Scoping Study for Reactions on Unstable Fission Products

Exit briefing to WANDA 2025

LLNL-PRES-860672

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The Office of Defense Nuclear Nonproliferation Research and Development (DNN R&D) seeks applications for projects led by the DOE/NNSA National Laboratories to understand and address the following gaps in nuclear data relevant to nonproliferation missions:

1) (α, n) reaction data relevant to safeguards and arms control verification
2) Fission data for safeguards and forensics applications
3) Cross sections for reactions involving short-lived fission products.

Regarding item (3): Isotopes far from stability can play an important role in a variety of nonproliferation applications, including modeling and understanding post-detonation nuclear forensics scenarios. Recent advancements in experimental facilities and techniques (e.g., radioactive beams and inverse kinematics) and improved nuclear reaction models can help quantify formerly inaccessible cross-section data for these short-lived isotopes. Applications are sought to complete a scoping study to determine how to leverage new capabilities to measure and model cross sections for reactions involving isotopes far from stability that are relevant to nonproliferation.

Scoping study on measuring and modeling cross sections on radioactive fission products

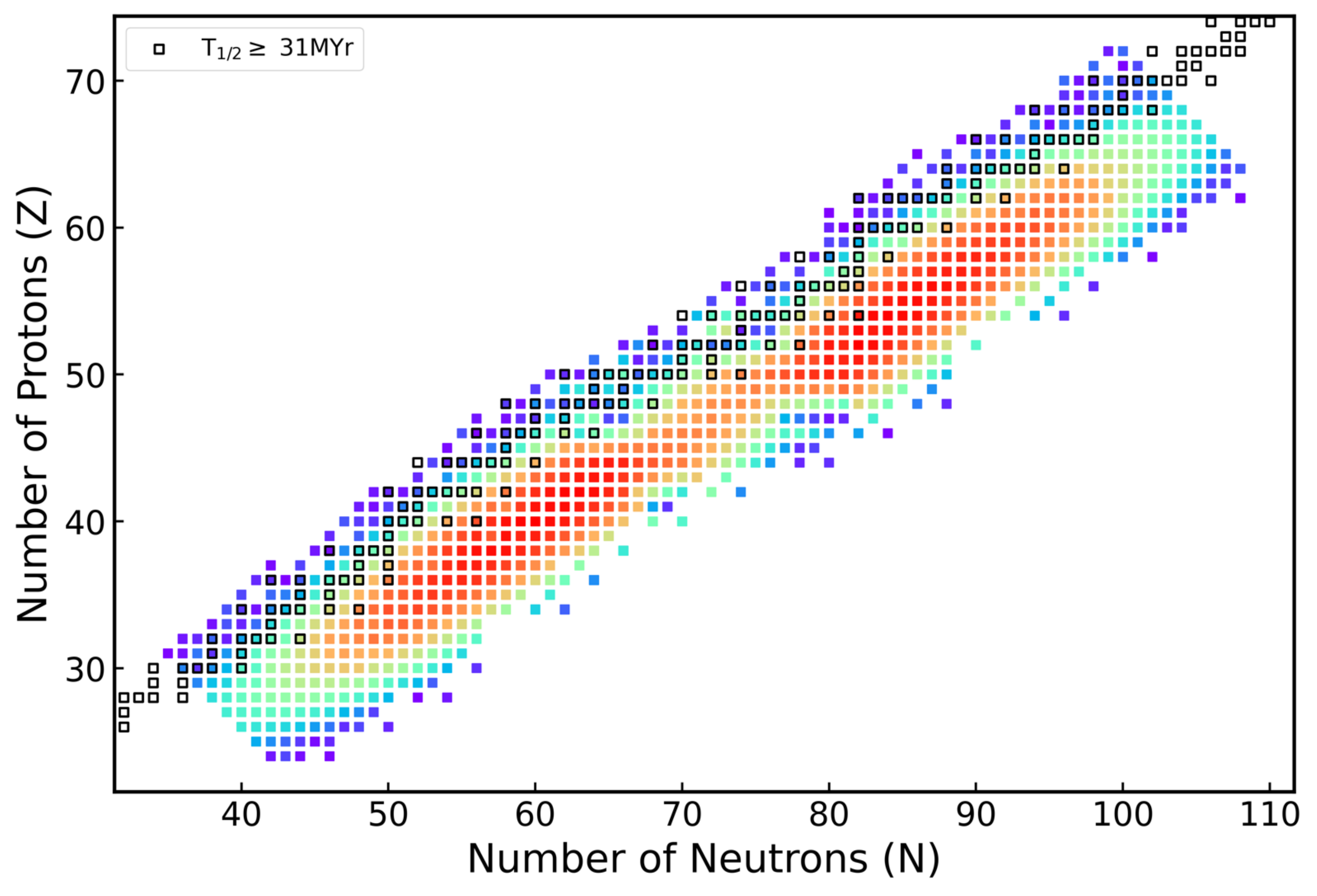
- We will identify:
  - Data needs for non-proliferation applications.
  - Current approaches for measuring and modeling cross sections on these exotic nuclei.
    - We will explore the relative strengths and weaknesses of the available approaches.
    - We will identify opportunities for investments in the development of techniques or equipment.
  - Opportunities offered by accelerator facilities in the United States
    - FRIB, nuCARIBU will create many beams of interest.
    - Powerful new detector systems.
    - We will identify key detection system capabilities required for these measurements, and the facility investments required to realize them.
  - The state of the art in the theory of nuclear reactions on exotic systems.
    - Nuclear structure of exotic systems is important, but challenge standard descriptions developed near stability.
    - We will discuss current approaches and the limits of their applicability.
    - We will identify areas where investments will enable the challenges posed by exotic nuclei to be met.

