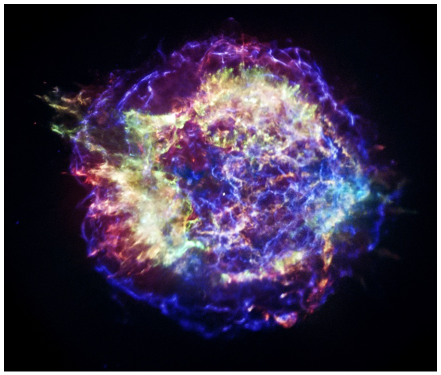
Nuclear Data for Nuclear Reactions

A. Couture

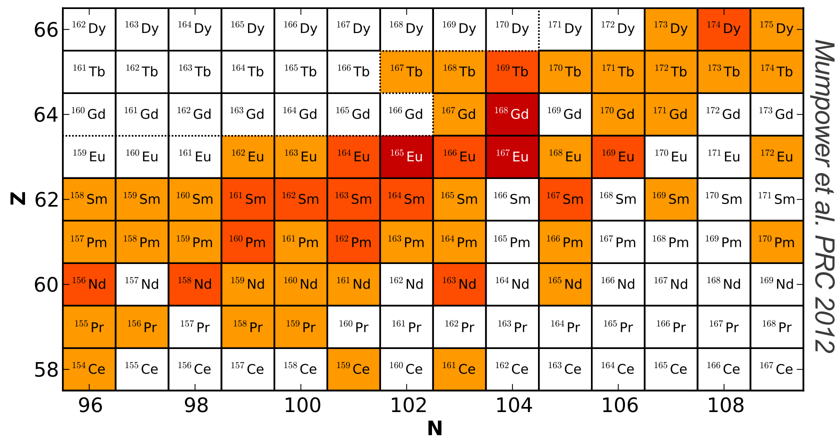
13 Nov 2022

Nuclear Reactions play roles across scientific studies on stable and unstable isotopes

Cassiopeia A
10^{44} Joules
10^{22} n/cm^2/sec

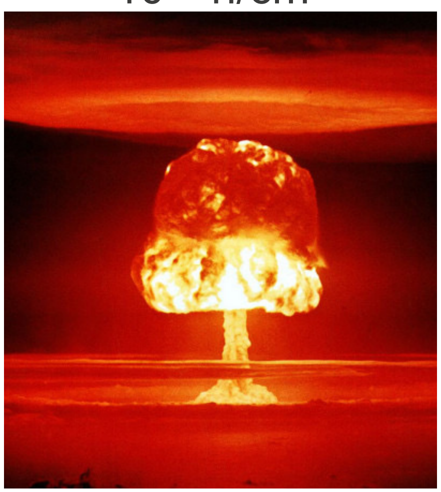


Nucleosynthesis

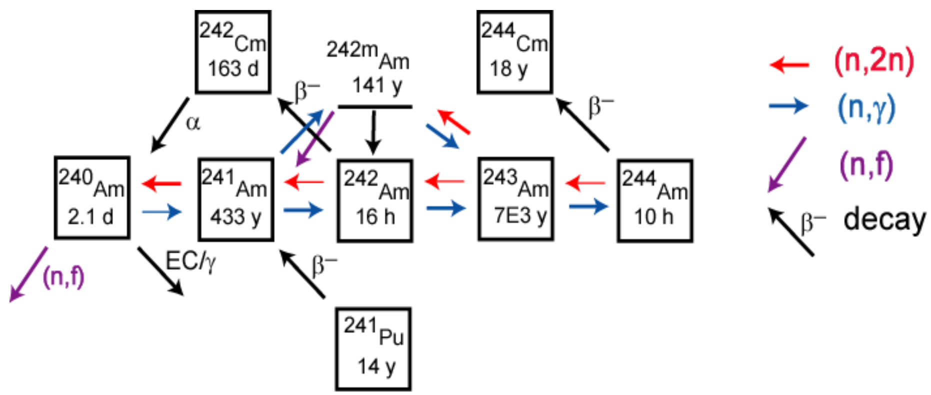


Relative abundances of heavy elements give information on stellar dynamics and evolution and cosmology. Individual cross sections have large impact on final abundances.

Castle-Romeo
4×10^{16} Joules
10^{23} n/cm^2



Transmutation of elements



$\Delta A = {}^{240}Am/{}^{241}Am$: a radchem diagnostic that does not require prior knowledge of initial Pu.

- *More reliable and sensitive*
- *Important for nuclear forensics*

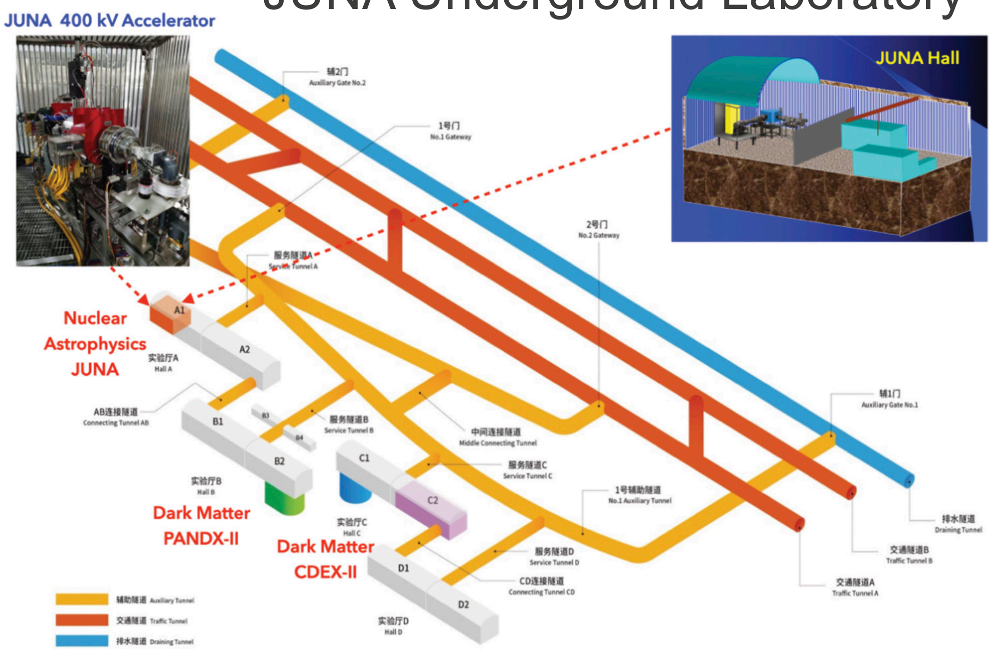
What are the types of Nuclear Data that are needed to support these efforts?

