Challenges in the Evaluations of Fission Data

Resolving Discrepancies, Using Fundamental & Integral Data

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Overview:

Challenges we face in evaluation

Three examples : FPY, PFNS, fission cross sections

Key Messages

- **Advancing our fission understanding, as embodied in ENDF files, will require integrated efforts in theory, experiment, & simulation**

- **Small scale science & integral measurements both essential**

- **Our progress is slow**
  - Difficult problems take a long time to solve
  - Even when they're ``solved'' we must corroborate our findings

Challenges in Creating Evaluated Data Files, Based on Experiment, Theory, Statistical Analyses & Integral Data

- **We endeavor to represent the reactions in the most accurate way possible – both physical fidelity, and numerical fidelity & completeness**

- **Experiments often discrepant. Evaluations are are best estimates with credible covariances**

- **Often much data already exists**
  - How to best incorporate new information from latest ``best ever” experiments, with supposedly smaller (& different) systematical errors [TPC, Chi-nu experiments]

- **How to incorporate integral information ?**
  - K-eff criticality
  - Semi-integral
    - reaction rates (cross sections in broad sources)
    - transmission data

ENDF files serve many purposes

- **Most accurate understanding of certain reactions, cross sections**
  - Standards (IAEA, NEA, ENDF)
  - Repository for our advancing knowledge – *stewarded by DOE/Science*

- **Usage in nuclear technologies, where predicting certain integral quantities accurately is essential**
  - Transport
  - Criticality
  - Energy deposition
  - Activation
  - …

Significant $ in this ($B) DOE/ NNSA, NE, ….

It is a challenge to satisfy all these goals, given our incomplete knowledge & understanding, & the range of our "customers"

This can lead to religious wars between two factions

- **One extreme: The fundamental-science fundamentalists**
  - Respect only differential measurements
  - Abhor integral data, and usually don't understand the applications
  - Perfectly happy to get the wrong integral answers for the right reasons

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  - Want an answer, don't care where it came from
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ENDF/B-VII strives for good judgment in seeking the middle ground:

- more rigorous and defensible, using many advances in physics, methods
- but judicious (even ad-hoc) "tweaks" made for integral performance
- created trust with our users, cited >4000 times

And By The Way, This Issue is Everywhere

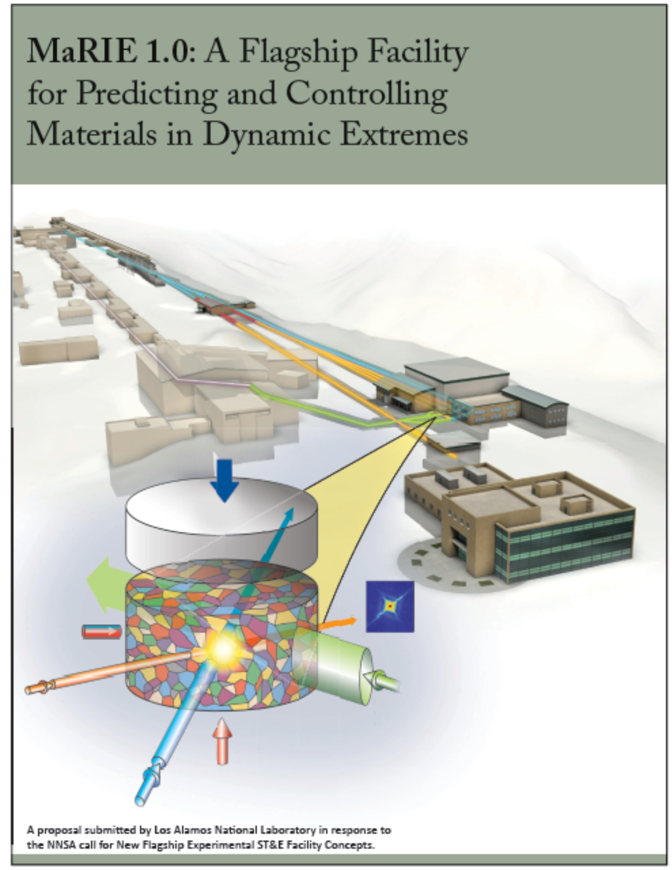
- **Material science**
  - metallurgy "heat and beat"

And By The Way, This Issue is Everywhere

- **Material science**
  - metallurgy “heat and beat”

  - v. fundamental physics “micron gap” MaRIE

– Los Alamos’ vision for a future flagship facility



MaRIE 1.0: A Flagship Facility for Predicting and Controlling Materials in Dynamic Extremes

A proposal submitted by Los Alamos National Laboratory in response to the NNSA call for New Flagship Experimental ST&E Facility Concepts.