Summary

- **Predictive theories for a variety of conditions are required.**
  - Exhaustive measurement campaigns are not feasible. Instead, measurements should be designed to constrain theory.
  - Theories should make testable predictions, and experiments should be fielded to test them.
- Phenomenological models constrained near stability are likely to fail away from it.
  - Phenomenological models are still valuable.
  - We should work towards building microscopic theories that are predictive because we understand the physics at play.
- Direct measurements of neutron-induced reaction cross sections will not be possible in the near term. Indirect constraints are required.
  - A variety of techniques exist. They should be benchmarked against each other and against data.
- Understanding the physics at play requires **sustained cooperation** between theory and experiment, and **sustained support** from sponsors and a range of facilities.

Fission Landscape

- Fission produces a wide variety of nuclei. Roughly:
  - 10% are stable, or have half-lives > 1 year. *These cross sections can be measured directly.*
  - 1% have half-lives between 1 year and 100 days. *These can often be measured directly, but at cost.*
  - 2% have half-lives between 100 days and 2 weeks. *These can sometimes be measured directly, but at great cost.*
  - The remaining 87% have half-lives too short for direct measurements.

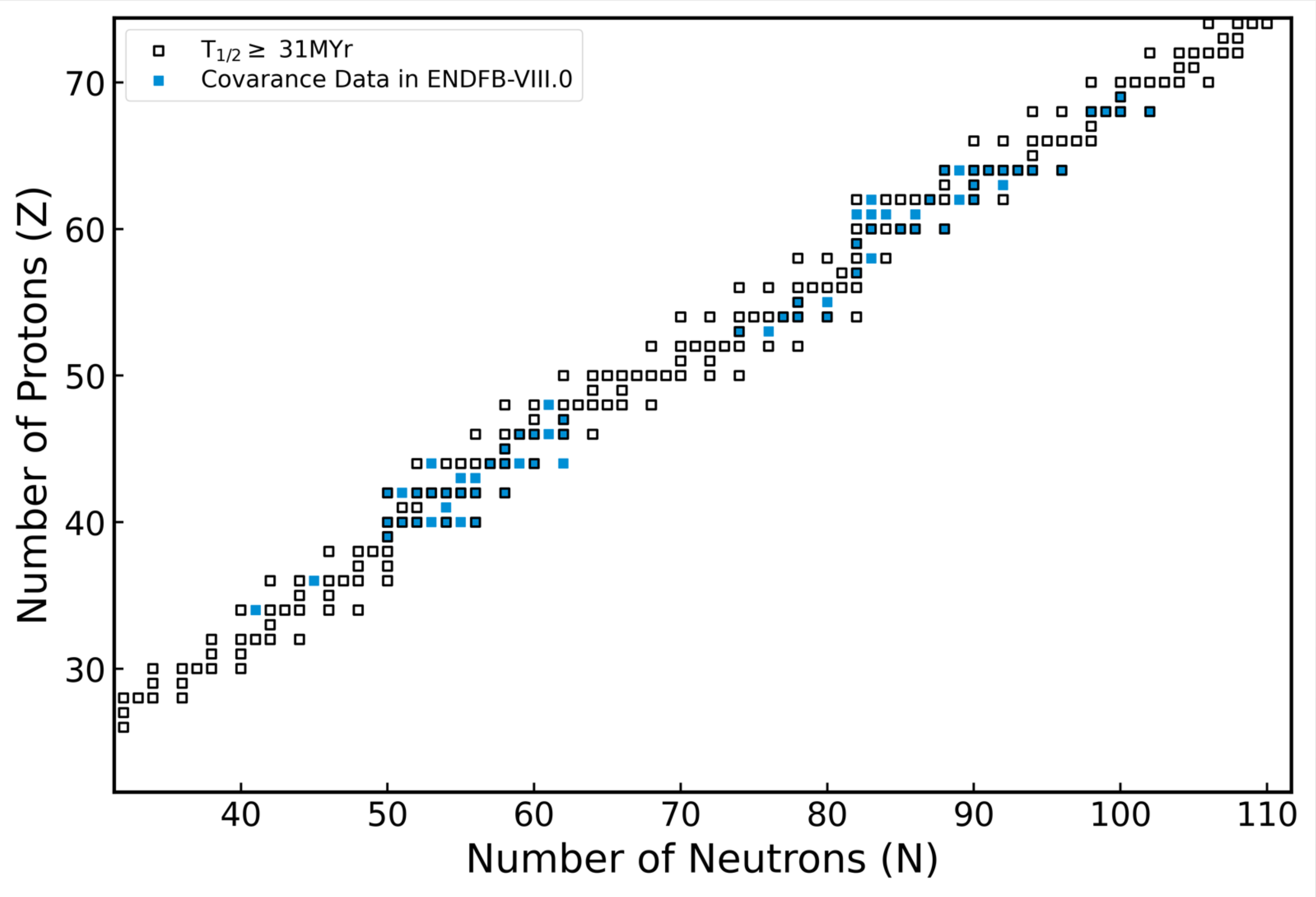


Independent Fission Product Yields for 30 fission parents (U, Pu, Th, Np, Cm, Pa, Es) from England and Rider, LA-SUB-94-170 (1994)