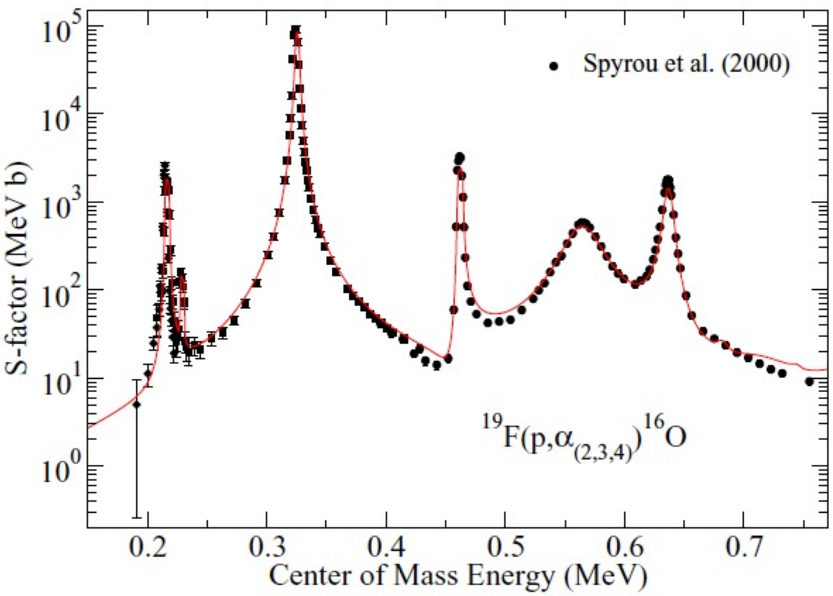
- Cross sections—Resonant and non-Resonant, Partial and Total–-are the primary quantity of interest
- The traditional tools and libraries for tracking many of these are well-developed
  - R-matrix theory
  - Resonance properties
  - Hauser Feshbach formalism
  - Ready place for new measurements of direct properties to be captures
- In some cases, new measurements, particularly on unstable isotopes, do not have a home to capture the physical measurement
  - Photon Strength Functions

Light Ion R-Matrix

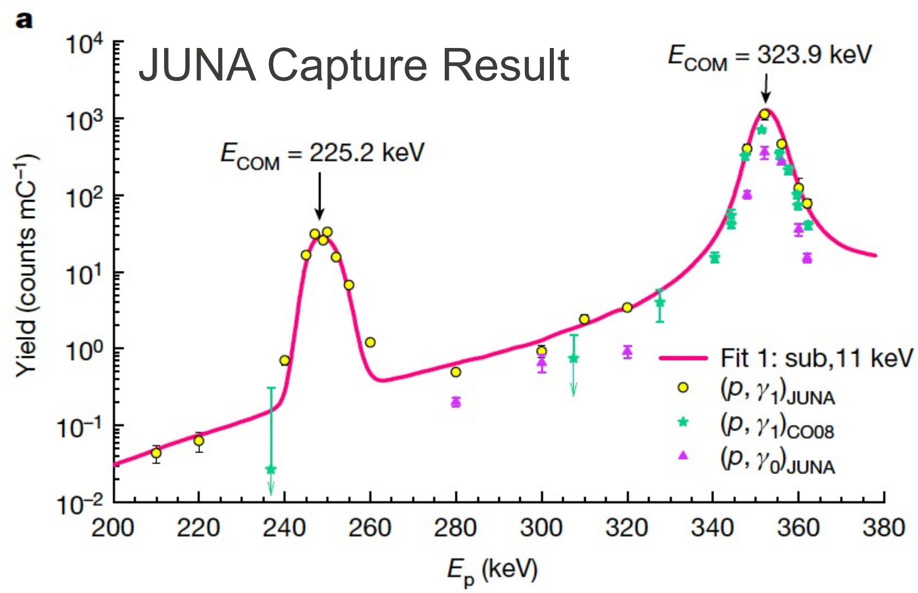
- New facilities open the door to measurements previously unachievable
- The r-matrix tools to analyze them are robust
- Recent efforts led through IAEA to cross-compare r-matrix calculations are welcome

