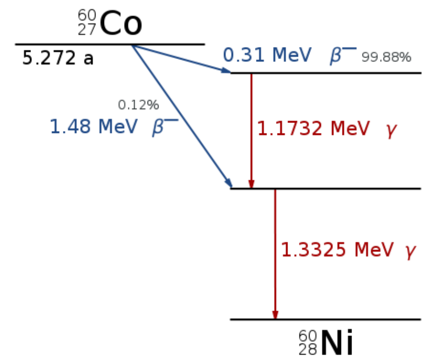
Unfolding
Iterative subtraction

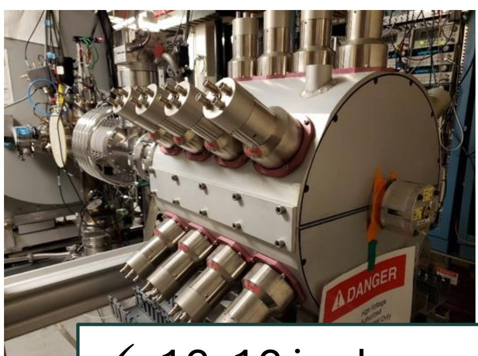
$$P(E_\gamma, E_x) \sim \rho(E_x - E_\gamma)\mathcal{T}(E_\gamma)$$

Normalization

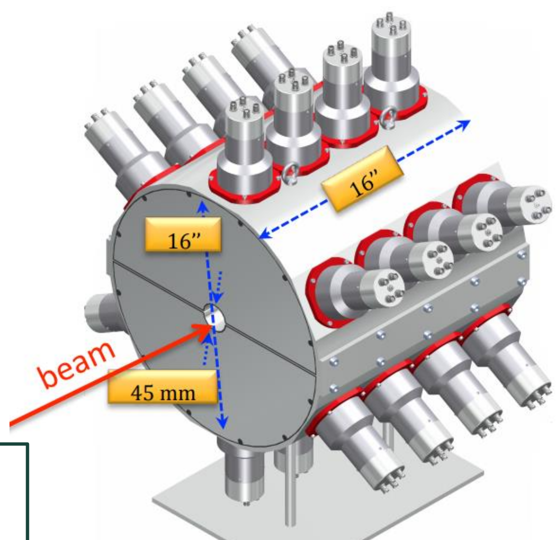
The Summing NaI(Tl) Detector as a total absorption spectrometer

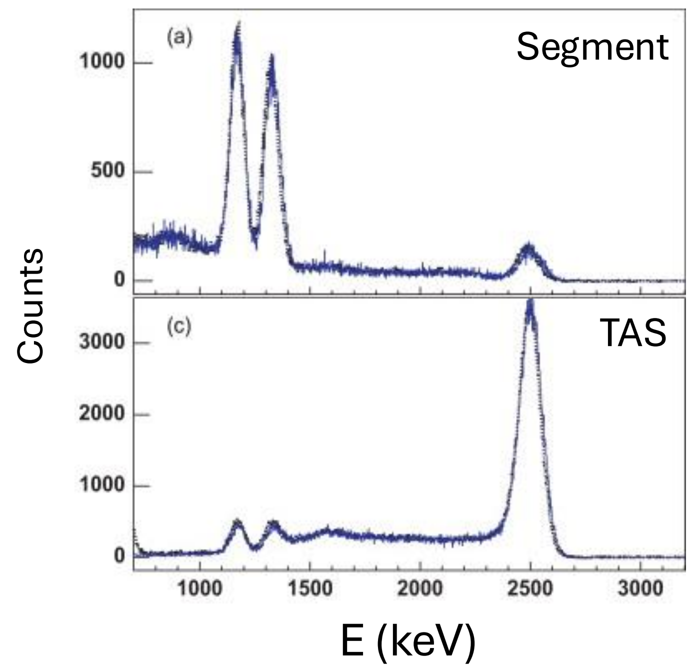
- Large size, high efficiency γ-ray detector
- Summing of all γ-rays gives the excitation energy
- Segmentation provides information about individual γ-rays
- Resolution at 1 MeV – 6%
- Efficiency at 1 MeV – 85%





- ✓ 16x16 inch
- ✓ 45 mm borehole
- ✓ 8 segments
- ✓ 24 PMTs

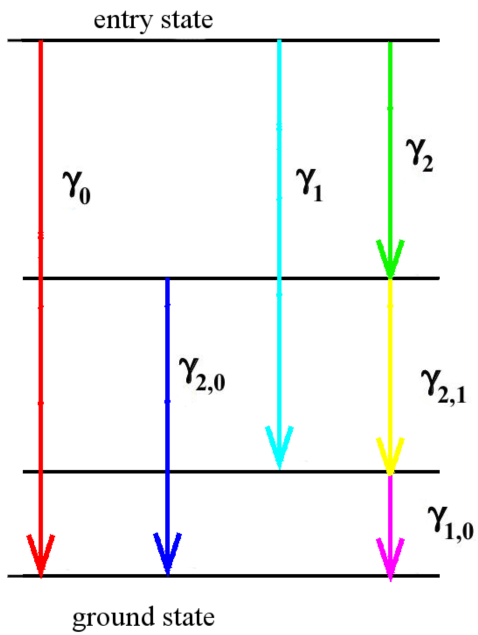




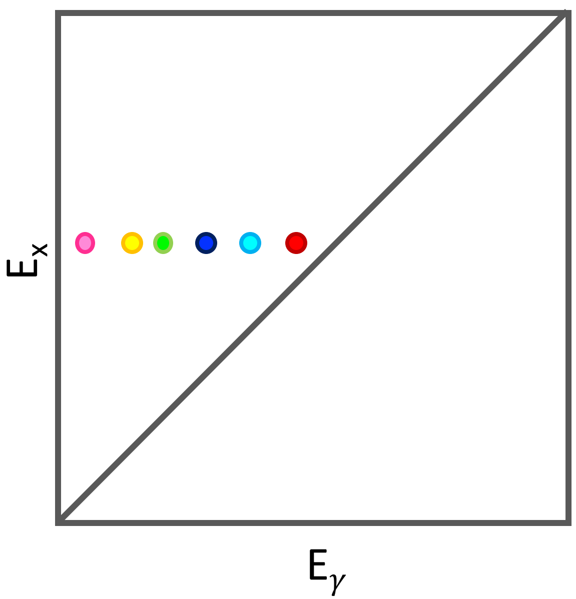
Simon, A., et al. *NIM A* 703 (2013): 16-21

Total Absorption Spectroscopy

Cartoon Decay Scheme



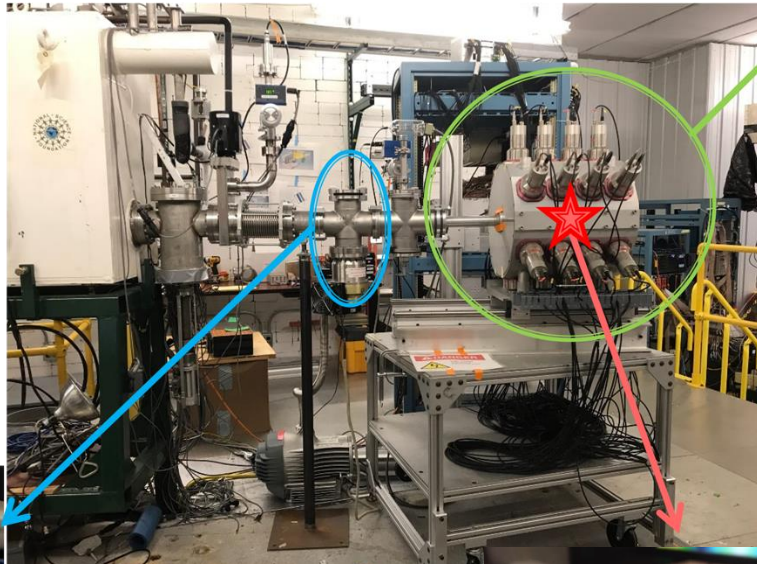
βOslo Matrix



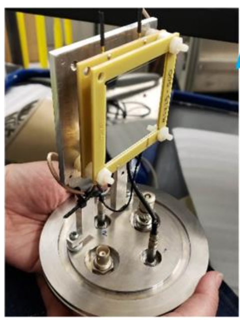
TAS = initial excited energies
Segments = individual gamma rays

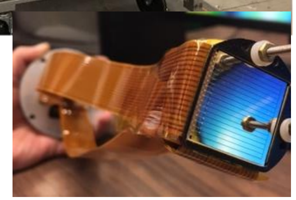
β-Oslo measurements performed with fast and slow beams