This affects evaluations relied on by applications

Evaluated Fission Product Data

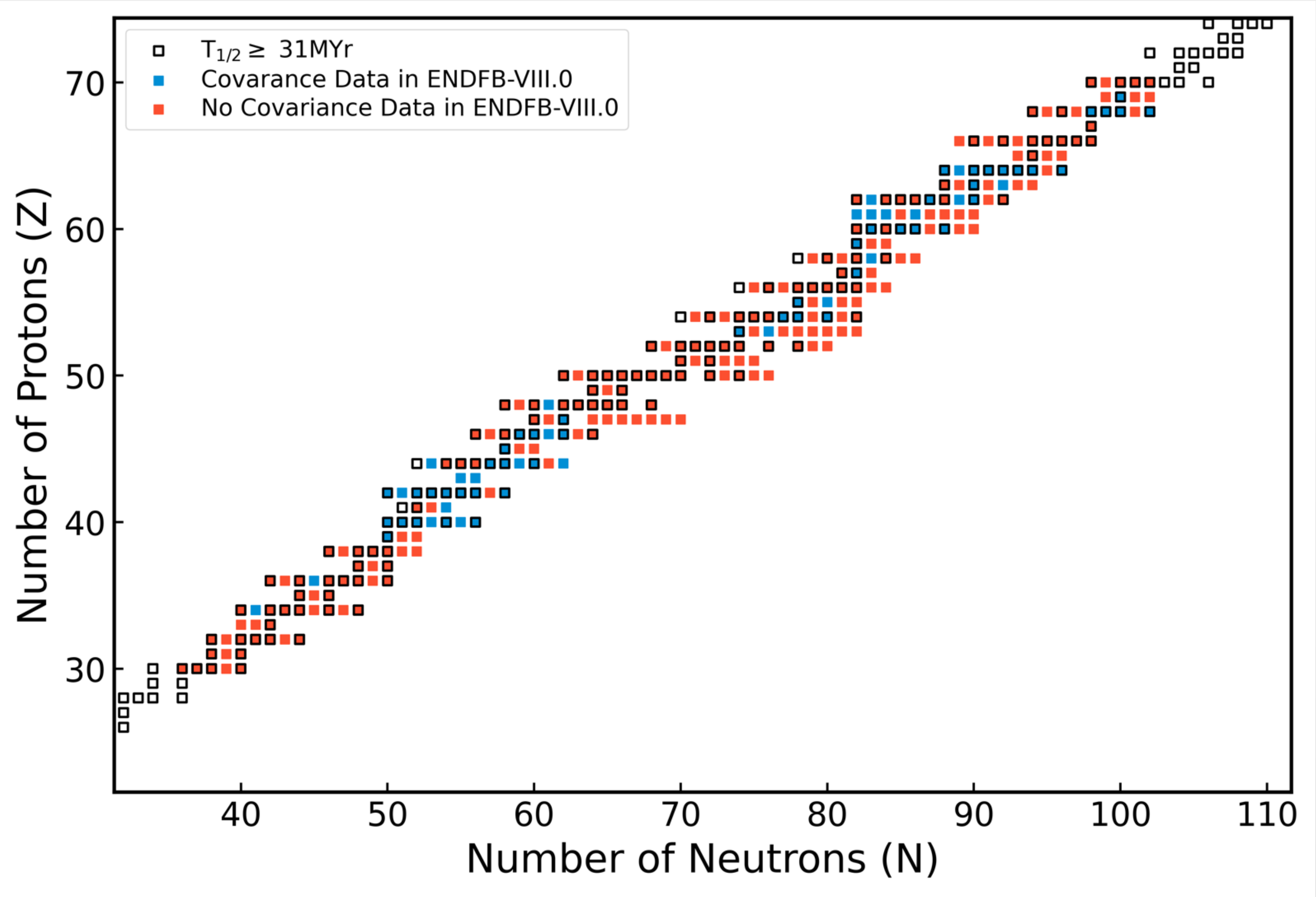
- Covariance data for fission products in ENDFB-VIII.0 is limited to those near stability. Only ~7% of fission products have any covariance data available.