JUNA Underground Laboratory





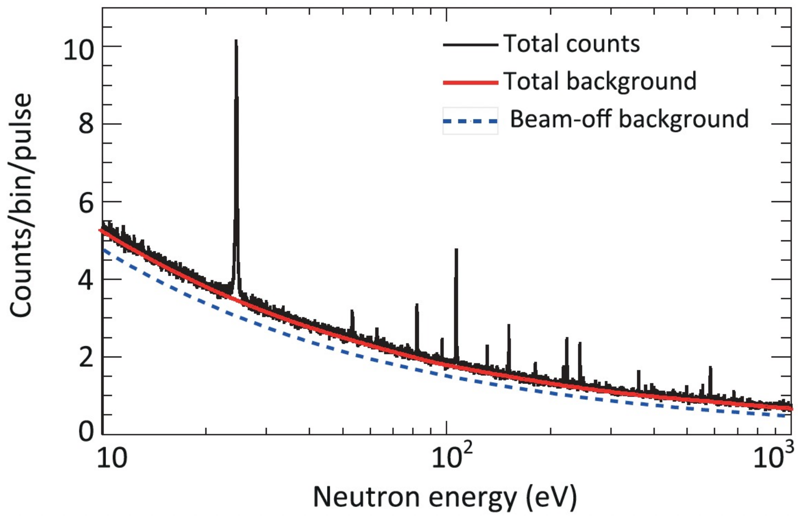
DeBoer et al. PRC 2021

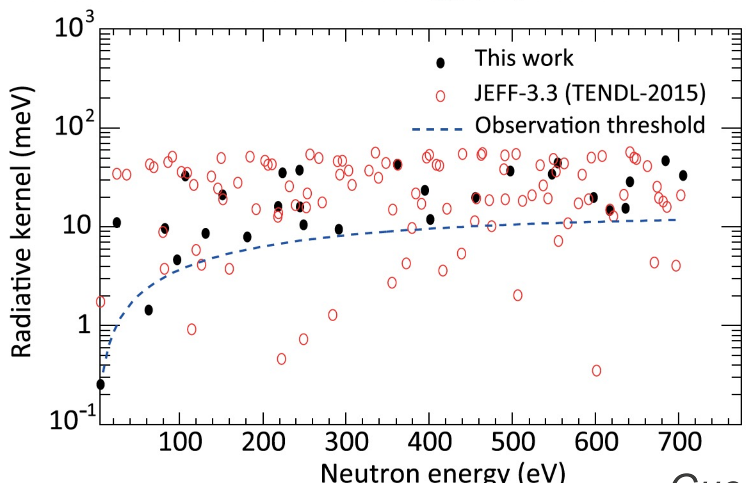


Zhang et al. Nature 2022

Combining techniques to measure radiative capture on ^{171}Tm

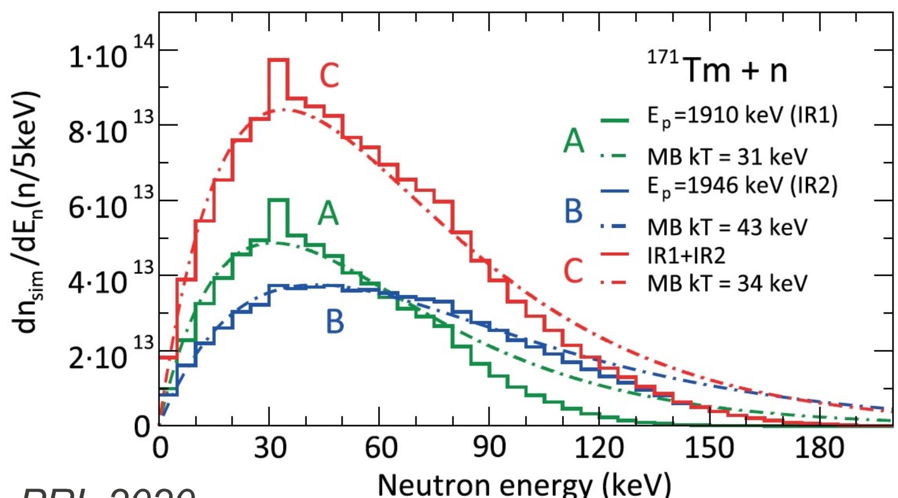
n_TOF resonance measurement





- n_TOF: proton spallation, 200m time-of-flight
- SARAF: high-power ^{7}Li(p,n)
- Combination of measurements with very different facilities increases confidence