Fast Beam Studies



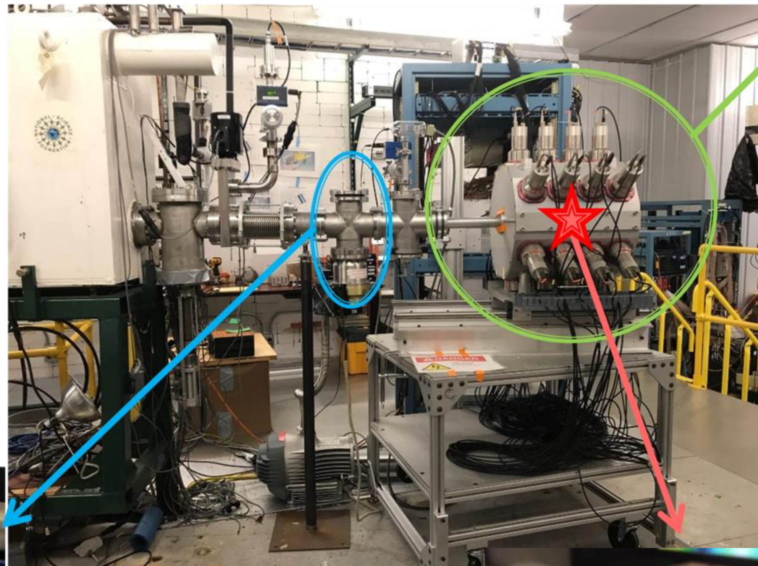
SuN

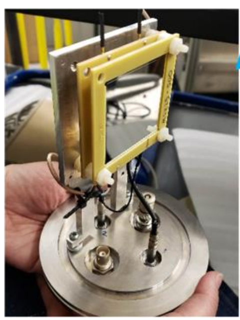


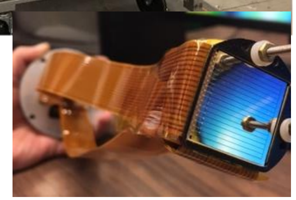


β-Oslo measurements performed with fast and slow beams

Fast Beam Studies

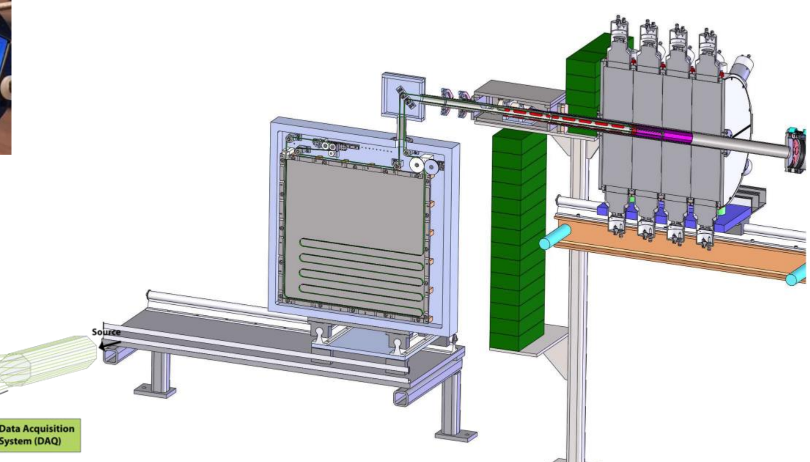


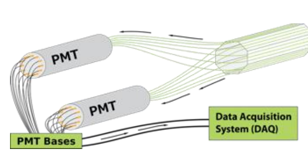




SuN

Stopped Beam Studies





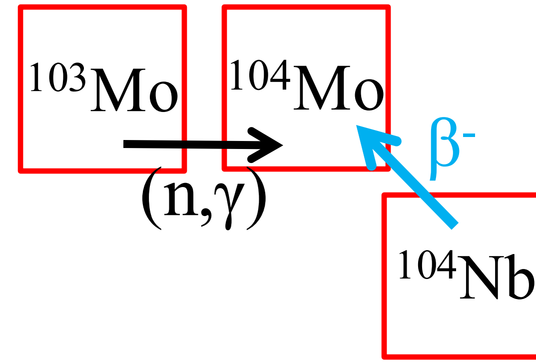
NSCL

FRIB

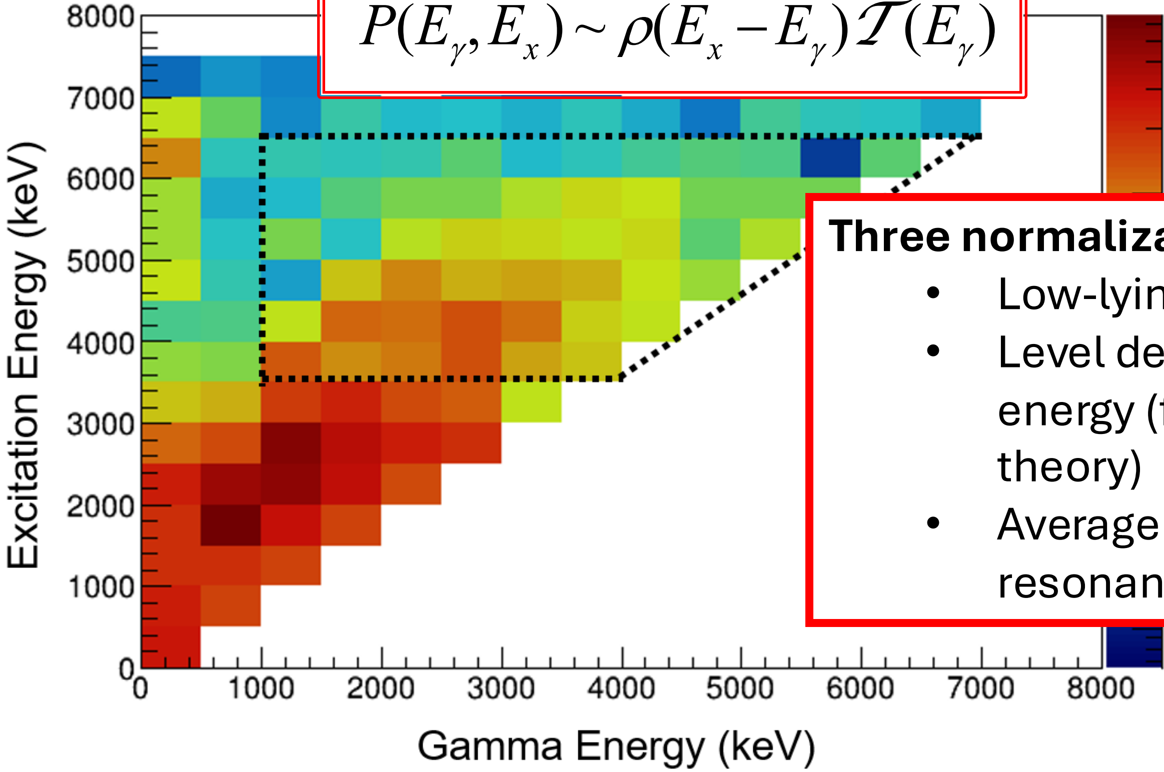
NSCL

Argonne NATIONAL LABORATORY

Neutron-capture constraints for $^{103}Mo(n,\gamma)^{104}Mo$



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

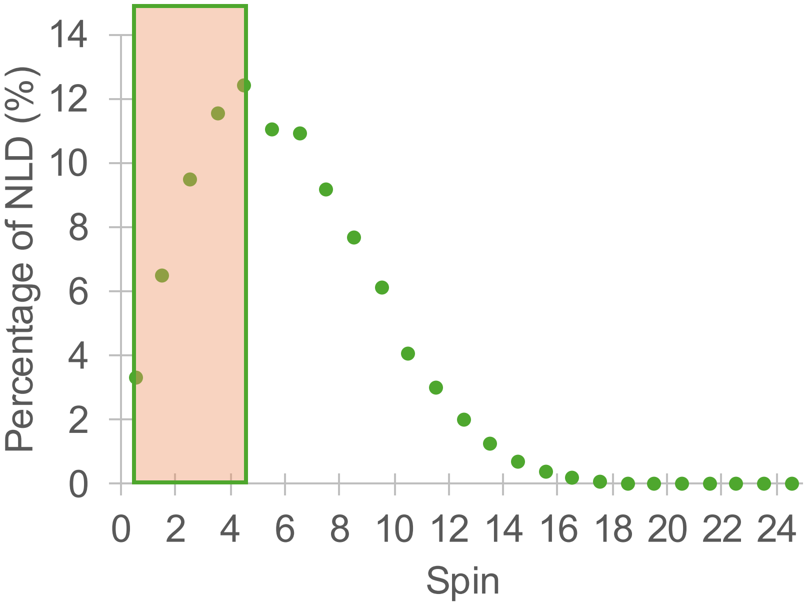


Three normalization points:

- Low-lying levels (from NNDC)
- Level density at neutron-separation energy (from previous data or from theory)
- Average radiative width or giant dipole resonance (GDR) data

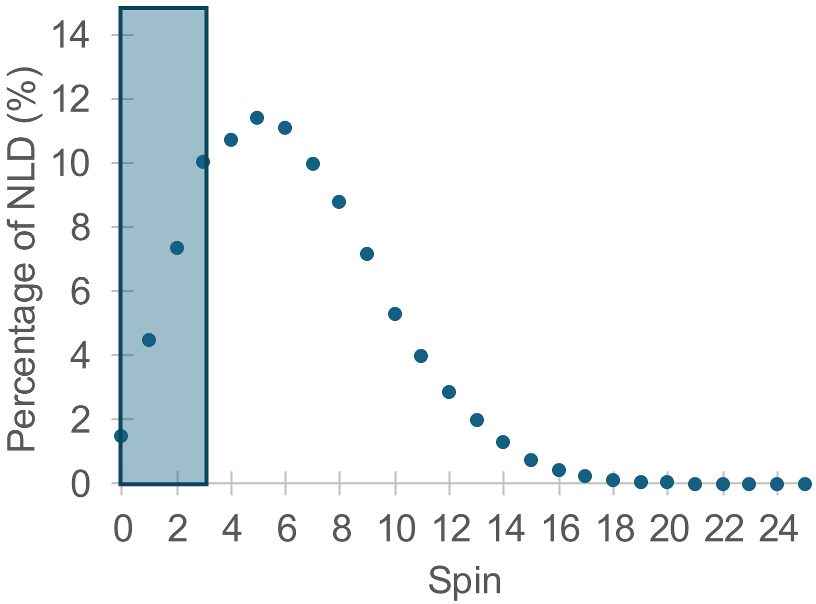
Spin Reduction from β-decay Selection Rules