Overlap between fission products and data in the ENDFB-VIII.0 evaluation

Evaluated Fission Product Data

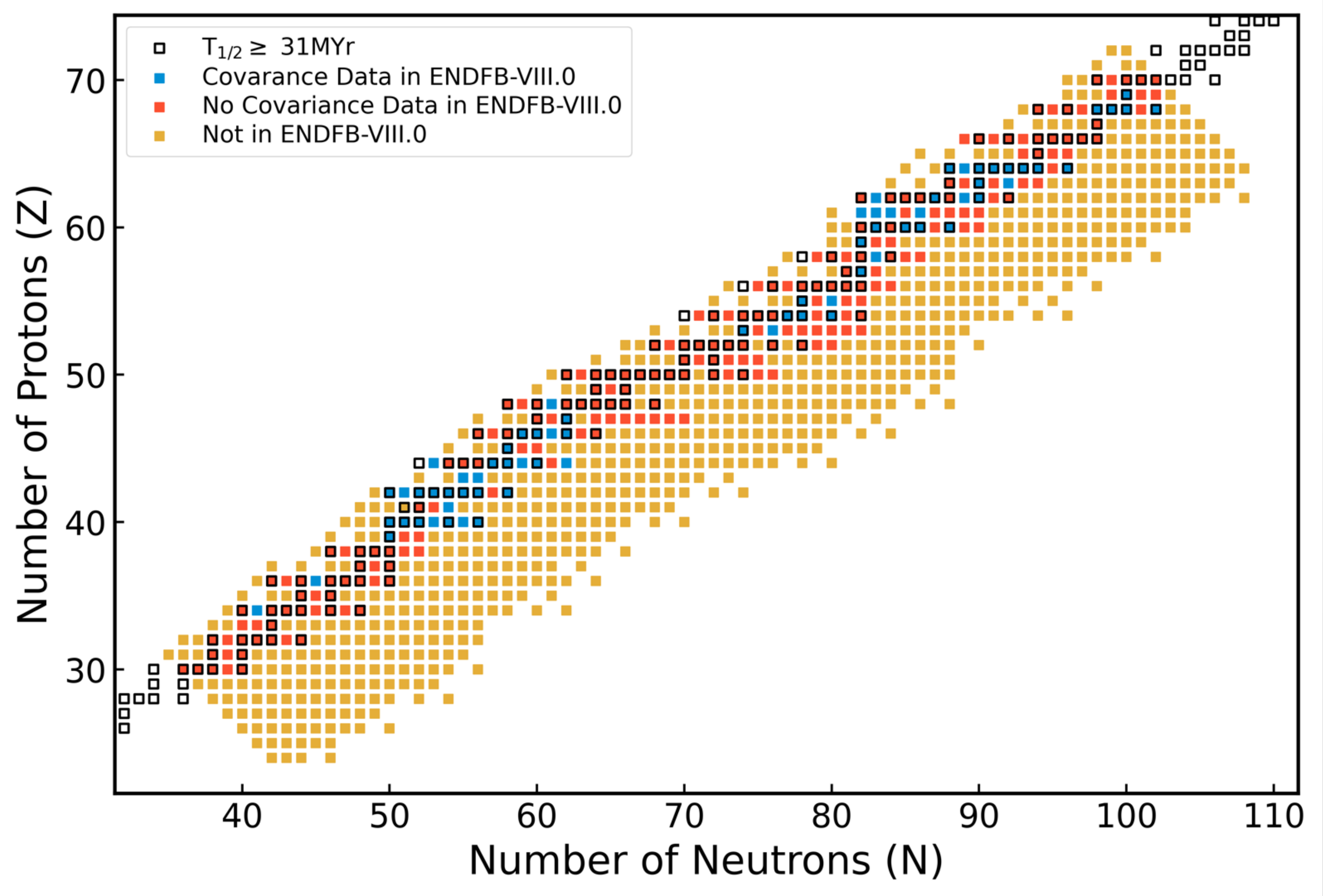
- Covariance data for fission products in ENDFB-VIII.0 is limited to those near stability. Only ~7% of fission products have any covariance data available.
- Another ~22% have some cross section data, but no covariance data.



Overlap between fission products and data in the ENDFB-VIII.0 evaluation

Evaluated Fission Product Data

- Covariance data for fission products in ENDFB-VIII.0 is limited to those near stability. Only ~7% of fission products have any covariance data available.
- Another ~22% have some cross section data, but no covariance data.
- No evaluated data for the remaining 71% of fission products are available in ENDFB-VIII.0.



Overlap between fission products and data in the ENDFB-VIII.0 evaluation

Addressing this gap will require changing how we think about nuclear data evaluations.

Nuclear Data Evaluations are based on data taken near stability.

- Evaluations are currently built by considering:
  - Nuclear data, **derived** from experiment.
  - Theory, which is often **most constrained by systematic experiments near stability**.
  - Interpolation between **experimental** data points and **theoretical** calculations.
- We will never develop the wealth of experimental data away from stability we have near it, so we need other ways to produce evaluation-quality nuclear data.
- ***Specifically,* we need to develop a predictive theory that integrates nuclear structure and nuclear reactions away from stability to produce evaluation-quality nuclear data.**

Building evaluation-quality theory requires a robust understanding of the underlying physics