SARAF Activation



Guerrero et al. PRL 2020

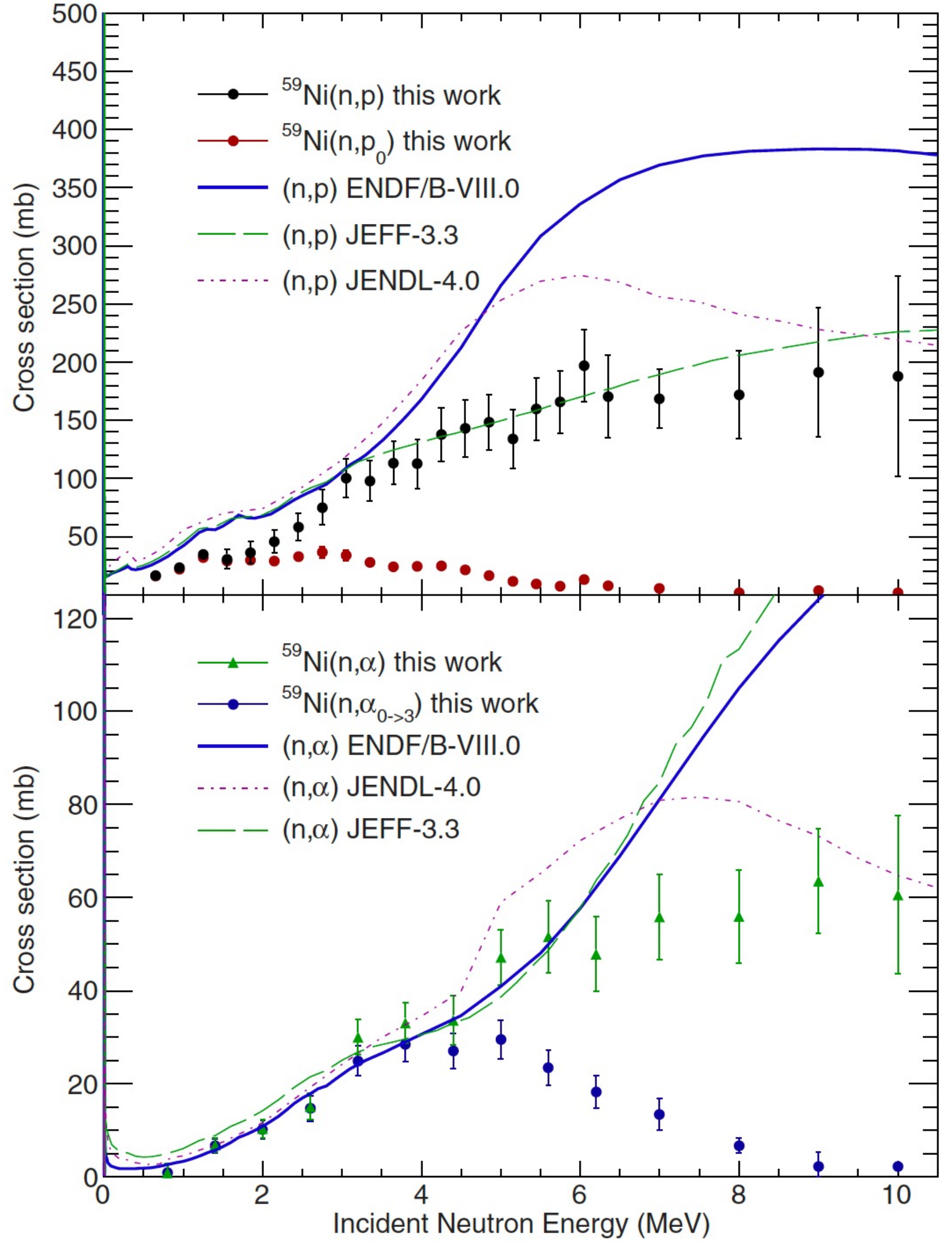
New direct measurements on radioisotopes

- The combination of advanced instrumentation, intense beams, and radioisotope production and separation has opened the door to new high-energy cross section measurements

LENZ: (n,α), (n,p)

Capability developed by H. Y. Lee

Direct ^{59}Ni(n,p) and (n,α) Measurements at LANSCE



Kuvin et al. PRC 2022

Initial take-aways for nuclear data and reactions

- Experimental advances are delivering cross-sections that have previously been inaccessible, often on unstable isotopes or very weak reaction rates
- The theoretical tools (often r-matrix) are robust and physically motivated
- From an evaluation, library, and nuclear data perspective, we understand how to utilize these measurements

Structure-Informed Reaction Modeling

- The Hauser Feshbach Formalism is the standard treatment for compound-nuclear reactions at reasonably high excitation

$$\sigma_\gamma(E_n) = \frac{\pi}{k_n^2} \sum_{J\Pi} g_c \frac{T_n T_\gamma}{T_n + T_\gamma} W_{n\gamma}$$

$$T_\gamma = \sum_{J'XL} \int_0^{E_0} 2\pi E_\gamma^{2L+1} f_{XL}(E_\gamma) \rho(E_x, J') dE_x$$

- Can we determine the input parameters when the cross section cannot be directly measured?

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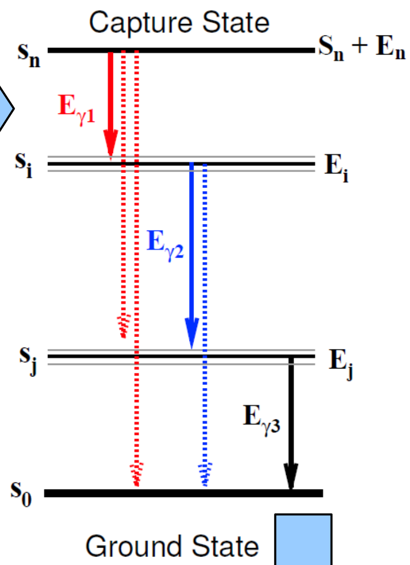
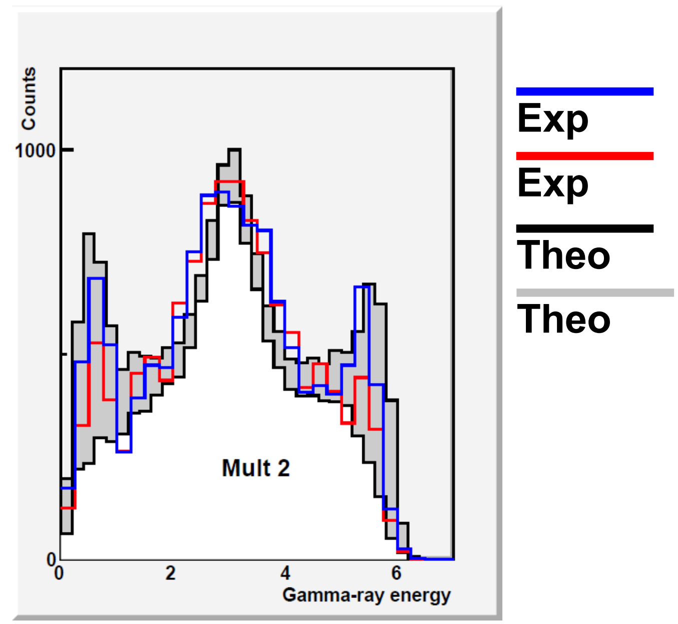
Flow for Theory:Experiment Comparison (From PSF studies on DANCE by B. Baramsai)