^{103}Mo



- From ^{103}Nb – $5/2^+$ g.s.
  - Spin range: 1/2 - 9/2
- 43% population

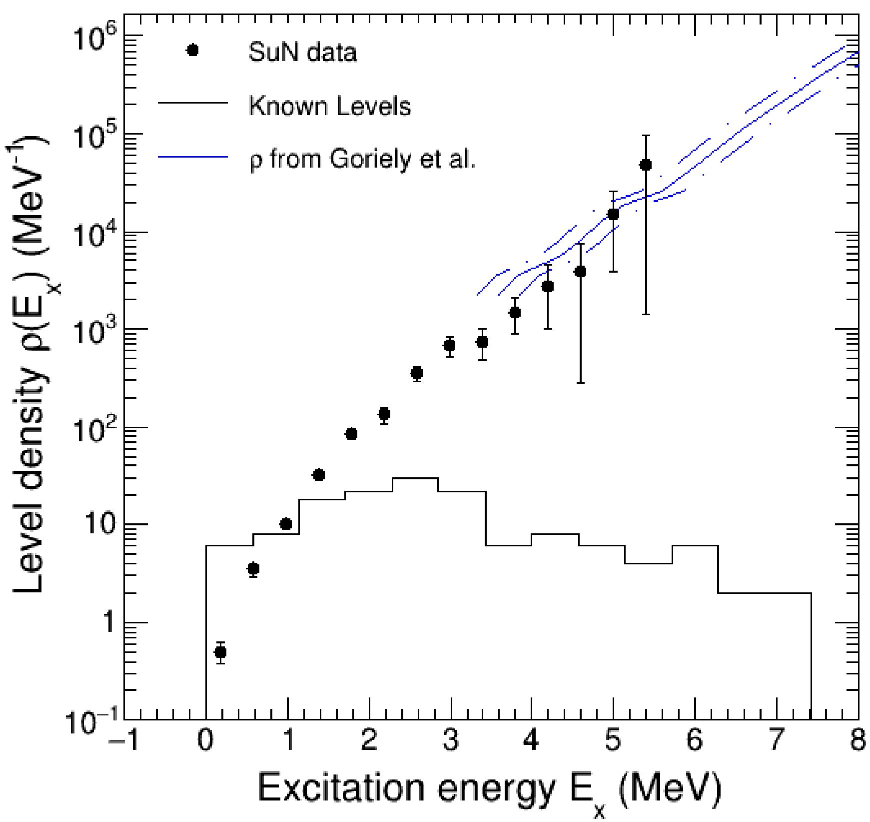
^{104}Mo

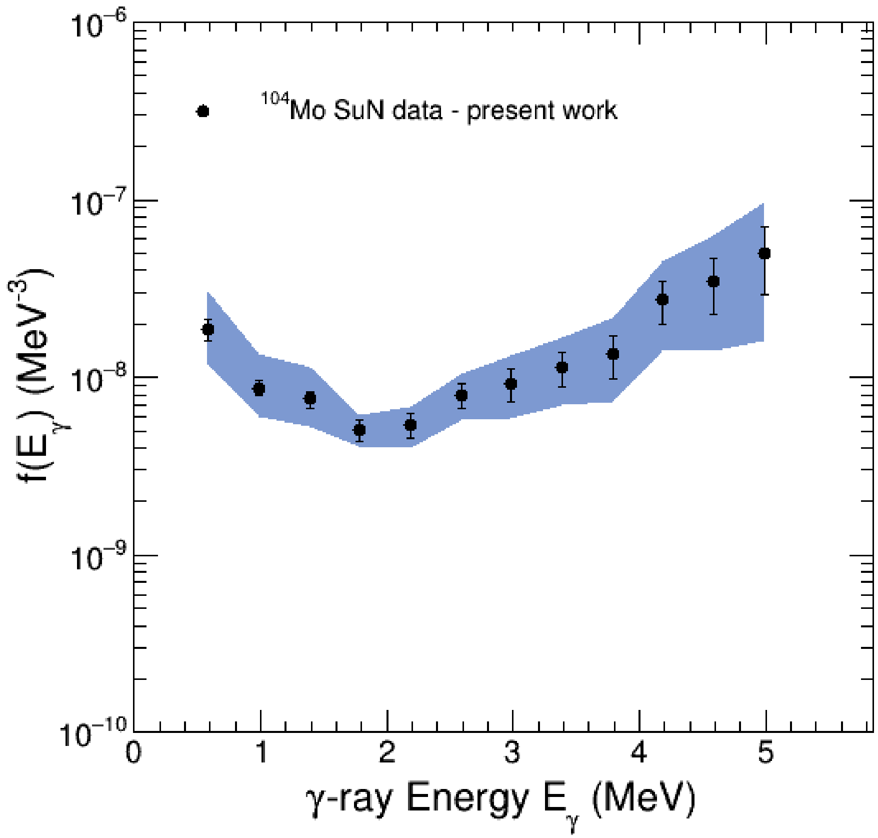


- From ^{104}Nb – (1^+) g.s.
  - Spin range: 0 - 3
- 23% population

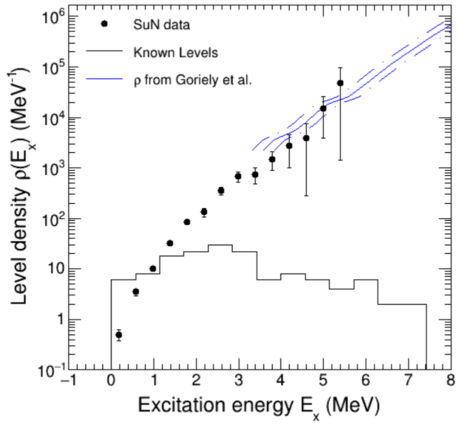
Goriely, Hilaire, and Koning, PRC **78**, 064307 (2008)

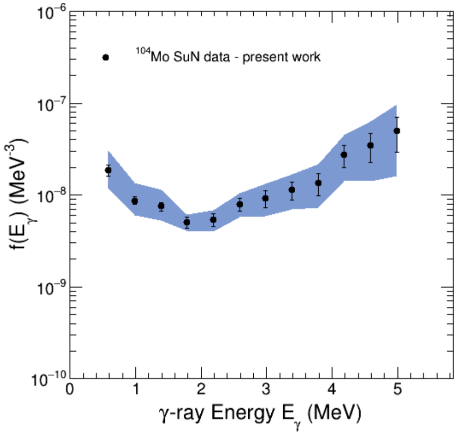
Neutron-capture constraints for $^{103}Mo(n,\gamma)^{104}Mo$