Recommendations for Developing a More Predictive Theory

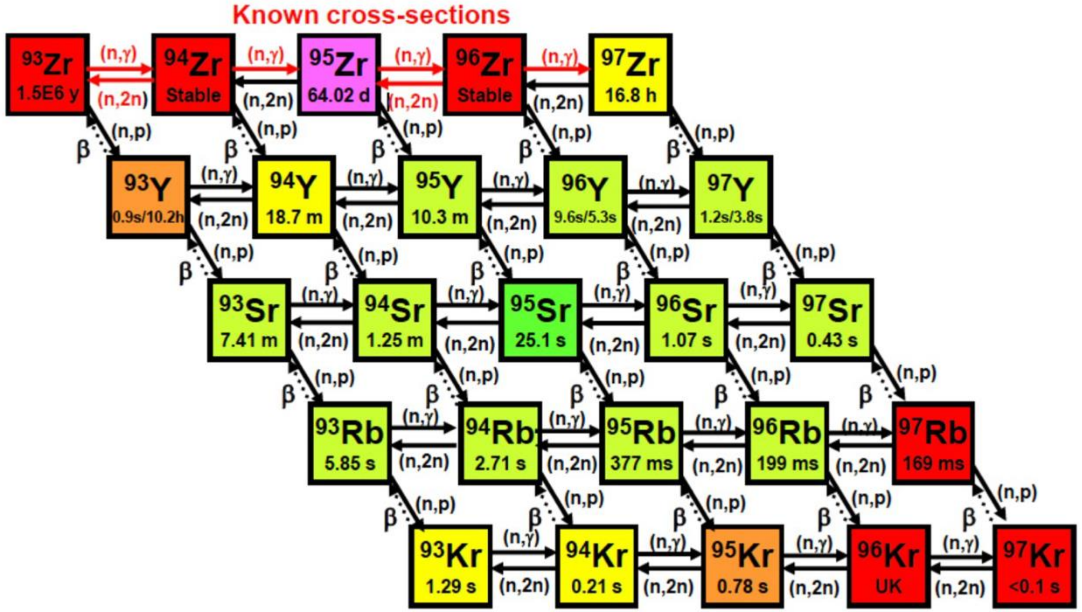
1. **Self-consistent *microscopic models*** of nuclear reactions on deformed and spherical radioactive fission products that are predictive because they describe the underlying physics should be developed. These models should include an assessment of the uncertainty in their predictions.

2. **Targeted experiments** should be performed on deformed and spherical fission products on, near, and away from stability to test the predictions of these models. These experiments should include an assessment of the associated uncertainties.

3. **Theoretical and targeted experimental studies** should be performed to determine when statistical assumptions are no longer valid.

Large-scale multi-physics codes are used for a variety of applications.

- Some application models use networks of nuclear reactions.
  - **A multi-dimensional problem.**
  - **Reactions on excited states** will play a role. However, measurements are typically made on the ground state (only 12 excited state cross sections have been measured for fission products). This lack of data adds to the model uncertainty.



- Well-constrained cross sections, **especially for (n,γ), (n,n`), and (n,2n) reactions**, with well-defined, well-understood uncertainties allow the propagation of uncertainties through applications models.

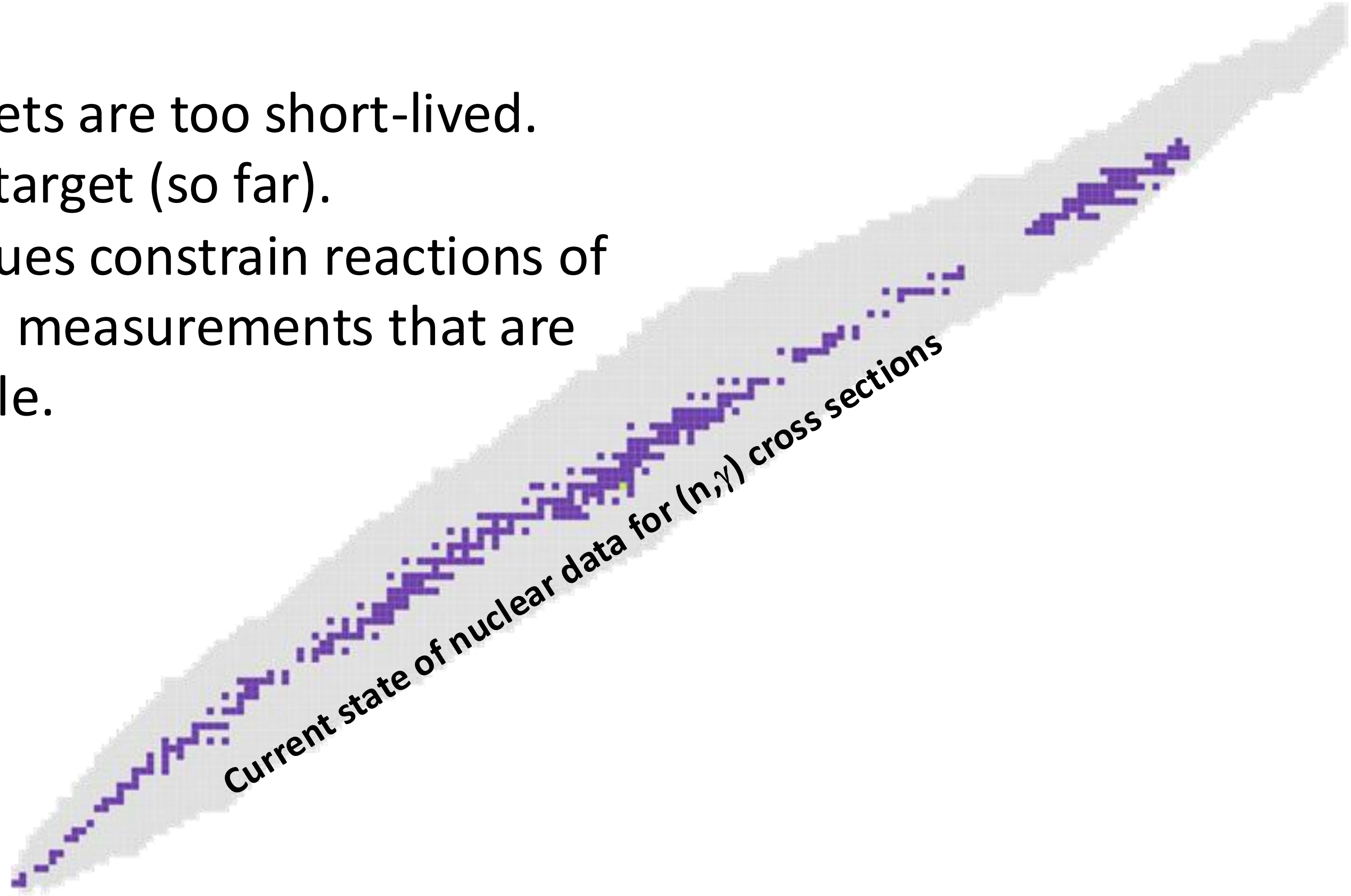
- **Sensitivity Studies** will help identify the components of the problem/model/application that are most constraining to investigate.