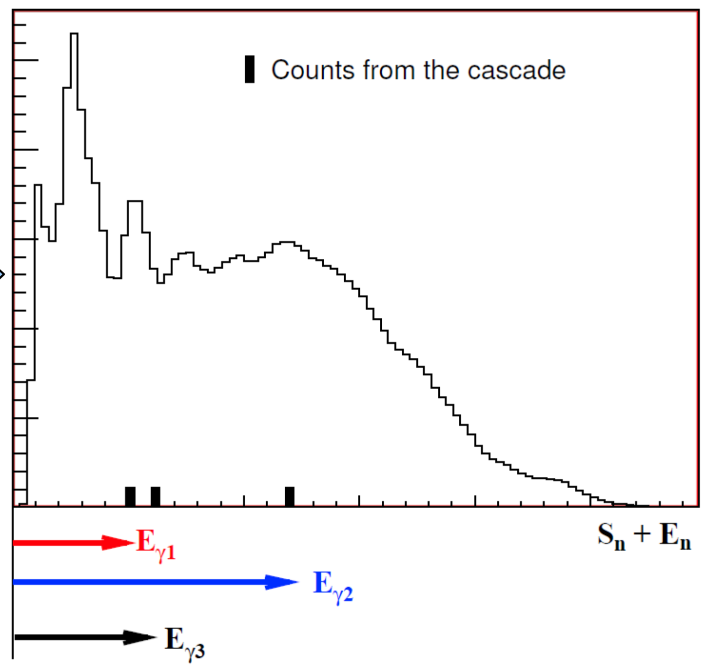
CGM/DICEBOX produces cascades



Comparison with data reveal best model of PSF in this work



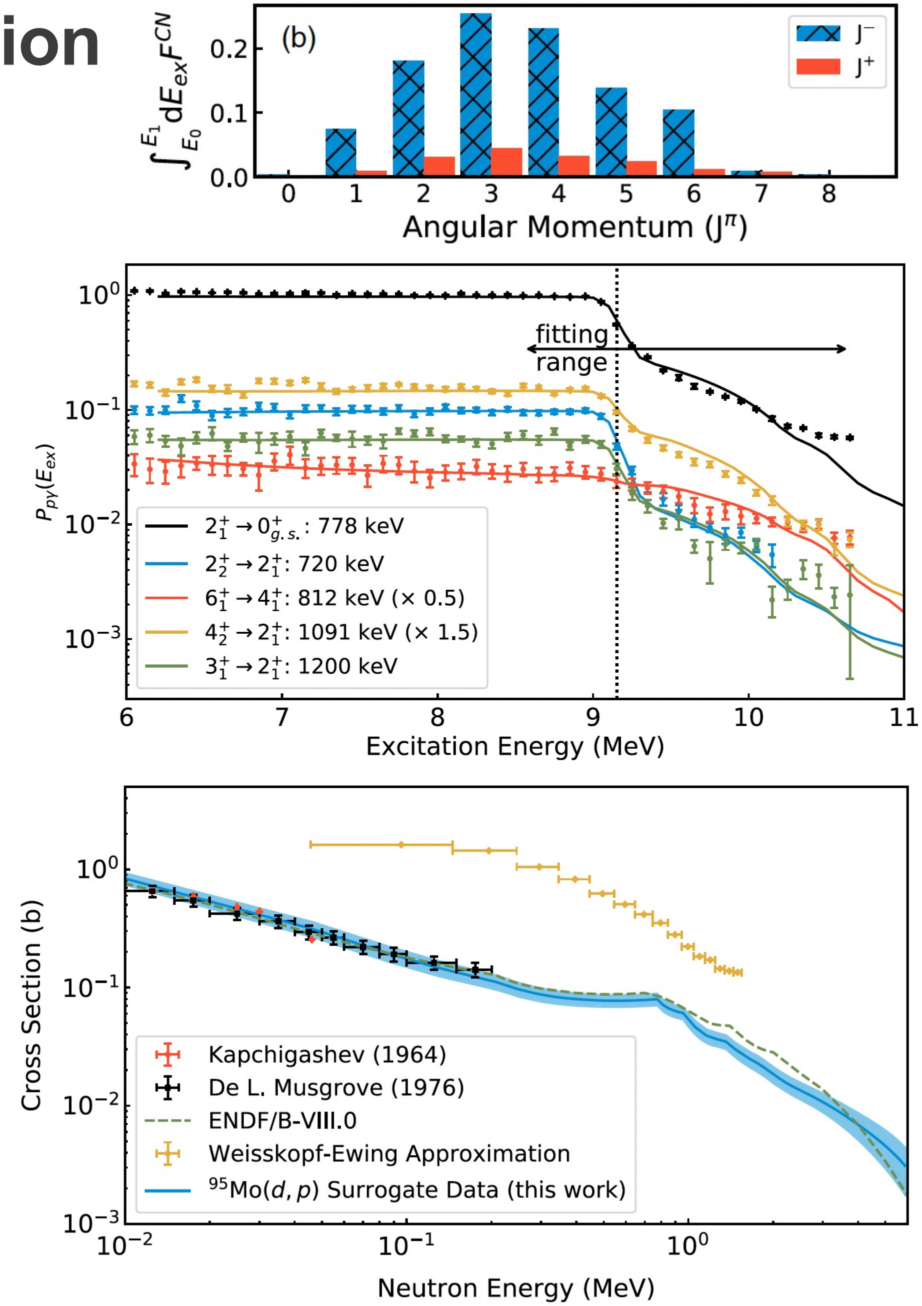
Cascade sent through GEANT simulation to create “experimental” spectrum