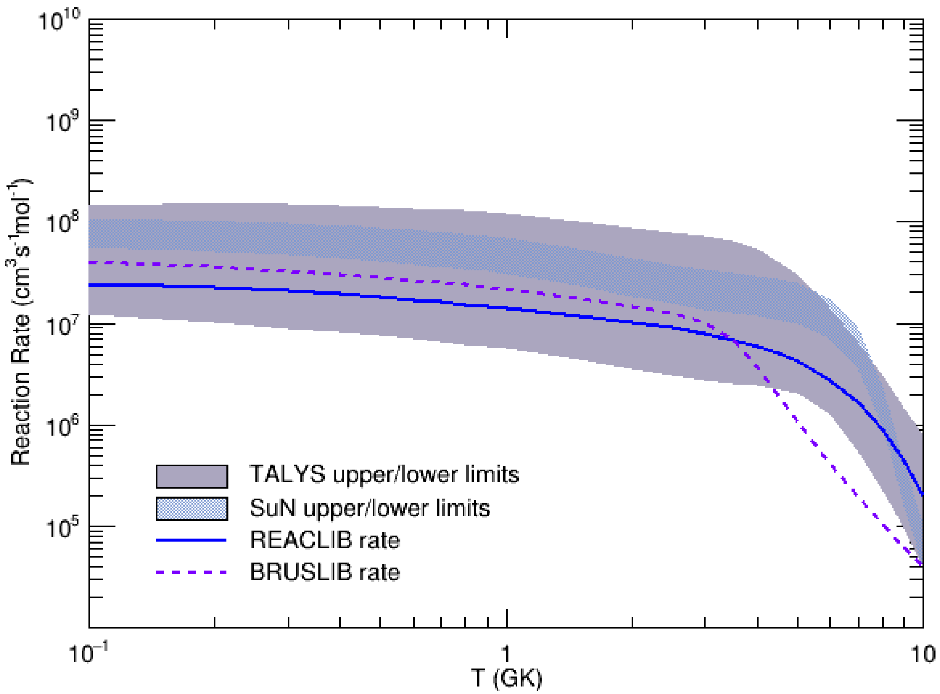




Neutron-capture constraints for $^{103}Mo(n,\gamma)^{104}Mo$

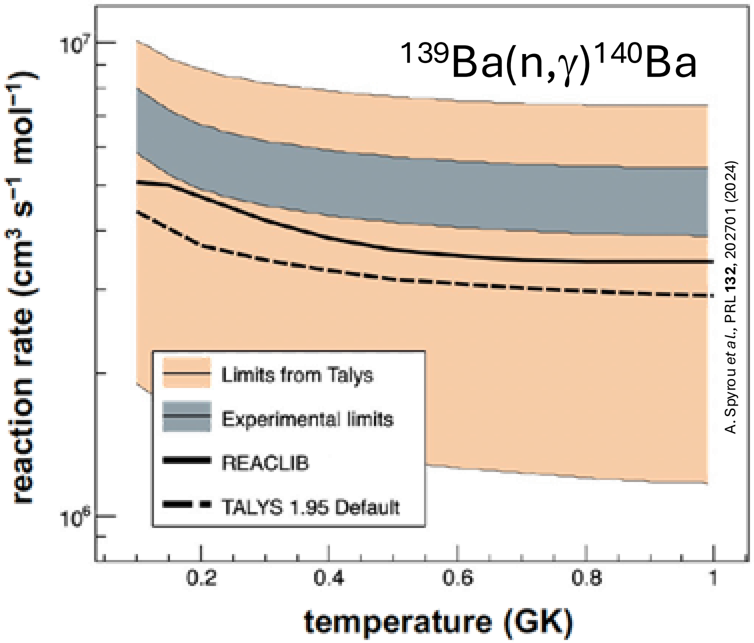


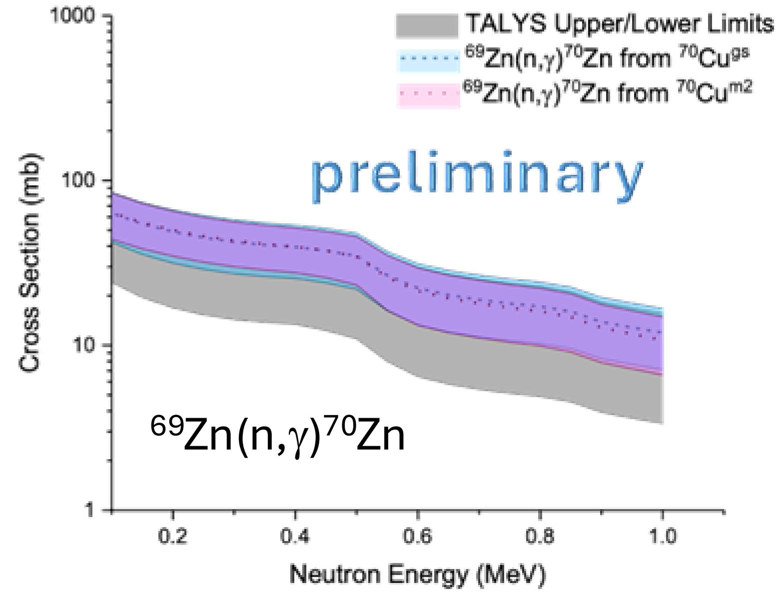


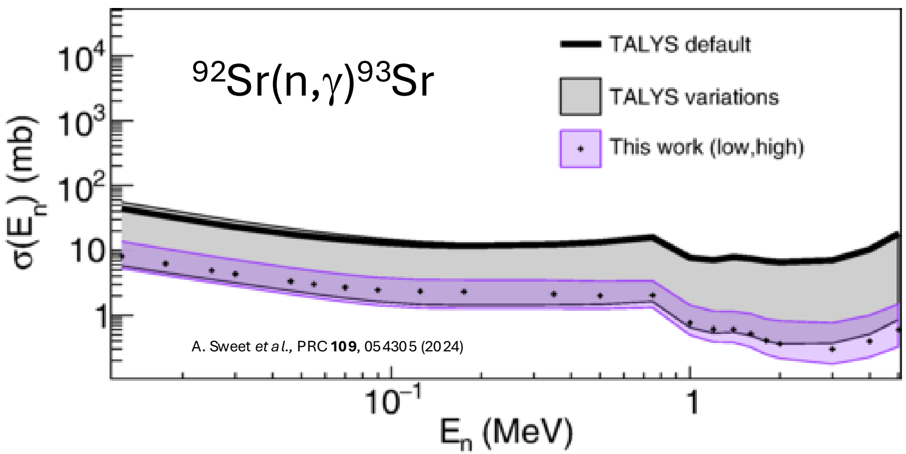


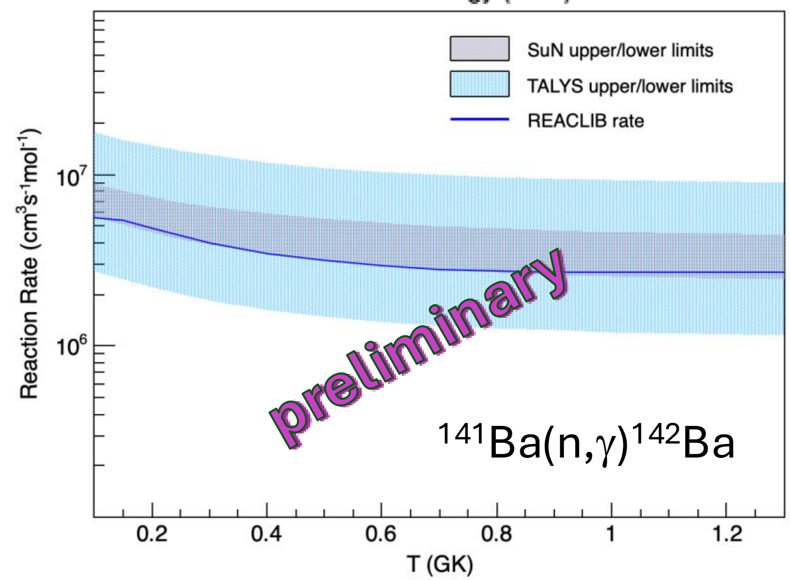
JINA-CEE

Recent Results from β-Oslo Studies





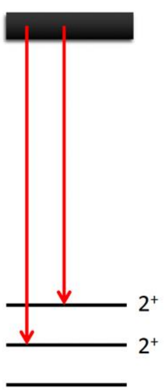


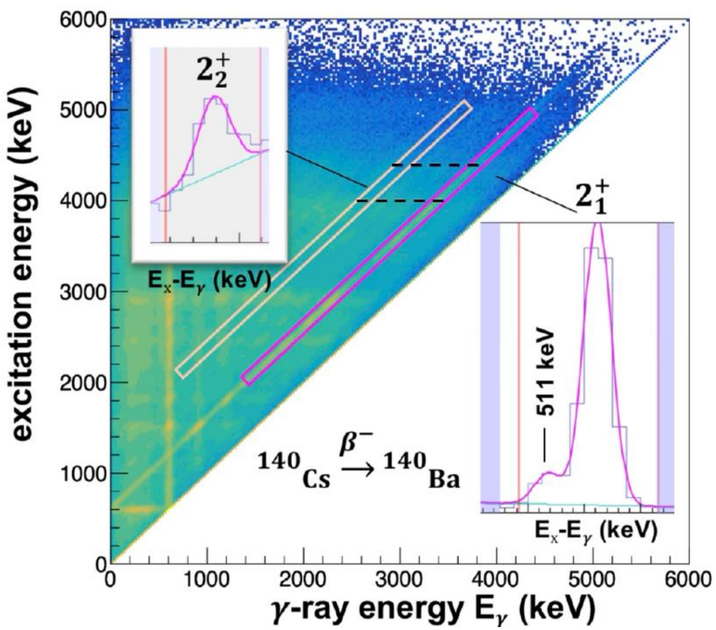


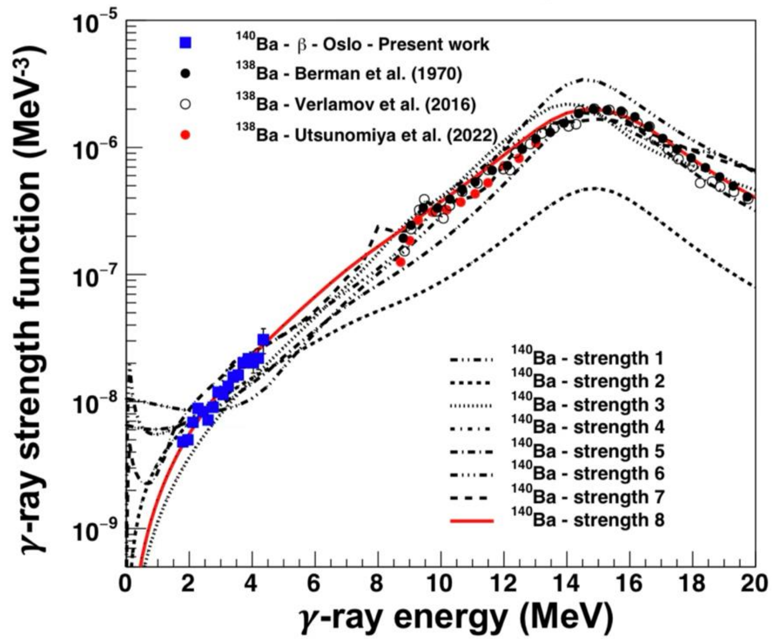
Half-lives, β-feeding intensities also extracted!

Shape Method: shape of γSF from data used for $^{139}Ba(n,\gamma)^{140}Ba$

- New normalization technique work is in progress
  - Shape Method for Oslo/inverse-Oslo data and ShapeIt for β-Oslo
- Relies on diagonals in the E_x vs. E_γ matrix to extract the shape of the γSF
  - Use γSF in β-Oslo analysis to extract a model-independent level density







M. Weideking, *et al.* PRC **104**, 014311 (2021)
D. Muecher, A. Spyrou *et al.*, PRC **107**, L011602 (2023)

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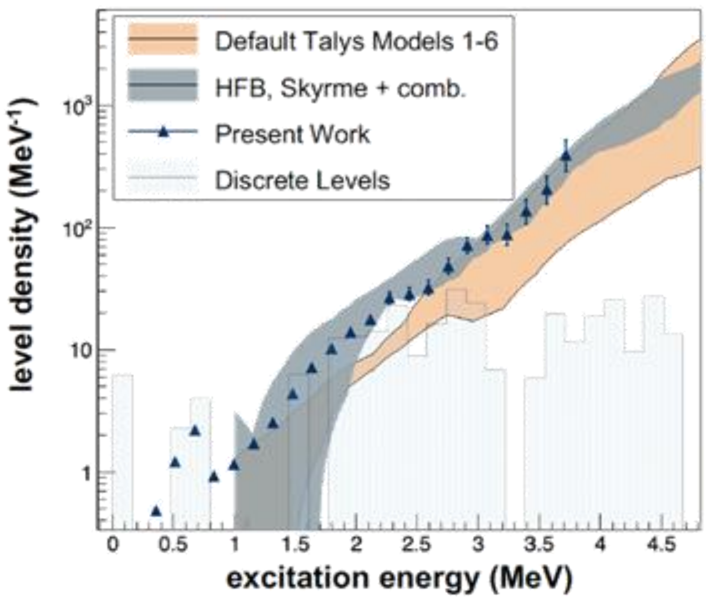
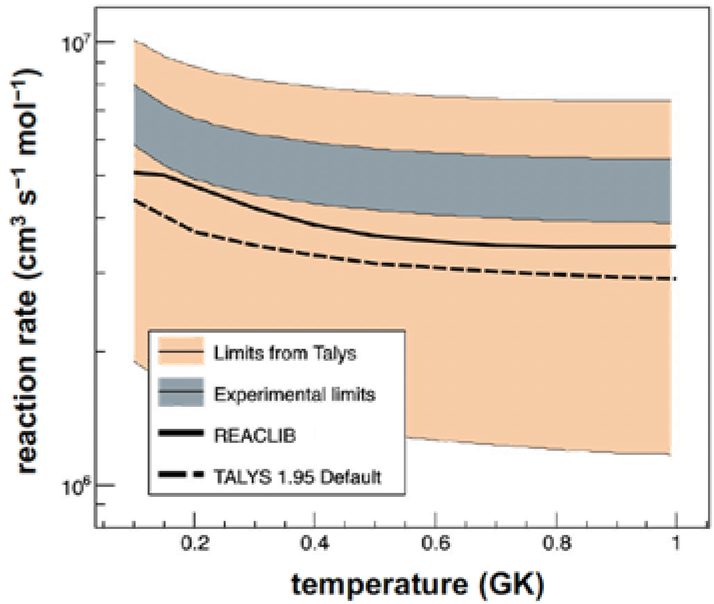
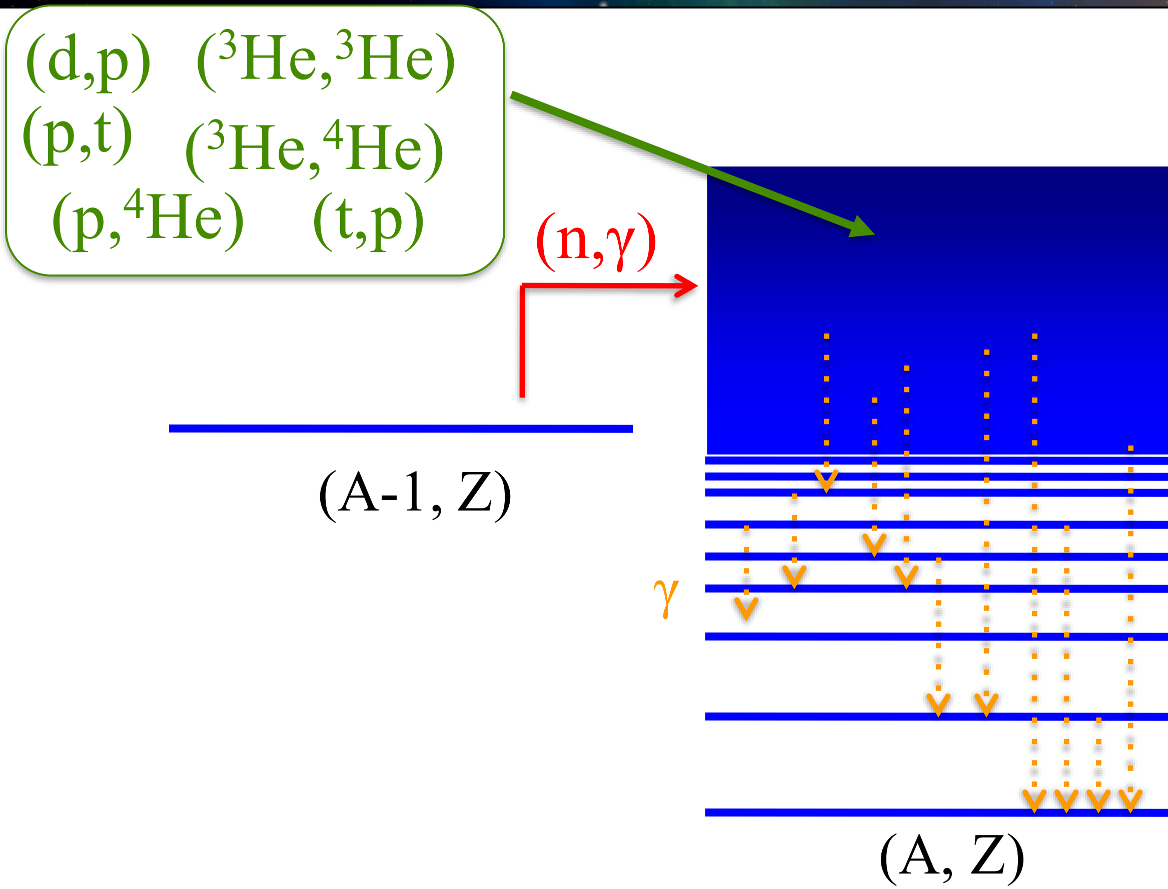