Recommendations for Large-Scale Multi-Physics Codes:

4. **Perform sensitivity studies** to:
   - explore a broad range of nuclei in the context of Hauser-Feshbach models and nuclear reaction networks; this will uncover where model deficiencies lie and where targeted experimental efforts will be most influential.
   - quantify the impact of reactions on excited states and identify the highest-value targets for experimental studies.
5. **Measure or constrain** differential cross sections on peak-fission-product chains from 10s of eV to ~20 MeV for (n,γ), (n,n`), and (n,2n) reactions.
6. **Measure or constrain** the differential cross section for the ^{146}La(n,γ) reaction from 10s of eV to ~20 MeV.
   - Predictions by the nuclear-reaction-model codes TALYS and STAPRE differ by ~500%.

Indirect techniques are required to constrain neutron-induced reactions on short-lived nuclei

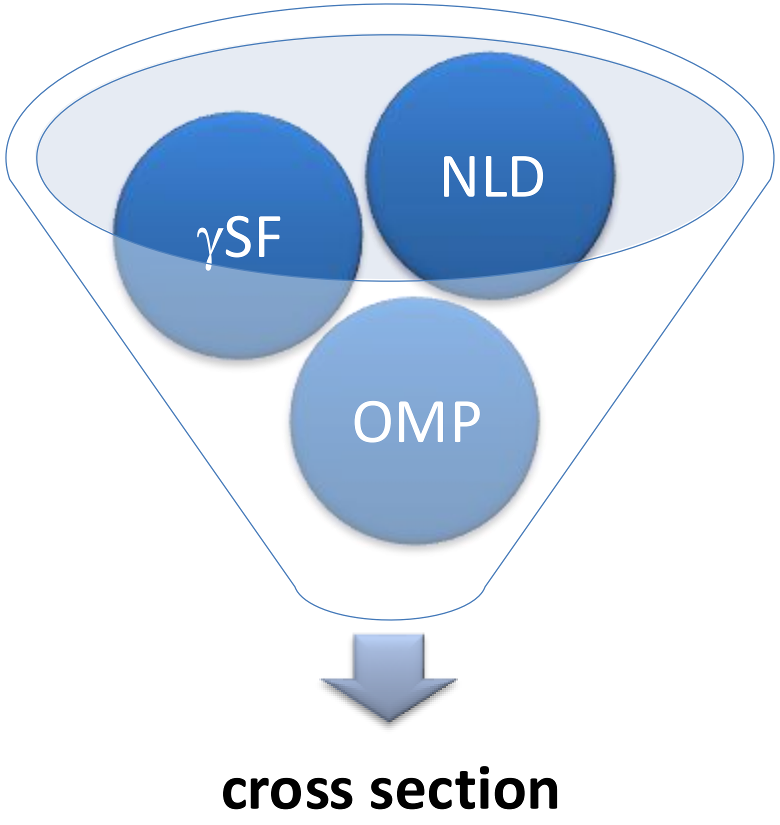
- Direct measurements are not currently possible:
  - Desired targets are too short-lived.
  - No neutron target (so far).
- Indirect techniques constrain reactions of interest through measurements that are currently possible.



Indirect techniques are required to constrain neutron-induced reactions on short-lived nuclei

Variety of techniques available

- Oslo Method(s)
  - Traditional
  - Inverse Kinematics
  - Beta-decay
  - Discussion of external theory and data needed
- The Surrogate Reactions Method:
  - Traditional
  - "No-γ" Surrogate Reactions Method
- Others:
  - *The Shape Method*
  - *Particle Evaporation Method*
  - *Coulomb-Dissociation*
  - *HiγS Measurements*



- These techniques all require constraining parameters used to describe the statistical behavior of nuclei, such as the nuclear level density and the γ-ray strength function.