Los Alamos’ history is of solving challenging multi-physics problems using both approaches synergistically

Example 1: Fission Product Yield (FPY) Evaluations to Resolve a Longstanding LANL-LLNL Discrepancy

The issue

- **Los Alamos & Livermore were discrepant on their views of the ^{239}Pu ^{147}Nd FPY**
- **Led to an offset in the "fission basis"**

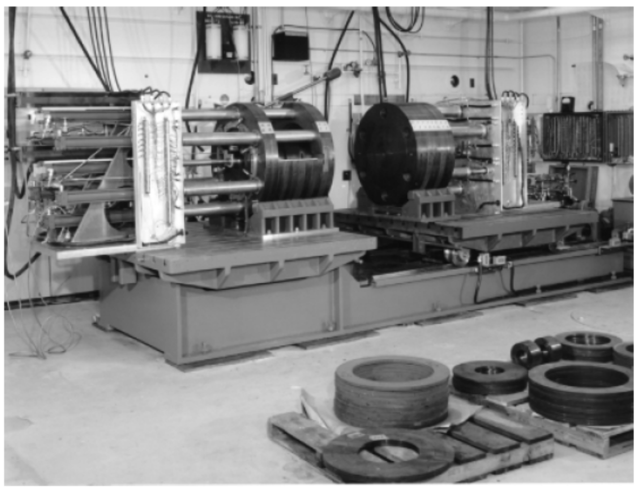
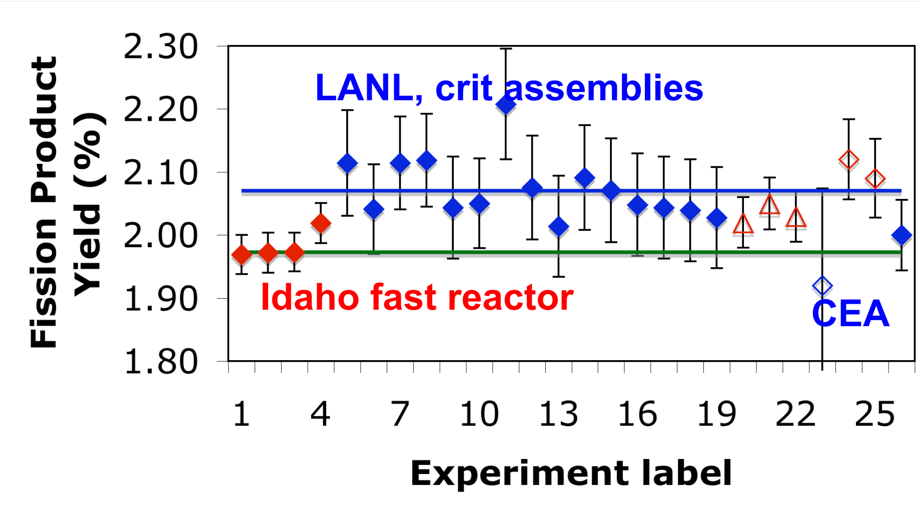


Figure 1. The Big Ten Assembly during Construction (1968).