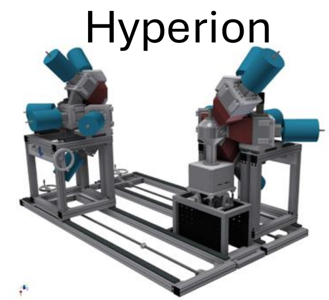


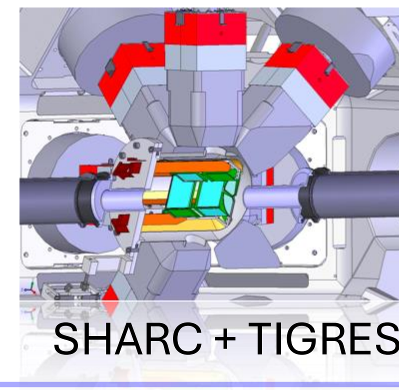
A. Spyrou *et al*. Phys. Rev. Lett. **132**, 202701 (2024)

Indirect Techniques are used to constrain (n,γ) rates



GODDESS 2021





- Populate the compound nucleus via (d,p), (p,d), inelastic scattering, ...
- Study nuclei far from stability
- Feasible with beam intensities > 10^6 pps

•Need:

✓ Radioactive Beam

✓ Segmented high-resolution γ-ray array

✓ Segmented charged particle arrays

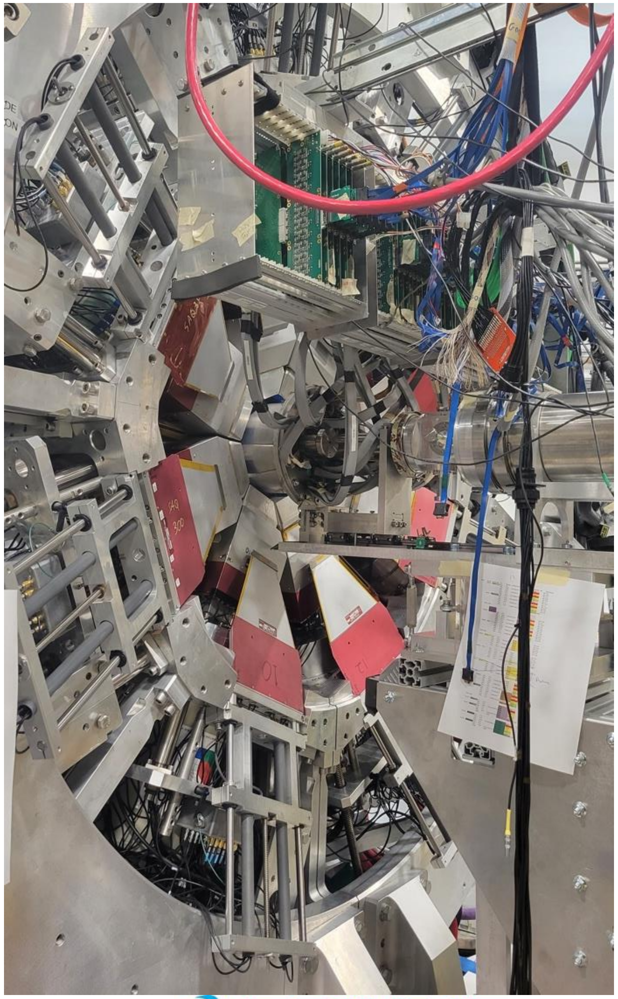
(Some) Experimental Setups for Surrogate Reactions

- Highly Segmented Silicon Arrays and High-resolution HPGe arrays

NSCL

FRIB

Argonne NATIONAL LABORATORY

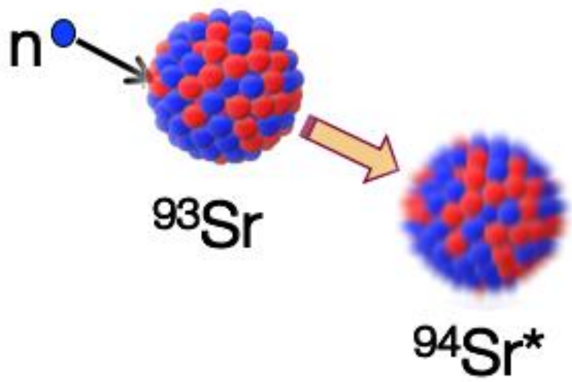


SHARC + TIGRESS

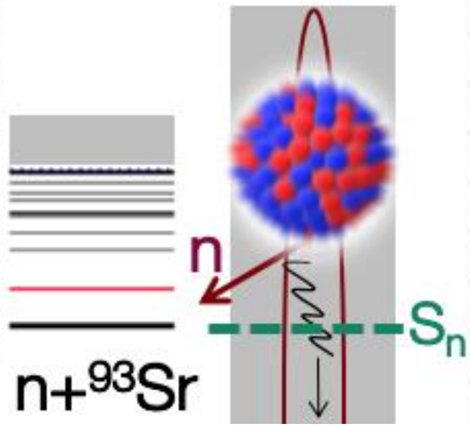
TRIUMF

Surrogate Reaction Method

Neutron capture



CN decay

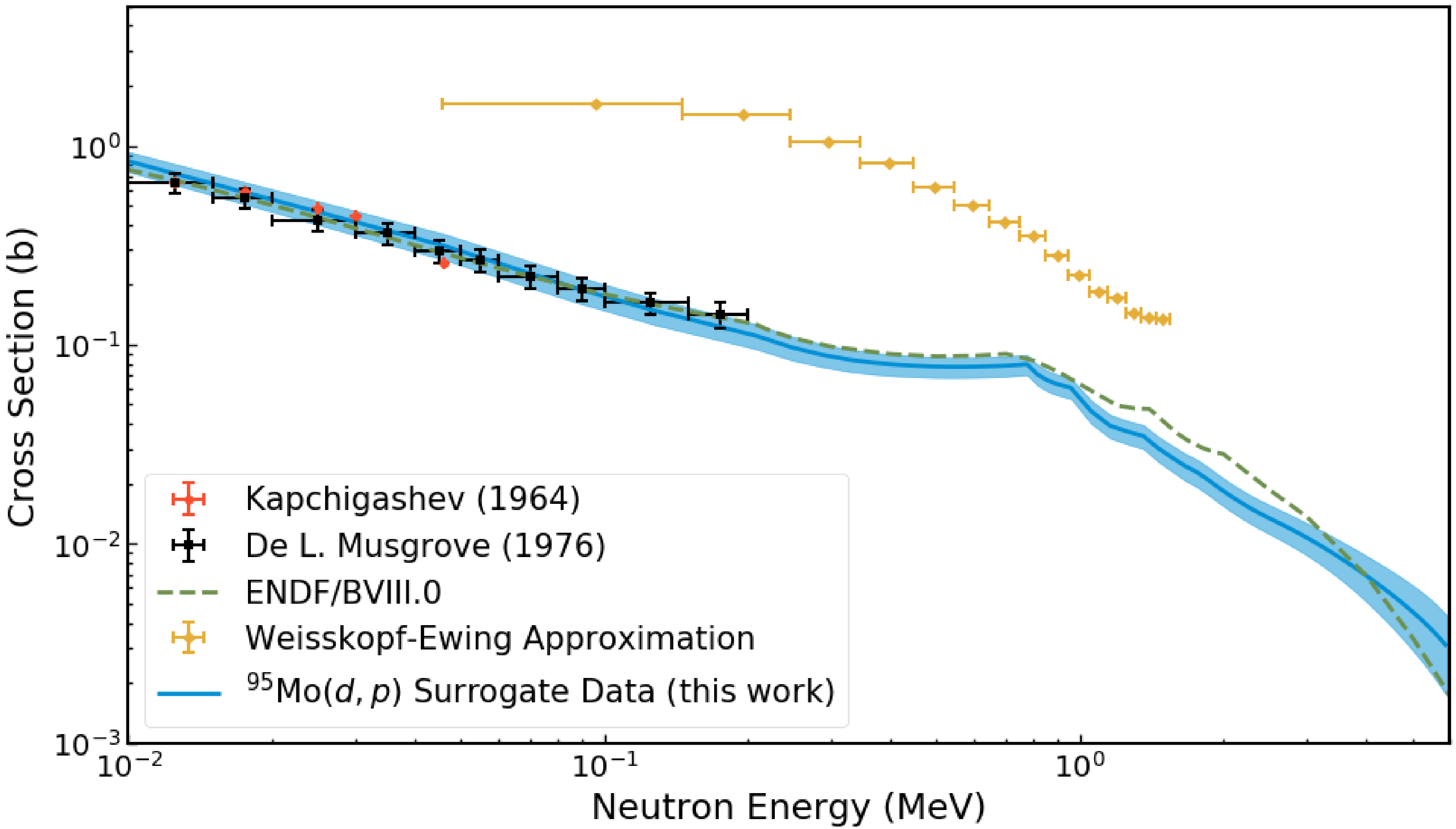


Neutron Capture

$$\boxed{\sigma_{(n,\gamma)} = \sum_{J\pi} \sigma_n^{CN}(E_n, J, \pi)\ G_\gamma^{CN}(E_n, J, \pi)}$$