Once correct input parameters are know, cross section predictions improve in accuracy

Major progress has been made in understanding partial reaction measurements

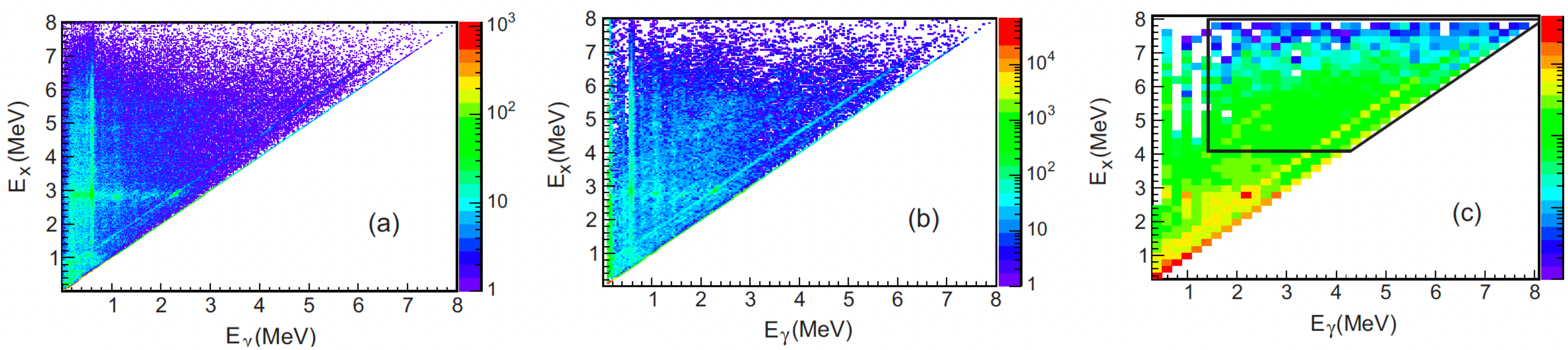
- Major theoretical and experimental work has gone into improving understanding *components* of the reaction
- This opens a wider range of measurements, particularly on short-lived species
- Yet it requires a certain caution in interpretation and archiving
  - Application wants a cross section
  - What is measured is typically a de-excitation property



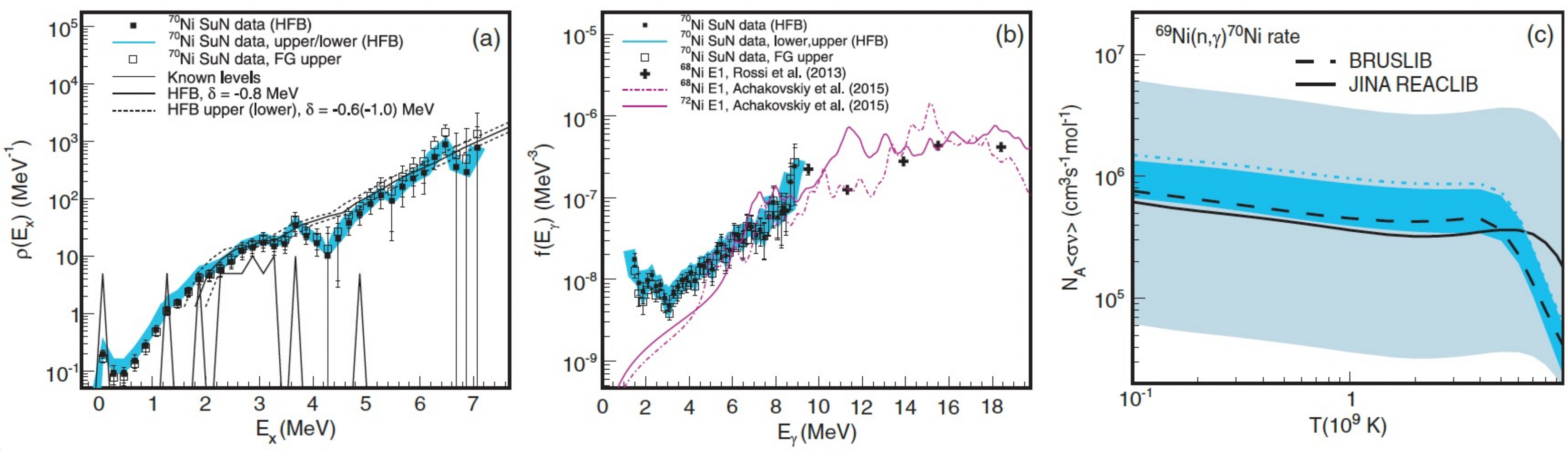
Ratkiewicz et al. PRL 2022

β-Oslo Determination of (n,γ) rates

- Extends the Oslo Technique for extraction of first-generation gamma rays to β-decay studies
  - Simplifies use of Total Absorption Spectroscopy
  - With β-decay, can use far less intense (but more neutron rich) beams