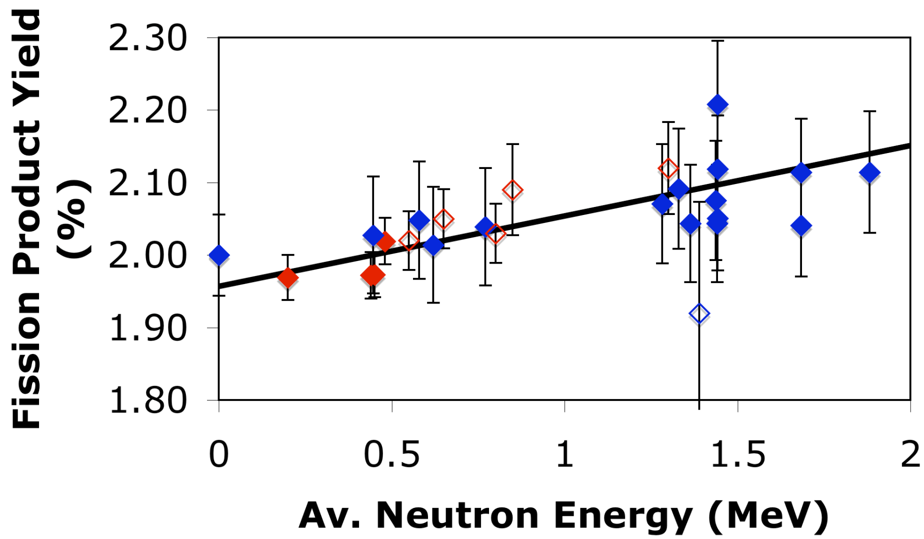
147Nd FPY Data set seemed to exhibit discrepant data (~10% spread):



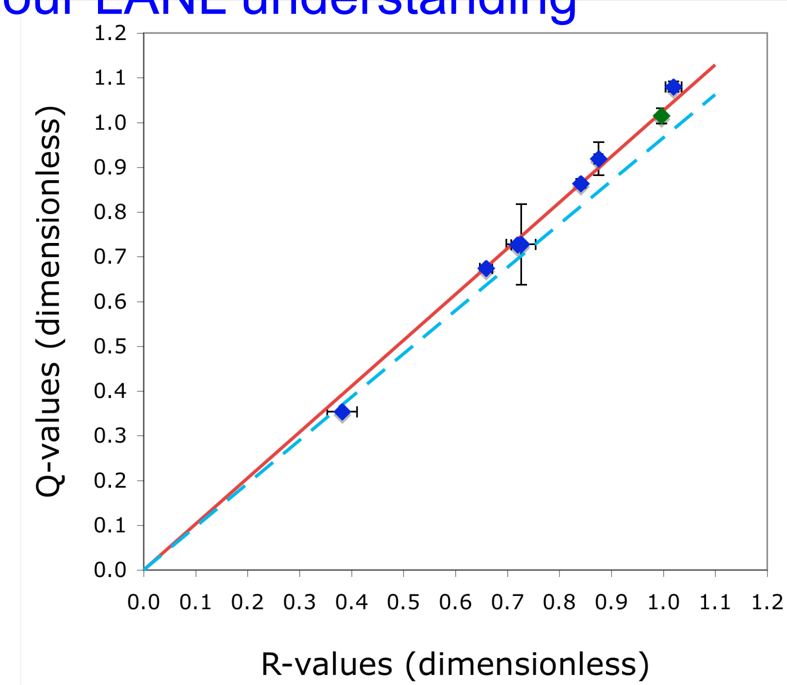
Goal: Resolve discrepancies & seek understanding @ ~ 2% level

Evaluation Work Looks for Patterns..
Allowed us to Determine the 147Nd FPY to ~2% @ 1.5 MeV

Identification of an energy-dependence



A statistical meta-analysis supported our LANL understanding



Next steps: corroborate our understanding with experiments & initiate a theory effort to understand FPY energy dependencies (see talks from Lestone, Sierk, Moller, & Younes work)

Theory progress on broader understanding of trends of FPY energy-dependencies in fast range

Lestone predictions (black points) compared with our ENDF/B-VII.1 trends (color lines)