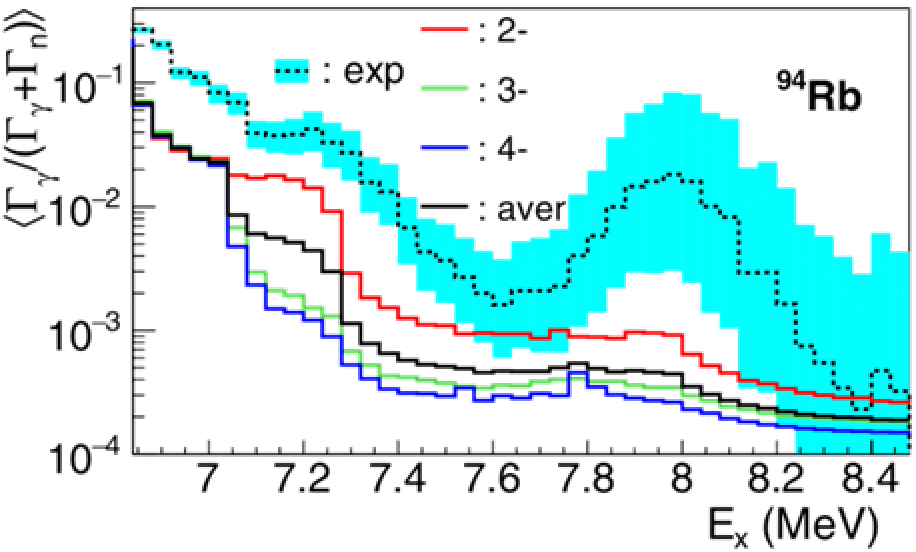
G. Potel *et al.*, PRC **92**, 034611 (2015).
J. Escher *et al.*, PRL **121**, 052501 (2018)

Surrogate Reaction Method Applied to $^{95}Mo(n,\gamma)^{96}Mo$

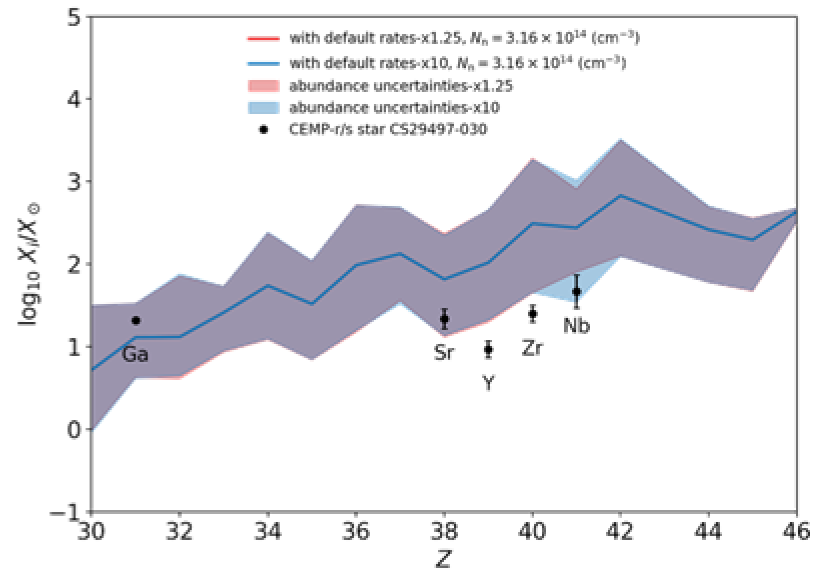


A. Ratkiewicz *et al.*, PRL 122, 052502 (2019).

Decay studies suggest enhanced capture rate for ^{93}Sr(n,γ)



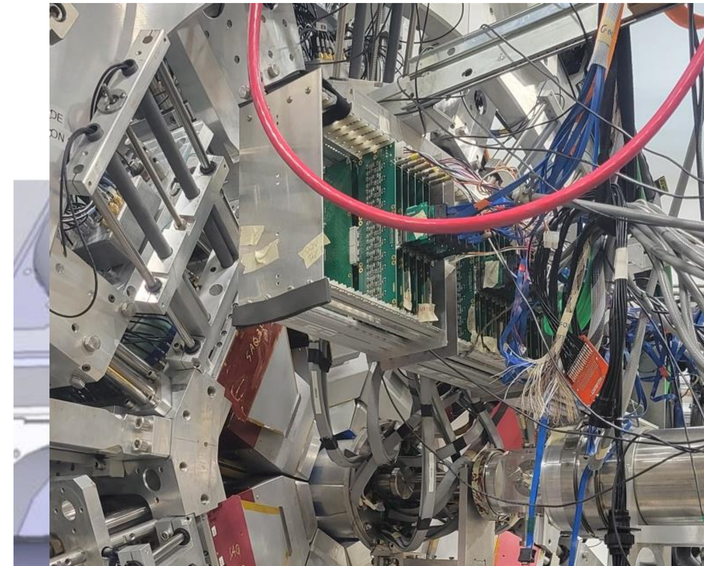
J. L. Tain *et al.* PRL **115**, 062502 (2015)



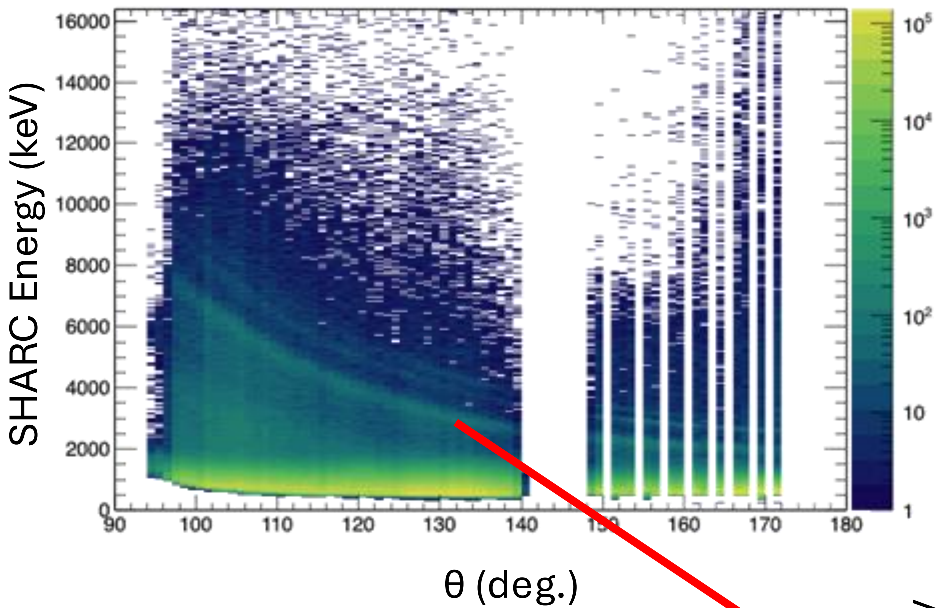
- β-decay studies following ^{94}Rb decay to ^{94}Sr show unusually high γ-decay branch above S_n
    - Enhancement in neutron-capture of ^{93}Sr?
- Constraining (n,γ) for ^{93}Sr imperative, but $t_{1/2}$ = 7.4 min… how do we measure it?

Surrogate reaction measurement of ^{93}Sr(d,p) at TRIUMF

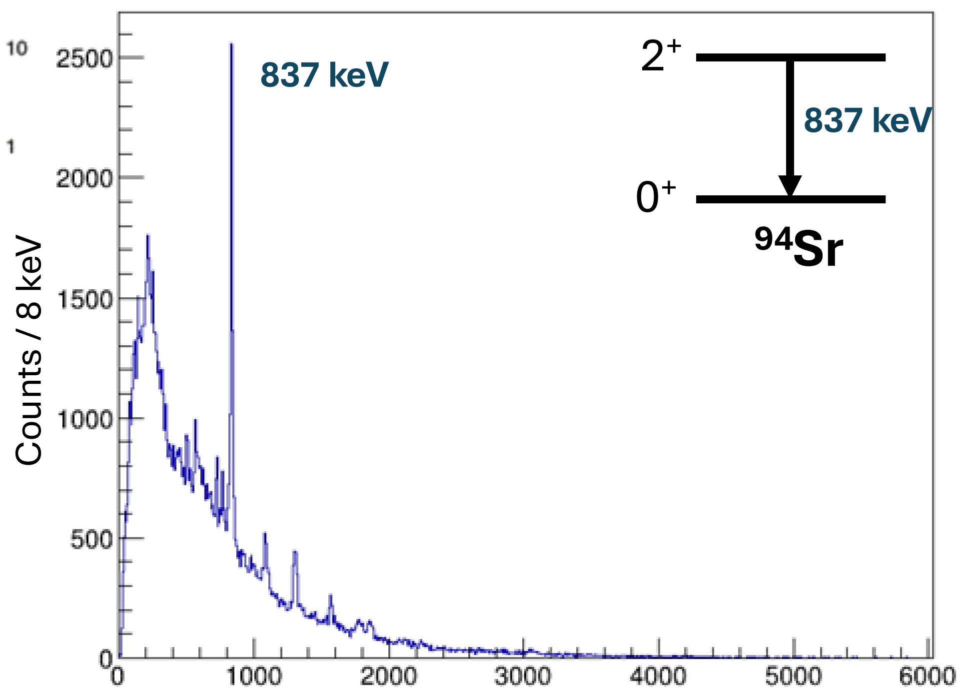
- 8 MeV/u ^{93}Sr beam impinged on CD_2 target (369 μg/cm^2, 446 μg/cm^2)
- Proton detection: SHARC
  - Segmented Si array
  - 80% of 4π coverage
  - ~80% efficiency
- Gamma detection: TIGRESS
  - 12 HPGe clovers
  - Efficiency (1 MeV) ~ 10%
  - ~2π coverage
- SHARC + TIGRESS enable particle-gamma coincidences