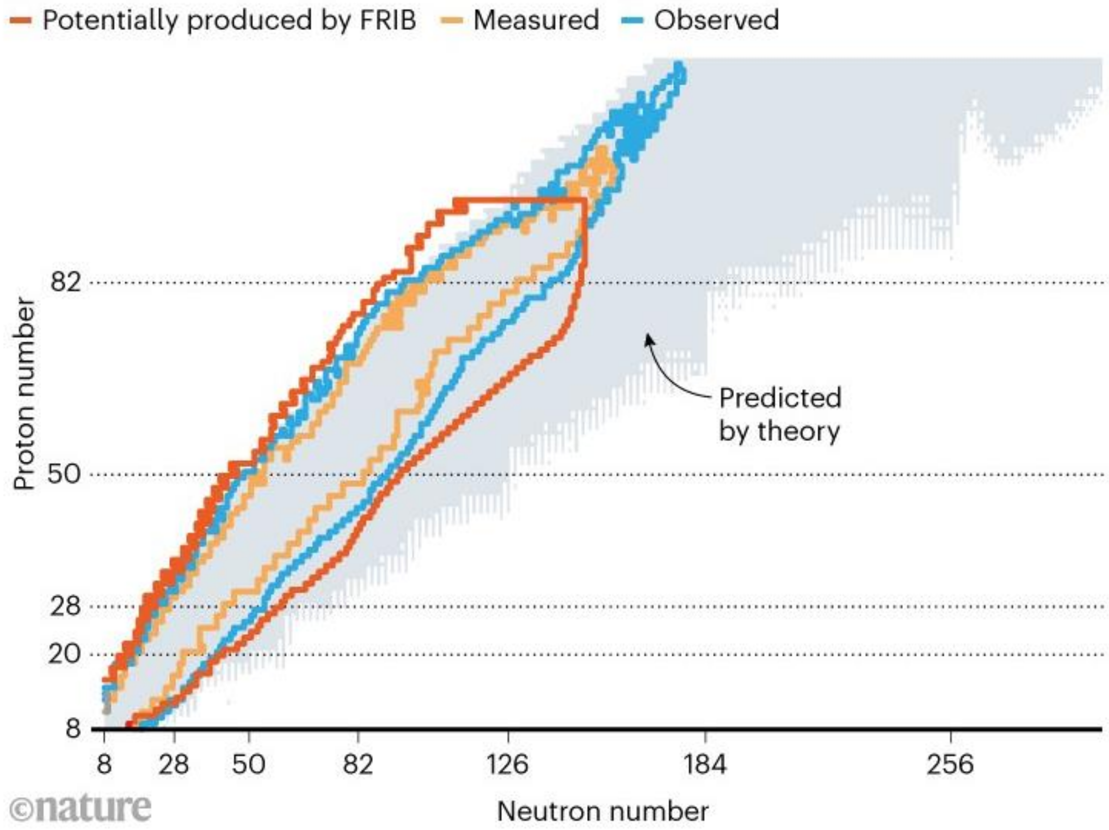
Recommendations for Indirect Methods

To extend theoretical and experimental techniques to probe reactions of interest to various applications:

7. **Perform benchmarking studies** to validate the indirect experimental techniques against each other and, where possible, against direct measurements. Perform benchmarking studies of the theory relied on by indirect techniques, and access the related uncertainties.
8. **Perform systematic studies** of trends in Nuclear Level Densities and γ-ray Strength Functions to inform predictions for neutron-rich fission products.
9. **Develop experimental** capabilities, instrumentation, isomer-resolved beams, and techniques to improve the sensitivity of measurements, for both the Oslo-type and Surrogate approaches.
10. **Develop/extend reaction theory** to describe the surrogate reaction mechanism for both transfers and inelastic scattering involving exotic (very neutron rich) nuclei. Investigate the limitations of the Hauser-Feshbach (statistical) description of weakly-bound nuclei, and as nuclear level density decreases.

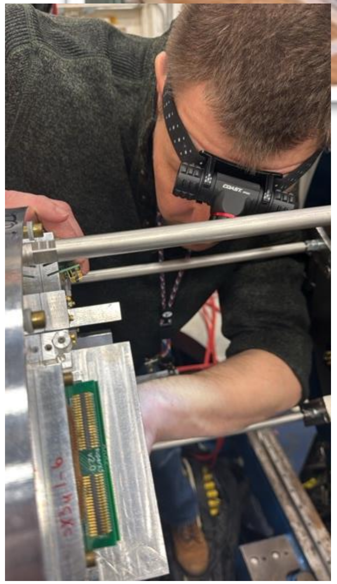
U.S. facilities house cutting-edge capabilities to probe nuclear properties and reactions on short-lived fission products.