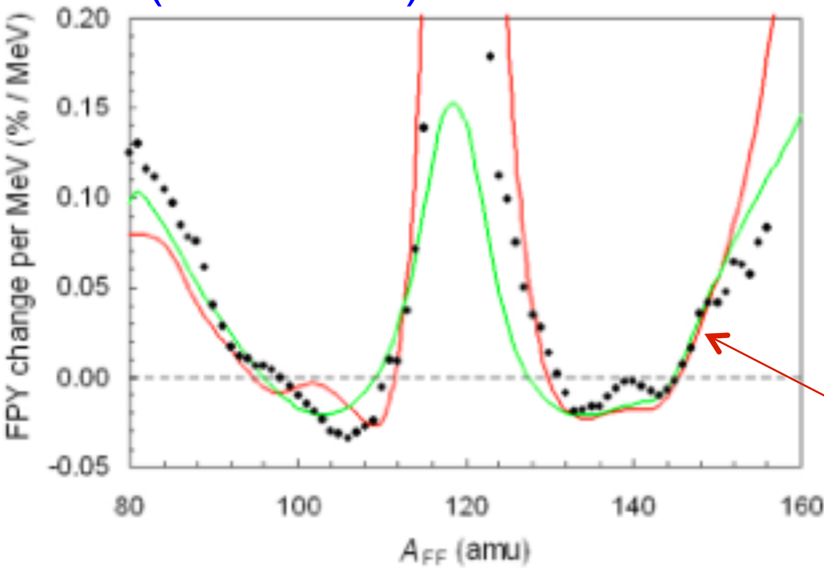
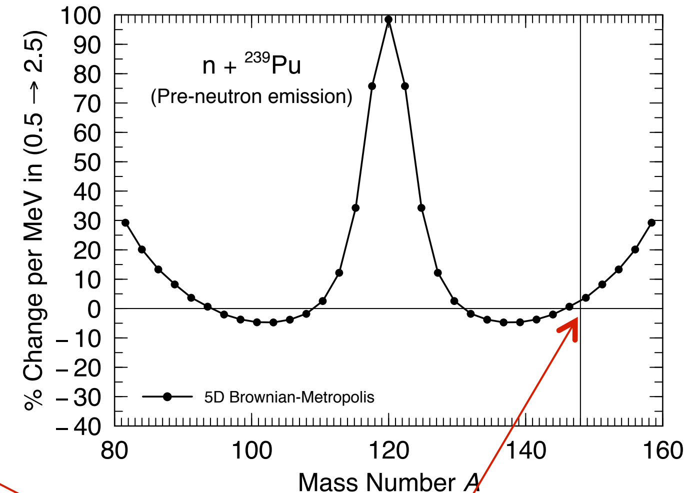


FIG. 29: The relative percentage changes in the n + ^{239}Pu FPY per MeV increase in the energy of the incident neutron versus the fission-fragment mass number. The solid-black circles show our calculated relative yield changes from E_n=0 to 2 MeV. The green curve shows the relative changes between broadened ENDF/B-VII.1 FPY at E_n=0.5 and 2.0 MeV. The red curve shows the relative changes per MeV between the E_n=0 and 2.0 MeV ENDF/B-VII.1 evaluations.

New Moller predictions



147Nd FPY has slightly positive energy trend

Follow- on Experiments from TUNL-LANL-LLNL Team

Progress

- **Probably best-ever activation measurements now made, at various mono-energetic energies (see Gooden, Tonchev talks)**
- **Corroborate our understanding at fission spectrum energies**
- **But raised new questions**
  - But raised more questions, *e.g.* 14 MeV
  - Energy dependencies as a func. of A

New TUNL data support our predictions for 147Nd

(see Gooden, Tonchev, Vieira, Wilhelmy, et a.)

Next steps, to help resolve these questons…

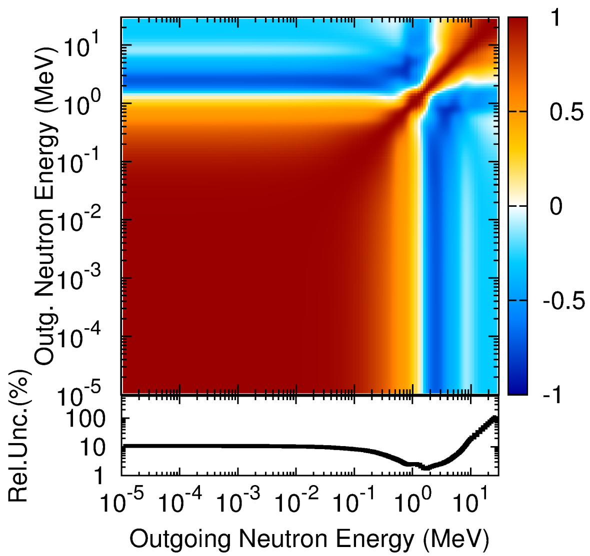
SPIDER detector measurements (Toveson)