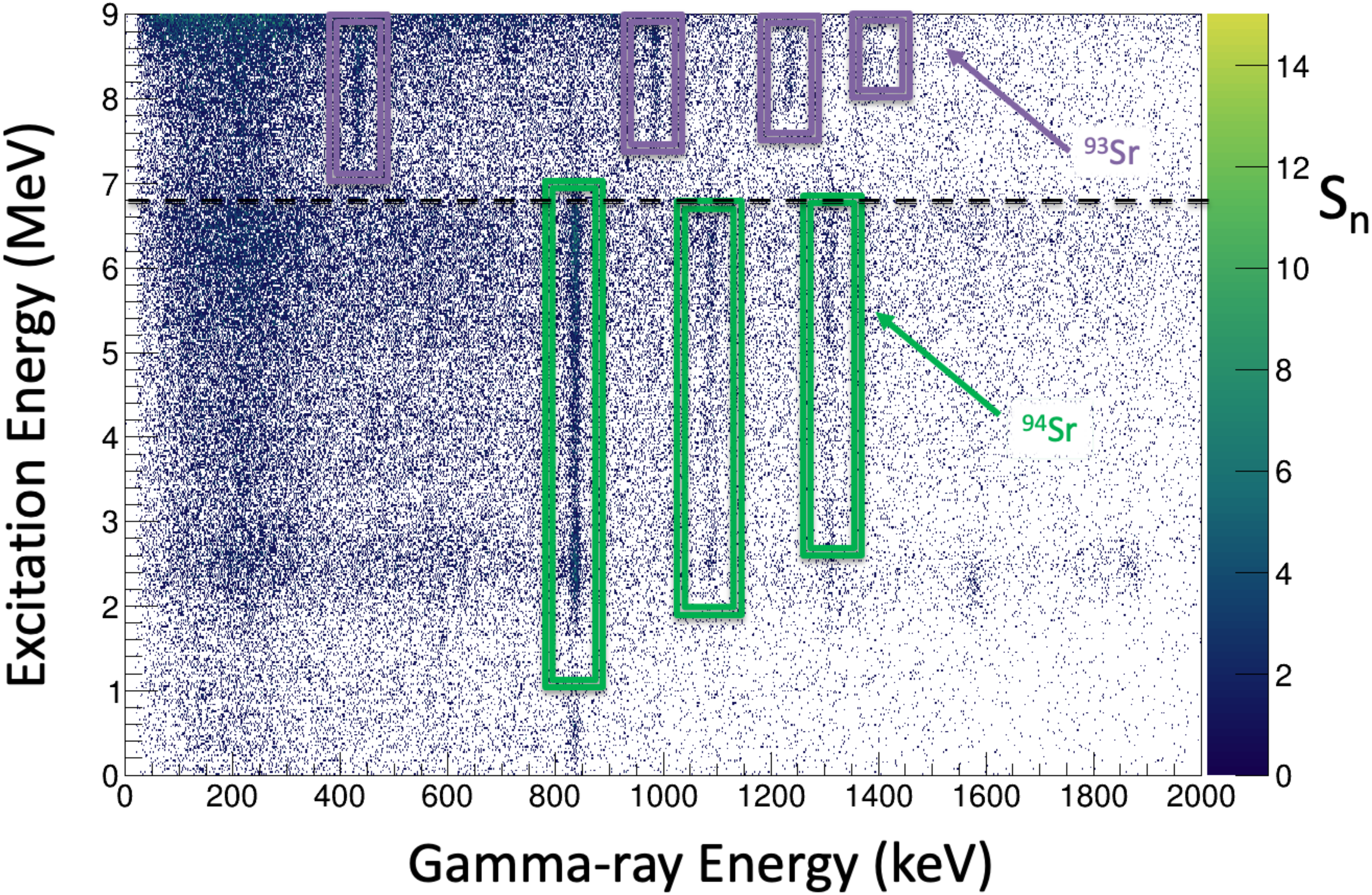
Preliminary particle-γ coincidence results



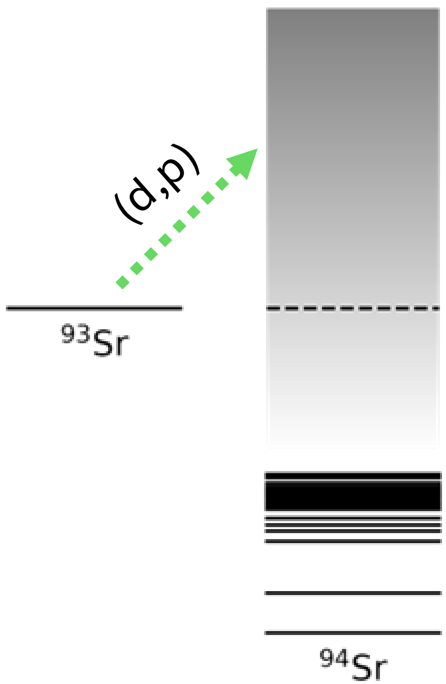
Doppler-corrected TIGRESS spectrum gated on (d,p) region



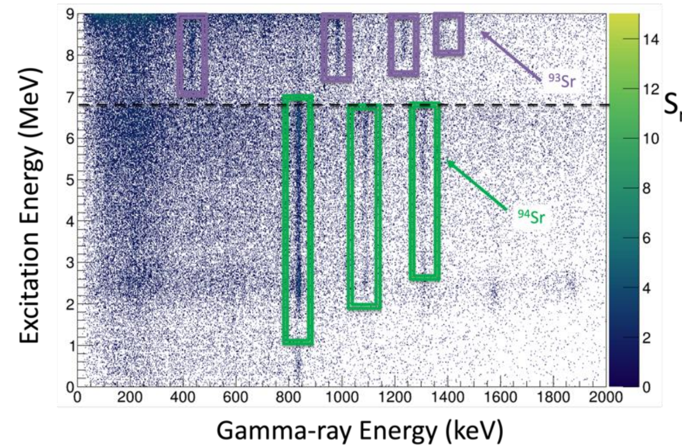
Particle-γ coincidences in both ^{94}Sr and ^{93}Sr are observed

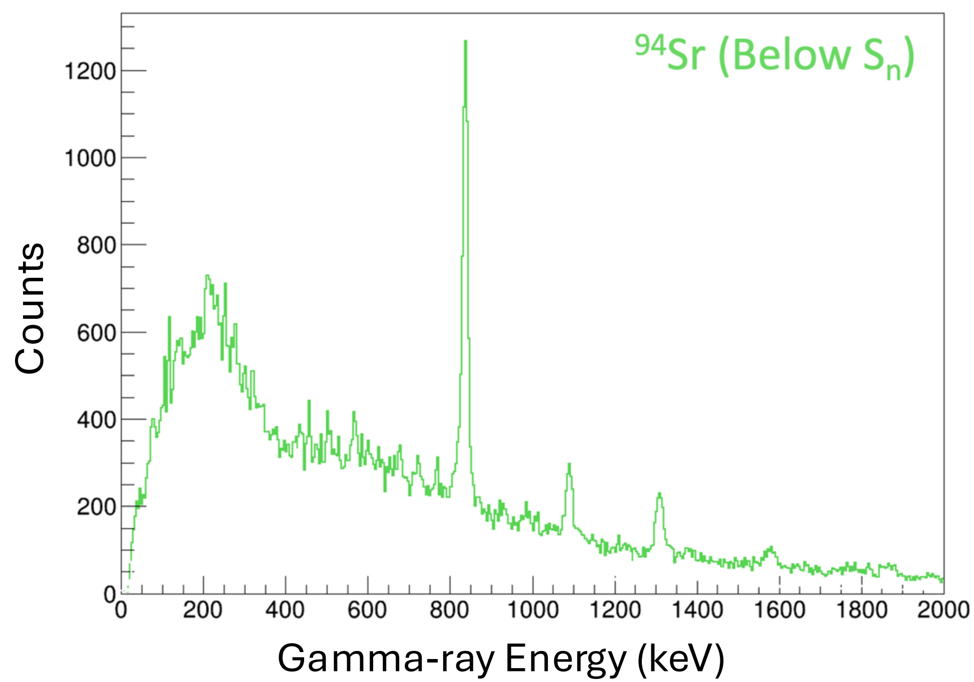


Gamma-ray emission above and below S_n



^{93,94}Sr levels from RIPL-3 (R. Capote *et al.*)





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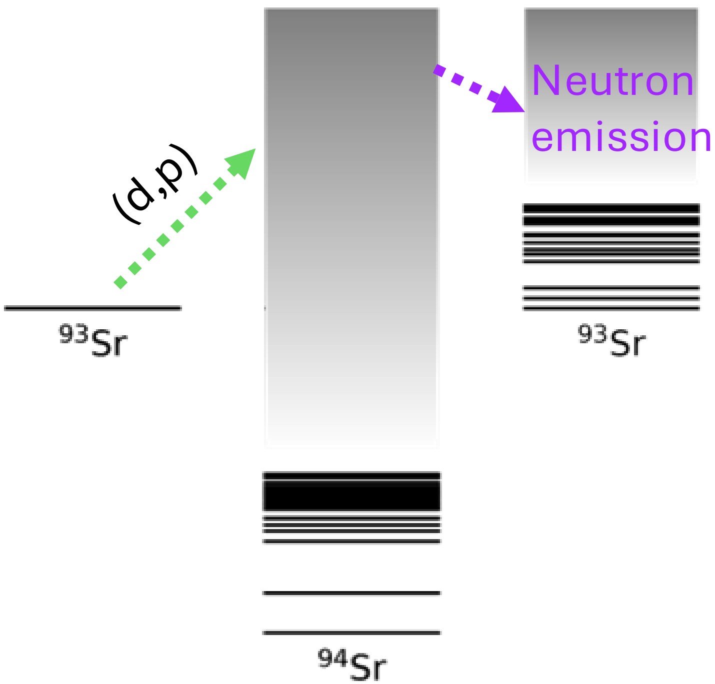