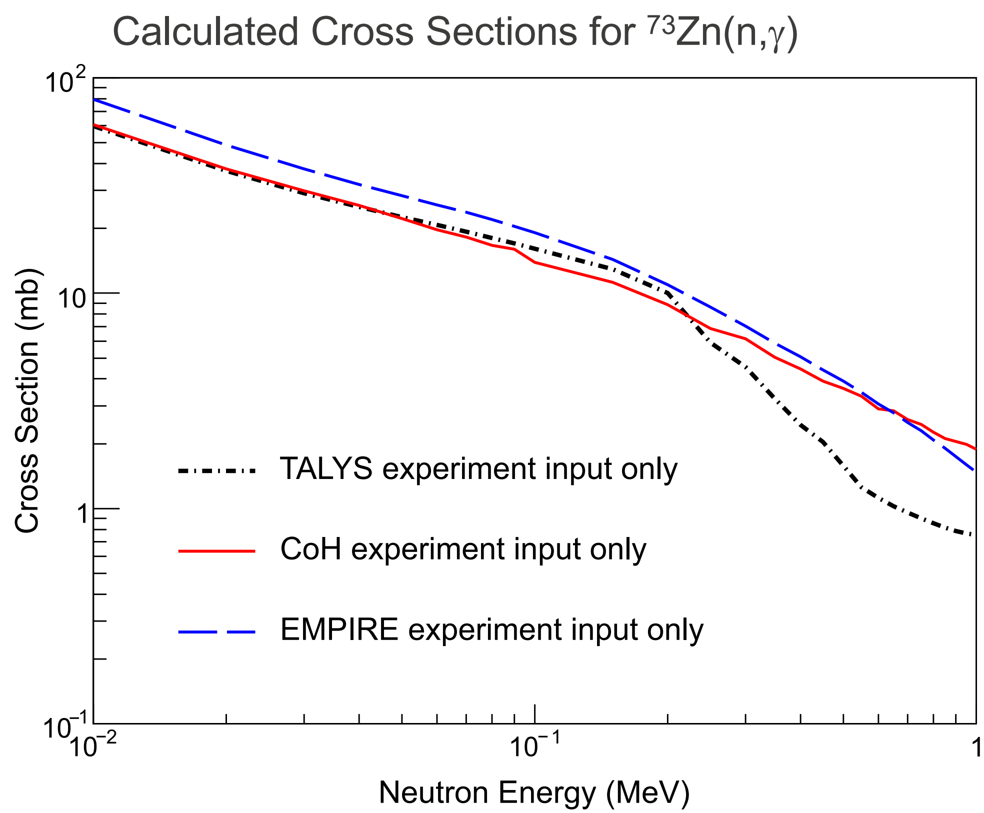
Lewis et al. PRC 2019



Liddick et al. PRL 2016

Structure (and Models) still affect Reactions

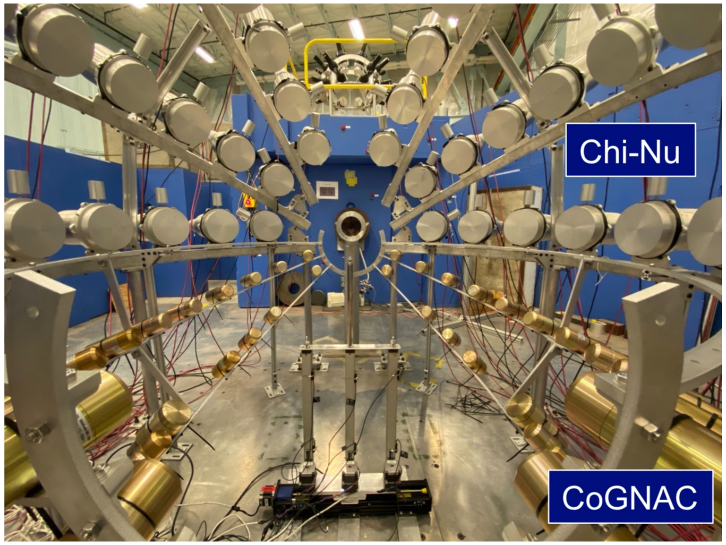
- Determining input components significantly improves reliability of HF calculations
- Other nuclear properties (like resolved structure) that may be poorly known off stability still impact calculations
- From a Nuclear Data perspective, it is important to
  - Take advantage of the improved inputs
  - Use and archive the data as what was measured, *not the derived cross section*
  - Neither EXFOR nor XUNDL is ready to accept PSF data
- This remains Structure Informed Reaction Modeling