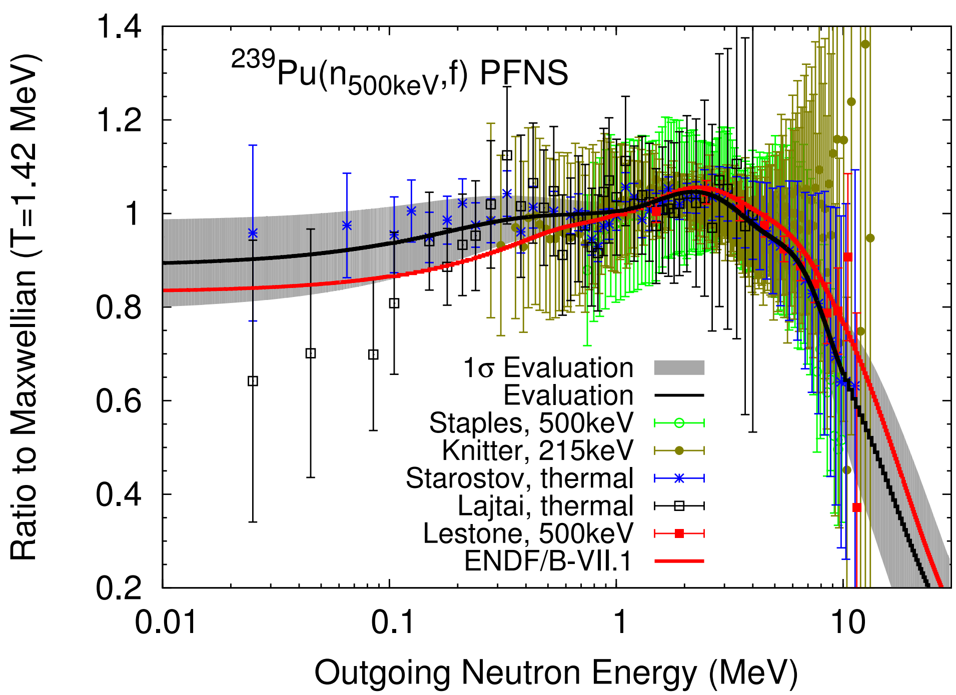
Example 2: Prompt Fission Neutron Spectrum….

- **Theory and experiment are both essential**
- **Both face challenges**
  - Theory predictive power is weak – different assumptions give vastly different predictions
  - Experiments suffer from a wide range of systematic error (data are all over the map)
  -

Prompt Fission Neutron Spectrum n(0.5 MeV)+^{239}Pu - With International Collaboration Via an IAEA CRP

- **Recent evaluations from T-Division based on:**
  - Extended Los Alamos model (anisotropy, different temperatures in light and heavy fragments, etc.)
  - Extensive analysis of past and present experimental data and setups
  - Use of NUEX data
  - Generalized least-square





Extend up to 30 MeV

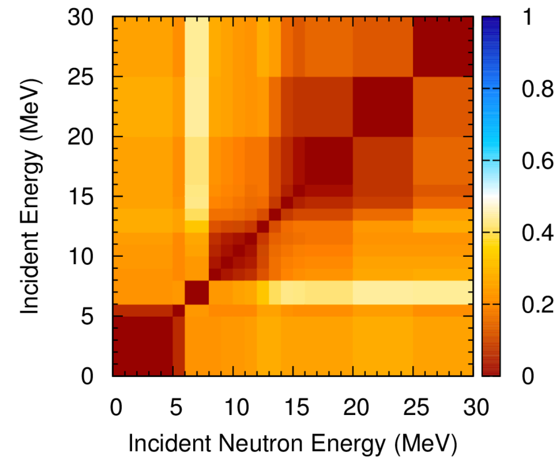
- Study from thermal to 30 MeV E_{inc}
- New data by CEA/LANL - Chatillon et al., BRC, 2014
- Take account of multi-chance fission and pre-equilibrium contributions