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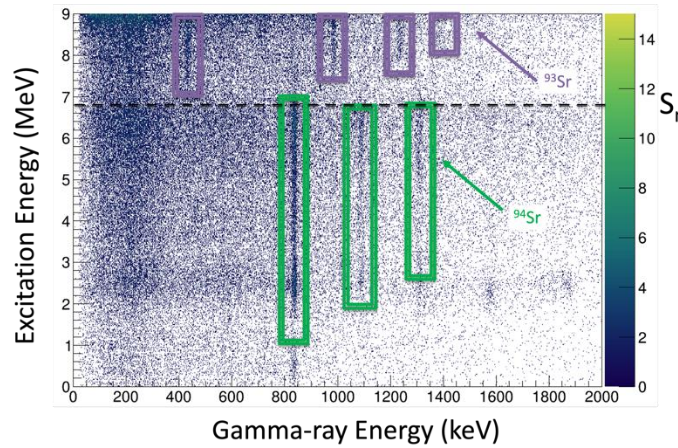
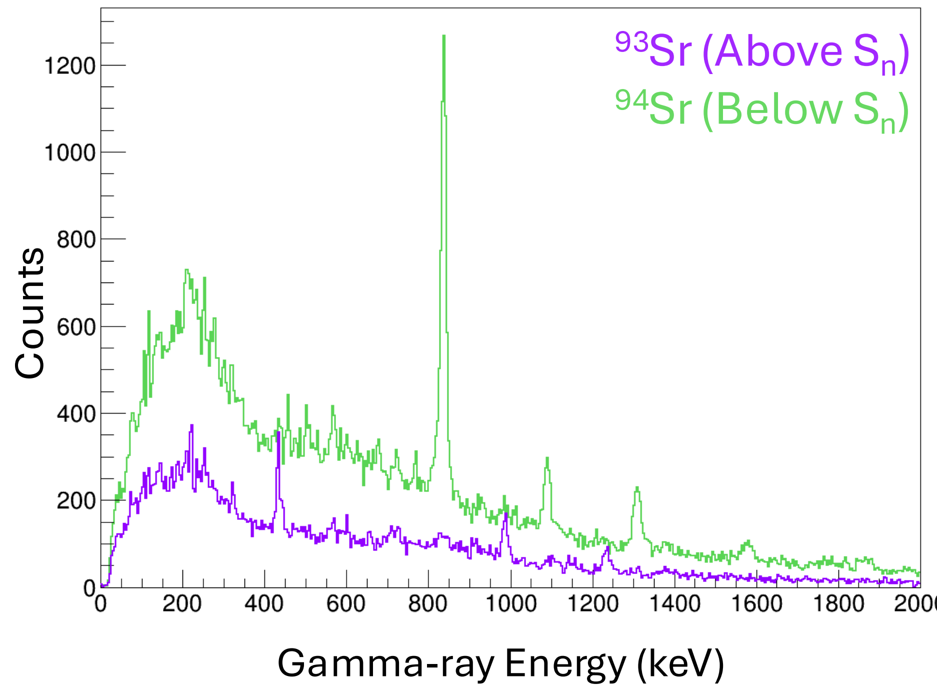
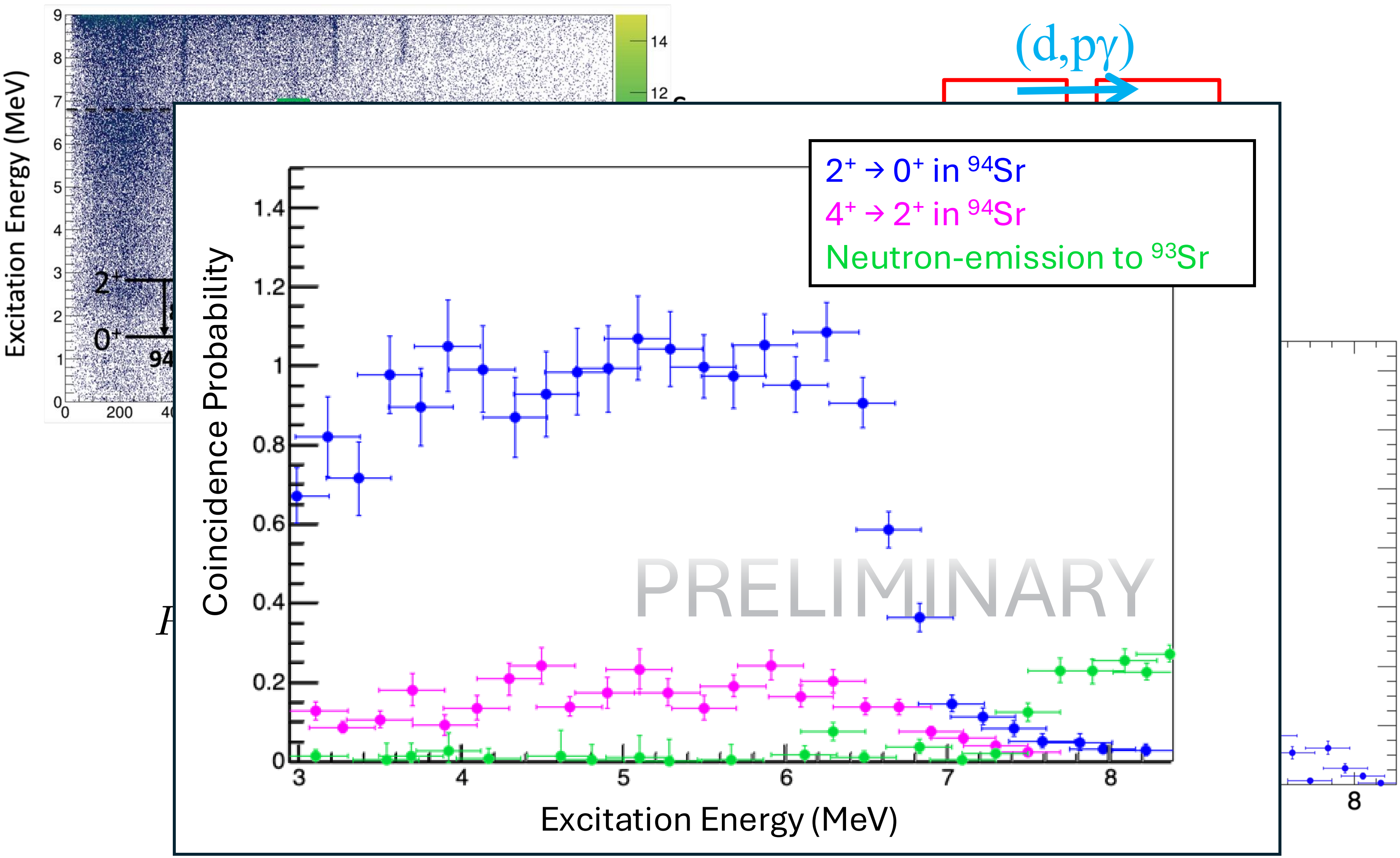


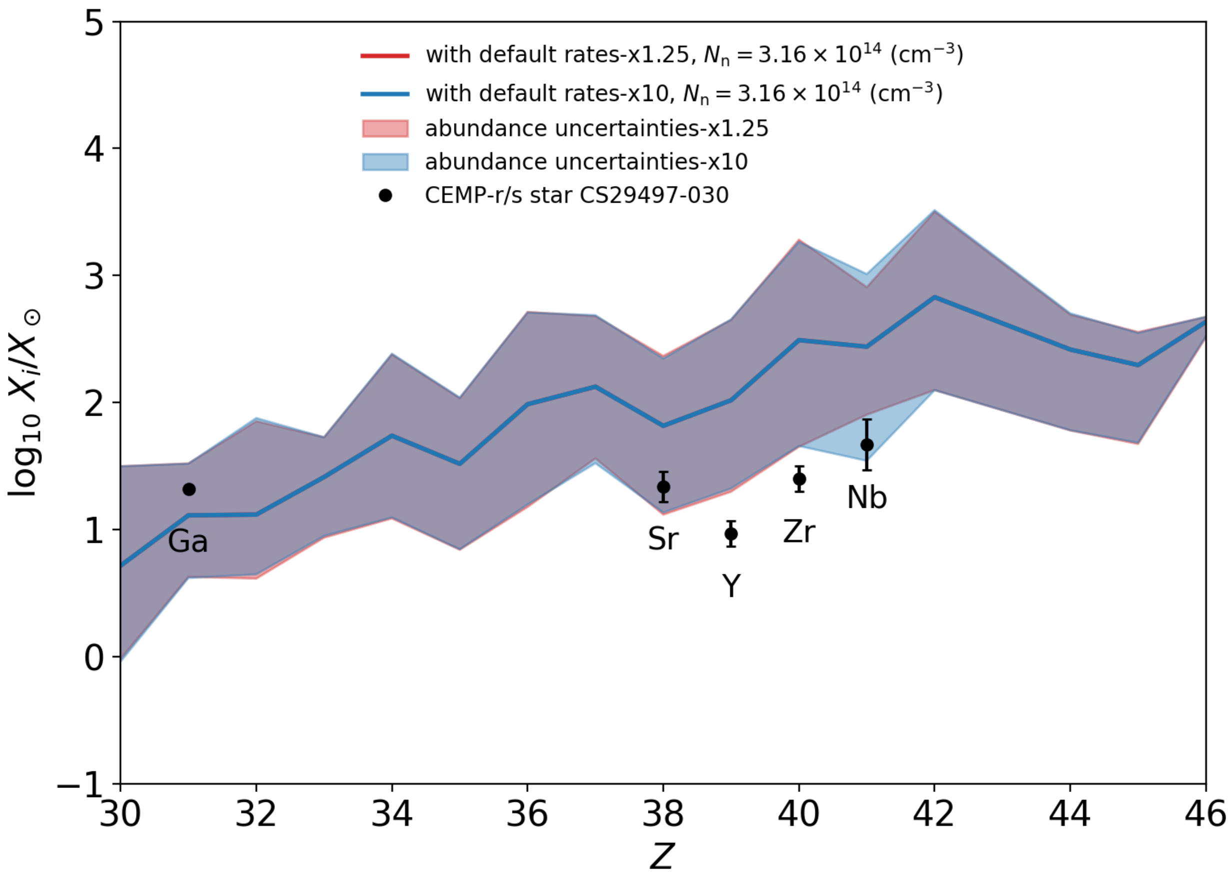


Preliminary Particle-γ Coincidence Probability Results

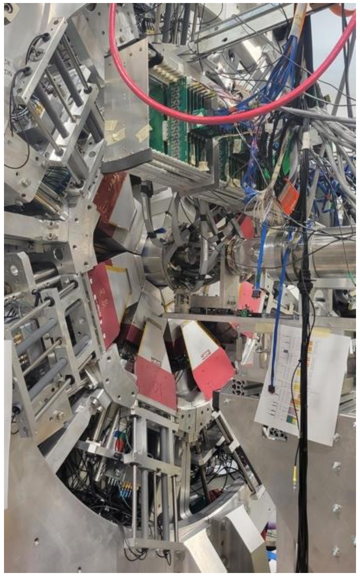


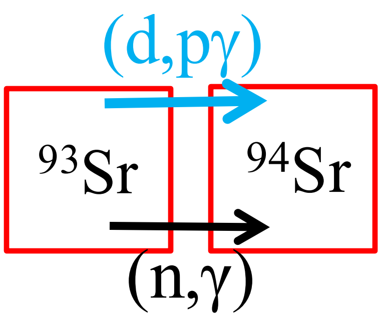
^{93}Sr(n,γ)^{94}Sr cross section via SRM

- ^{93}Sr(d,pγ)^{94}Sr using ^{93}Sr RIB



Based on work from LLNL Summer Intern Lauren Harewood (ND)





So… what now?

- We’ve done a rapid-fire coverage of mostly neutron-capture processes and experimental techniques.
- We did NOT cover in depth how to measure structure properties like P_n values, masses, β-decay rates, etc.
- Still many things to measure and many new developments not discussed
  - Role of isomers in astrophysics (astromers)
  - Charge-exchange reactions for astrophysics
  - Triton beam development
  - Particle-Evaporation level densities
  - Activation techniques
  - NIF
  - Theory development

This is why we need all of you!

Nuclear Astrophysics Networks are Critical for Progress

JINA-CEE

CaNPAN

CeNAM

BRIDGCE
UK NETWORK

NUGRID

ChETEC
Action

ChETEC
INFRA

EMMI

VIRGO
KAGRA
KAGRA Observatory

IANNA
IBERO AMERICAN NETWORK OF NUCLEAR ASTROPHYSICS

UKAKUREN/JaFNA

Thank you!

Questions?