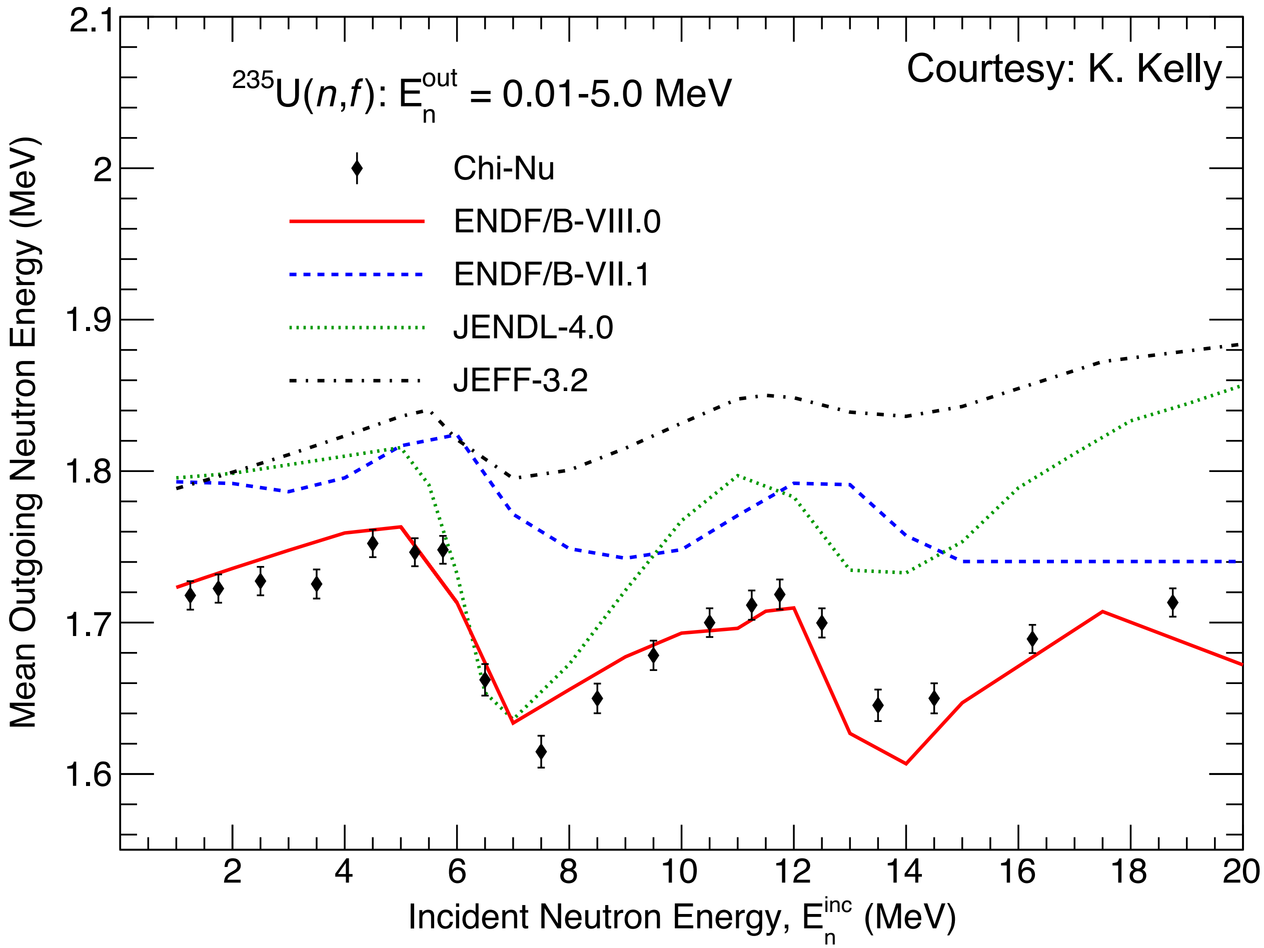


Opportunities: Coupling Measurement to Evaluation

Measurements of the Fission Neutrons Spectrum

- Past measurements inadequately accounted for neutron scattering
- Chi-Nu provided new data *and* drove a reinterpretation of past measurements
- **Direct engagement of evaluation at all stages of the measurement**



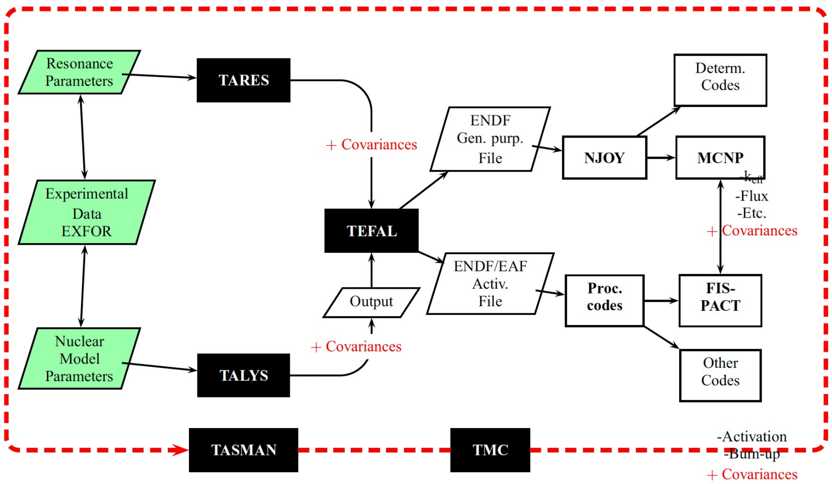


ENDF/B-VIII: D. A. Brown *et al. NDS* **148** (2018) 1.
CIELO Collab.: M. B. Chadwick *et al. NDS* **148** (2018) 189.
Uncertainties: D. Neudecker *et al. NDS* **148** (2018) 293.
^{235}U PFNS: M. Devlin *et al. NDS* **148** (2018) 322.

Opportunities: The Uncertainty Frontier

- Many applications are looking for uncertainty estimates
- Sensitivity studies have tended to approach this by independently sampling the uncertainty phase space
  - It is fast
  - We can do it today
  - It's probable not right
- For Light Ion Reactions, Longland *et al.* provided PDFs which could be sampled
  - These were generally resonance-dominated charged particle reactions
- Large libraries are often a combination of theory and measurement—Can a consistent set of reaction samples be generated for use?

"Total" Monte Carlo, a la TENDL



Monte Carlo: 1000 runs of all codes

Koning and Rochman, NDS, 2012

Opportunity: Complete Libraries

- One of the strengths of ENDF is its experimentally-driven
- *But* many applications require cross sections where no measurements exist
  - This leads to a large-scale adoption of other models/approaches

- JEFF has historically provided an “activation file” that is not a complete transport library, but does provide a much broader set of cross sections. Is this worth considering?

Conclusions and Future

- Both application needs and reaction measurements have advanced rapidly in the past decade
- Recent advances in techniques, *particularly those providing statistical data that sits at the boundary of structure and reactions*, challenge the current Nuclear Data Tools for evaluation, reporting, and archiving
- This offers an opportunity to expand the range of measurement-driven reaction data as part of the nuclear data effort\

- Why Nuclear Reactions Matter
- Where new reaction measurements have a home in Nuclear Data
- Homeless Nuclear Reaction Measurements
- Opportunities in the Next Decades