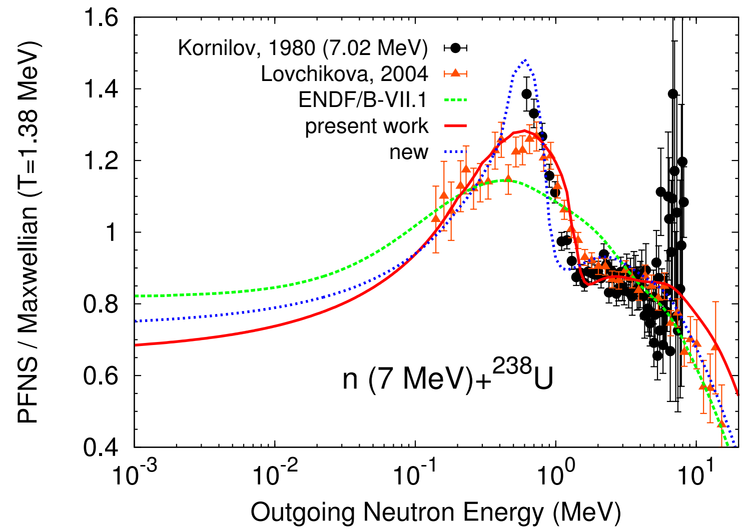
We recognized that a new LANL-LLNL experimental effort would be needed to reduce PFNS uncertainties – Chi-nu

But we are learning the challenges of identifying & reducing syst. errors

- Errors plagued previous experiments
- MCNP simulation is now playing a much larger role in guiding exp design

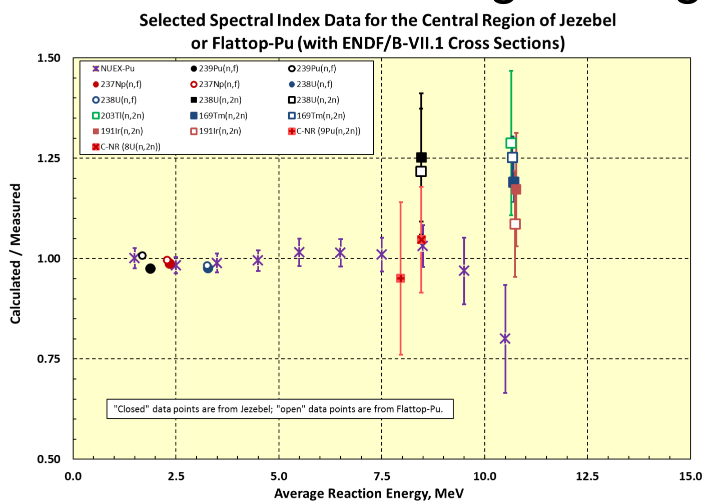
Mean of difference between corrleations of different E_{inc}



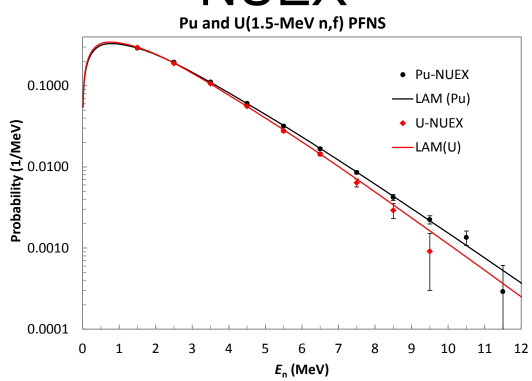


PFNS Solution will depend upon insights from Chi-nu & from various integral experiments