Facility for Rare Isotope Beams at Michigan State University



Neufcourt, L. *et al. Phys. Rev. C* **101**, 044307 (2020)

LBNL 88" Cyclotron Laboratory



ANL ATLAS and CARIBU Facilities

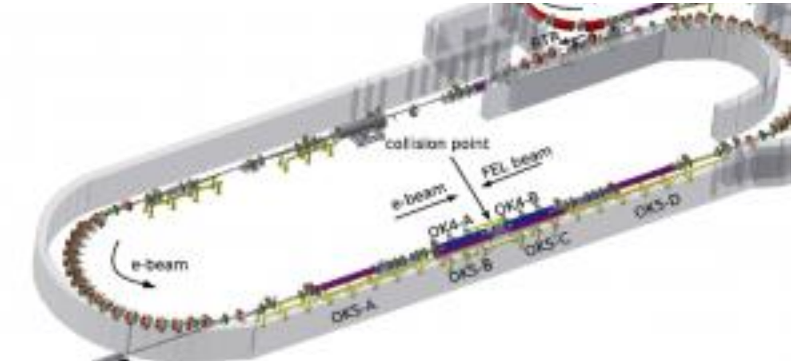
The nuCARIBU and N=126 factory upgrades will provide expanded availability and greater intensities of rare isotopes.

ARUNA laboratories provide essential capabilities for nuclear physics and rare isotope research.

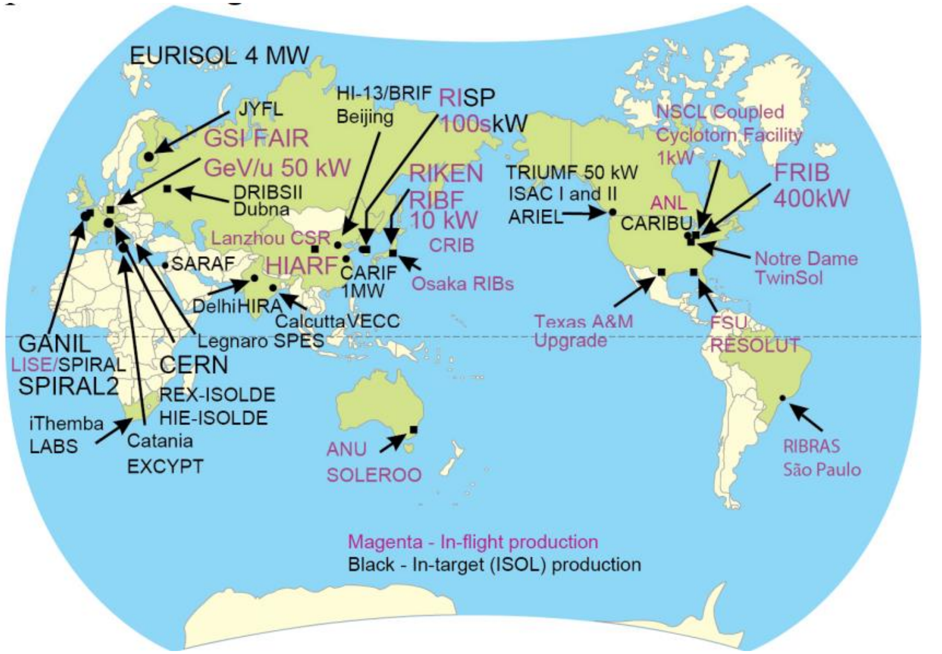
Texas A&M University

TWINSOL @ Notre Dame

HIγS at TUNL



Putting the US capabilities into the global rare isotope facilities landscape.



J. Wei, Conference Proceeding, NAPAC (2019).
doi:10.18429/JACoW-NAPAC2019-FRXBB1

The landscape exists because of generational investments in U.S. nuclear physics.

Opportunities from recent U.S. investments in RIB production

- **Unprecedented access to beams of fission products at DOE User Facilities:**
  - **FRIB:** Operational power ramping up (reached 20 kW/10% operations in 2024).
  - **ATLAS:** First PAC call including nuCARIBU beams of U-fission products (at 10% design intensity) in 2024.

Beam time at User Facilities is highly and increasingly competitive (30% acceptance rates for proposals).

- **University facilities** can be leveraged:
  - Development/benchmarking of techniques/theory/instruments – critical proof-of-principle needed to support proposals at User Facilities.
  - Measure important nuclei near or on stability.
  - Crucial pipeline to engage/train junior scientists.

- **Many promising new experimental techniques/approaches**
  - No-γ experiments use recoiling nucleus, rather than discrete γ rays, for identifying reaction channels.
    - Potential for simpler, higher efficiency experiments.
    - Needs rigorous testing/benchmarking.
  - TAS for reactions
    - Potential order-of-magnitude gains in efficiency (10% → 90%) c.f. discrete spectroscopy.
    - Simpler/robust experimental signature.
  - Advanced targets (cryogenic, active)
    - Factor of ~3+ improved energy resolution:luminosity → tighter constraints on theory.

Suggestion for U.S.-based Fission Product Measurements

Future FOAs could consider modest support for application-specific instrumentation needed to realize these opportunities created by U.S. investment in fission product production.

Opportunities for improvement to the Student Pipeline

Challenges to support / pipeline

- Students can't just be picked from the "second-year grad student tree." Students must be supported during their first years and through to their thesis in 5-6 years.
- Discrepancy between timelines of labs/funding/students

Funding (ex: 3-year LDRD)

Student career from admission through thesis

Postdoc (hire to Y3)

Suggestions for Student Pipeline:

Future FOAs could consider:

- Providing modest support for mentors to mentor, read theses, serve on qualifying committees.
- Entertaining five-year grant requests with variable funding each year—bulk of work delivered in three years with nominal student support level for two years to finish dissertation.

Thanks to workshop participants for their excellent advice and valuable input

Thank you for your attention!

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