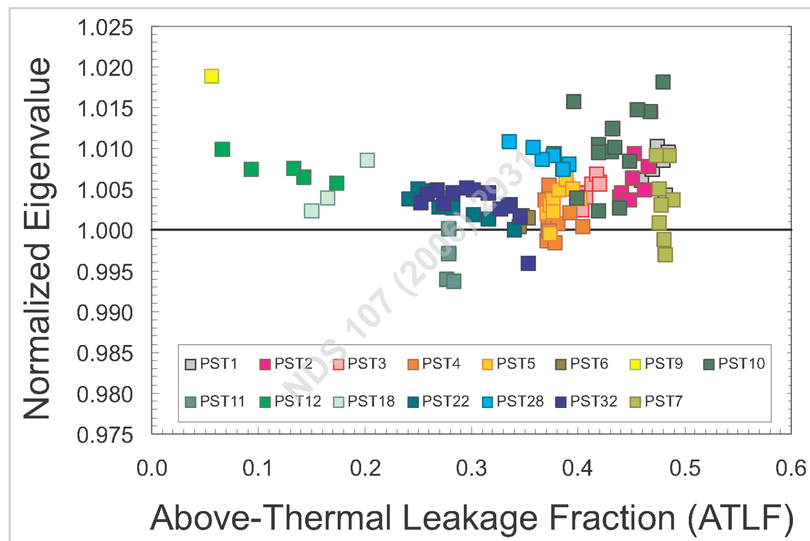
Activation – for the high-energy tail



NUEX



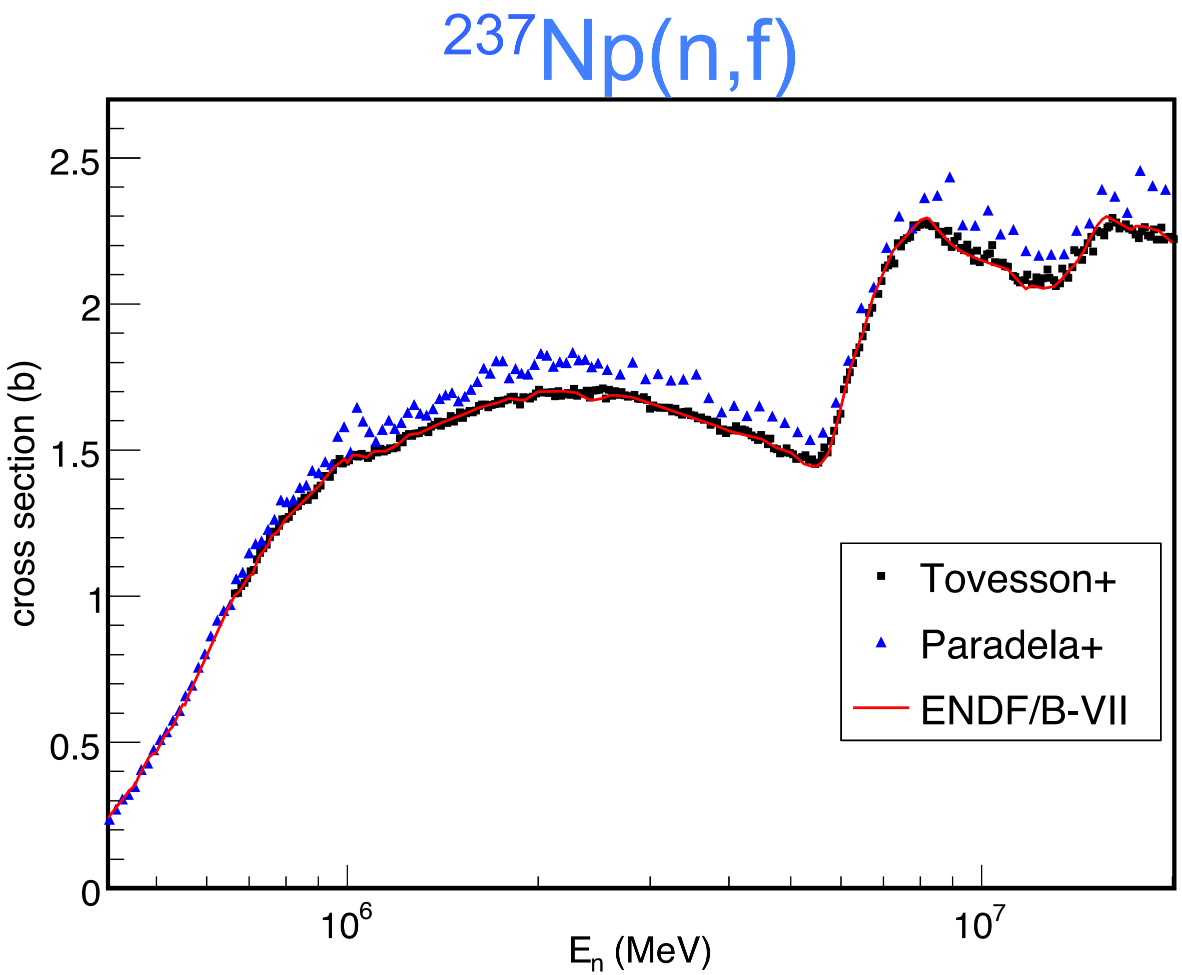
Criticality



At thermal there are fewer channels open.

Increasingly likely that thermal PFNS will be slightly ***harder*** than ENDF/B-VII, which may be inconsistent with modifications at higher incident energies (which ted to be ***softer***)

Example 3: Resolving Fission Cross Section Discrepancies will Require TPC



- LANL notes that semi-integral LANL fission spectral indices in crits support ENDF data
- CERN responds that puzzles regarding the simulation of the LANL-integral crit data for our Np-HEU sphere can be explained by their data

Example 3: Resolving Fission Cross Section Discrepancies will Require TPC

TABLE XXIX: Comparison of calculated spectra indices for ENDF/B-VII.0 with measured values in the center of various Los Alamos critical assemblies. U238f/U235f refers to the ^{238}U fission rate divided by the ^{235}U fission rate, *etc.* Because ^{238}U and ^{237}Np are threshold fissioners, the spectral indices for these isotopes (in ratio to ^{235}U) measure the hardness of the neutron spectrum in the assembly Exp-A refers to experimental data as documented in the CSEWG Fast Reactor Benchmark Compilation, BNL 19302 (June 1973); Exp-B refers to the same measurements, but as reanalyzed by G. Hansen, one of the lead experimentalists, and transmitted to R. MacFarlane in 1984. The C/E ratios are based on the Hansen values where available.

Assembly	Quantity	U238f/U235f	Np237f/U235f	U233f/U235f	Pu239f/U235f
Godiva	Calc	0.15774	0.83002	1.56884	1.38252
(HMF001)	Exp-B	0.1643 ±0.0018	0.8516±0.012		1.4152 ± 0.014
	Exp-A	0.1642 ±0.0018	0.837 ±0.013	1.59±0.03	1.402±0.025
	Calc/Exp	C/E=0.9601	C/E=0.9747	C/E=0.9867	C/E=0.9769
Jezebel	Calc	0.20854	0.97162	1.55632	1.42453
(PMF001)	Exp-B	0.2133 ±0.0023	0.9835 ±0.014		1.4609 ± 0.013
	Exp-A	0.2137 ±0.0023	0.962 ±0.016	1.578 ±0.027	1.448 ±0.029
	Calc/Exp	C/E=0.9777	C/E=0.9879	C/E=0.9863	C/E=0.9751
Jezebel-23	Calc	0.21065	0.98111		
(UMF001)	Exp-B	0.2131 ±0.0026	0.9970 ±0.015		
	Exp-A	0.2131 ±0.0023	0.977 ±0.016		
	Calc/Exp	C/E=0.9885	C/E=0.9841		
Flattop-25	Calc	0.14443	0.77114	1.56725	1.35918
(HMF028)	Exp-B	0.1492 ±0.0016	0.7804 ±0.01	1.608 ±0.003	1.3847 ±0.012
	Exp-A	0.149 ±0.002	0.76 ±0.01	1.60 ±0.003	1.37 ±0.02
	Calc/Exp	C/E=0.9681	C/E=0.9881	C/E=0.9747	C/E=0.9816
Flattop-Pu	Calc	0.17703	0.85254		
(PMF006)	Exp-B	0.1799 ±0.002	0.8561 ±0.012		
	Exp-A	0.180 ±0.003	0.84 ±0.01		
	Calc/Exp	C/E=0.9840	C/E=0.9958		
Flattop-23	Calc	0.18691	0.90801		
(UMF006)	Exp-B	0.1916 ±0.0021	0.9103 ±0.013		
	Exp-A	0.191 ±0.003	0.89 ±0.01		
	Calc/Exp	C/E=0.9755	C/E=0.9975		

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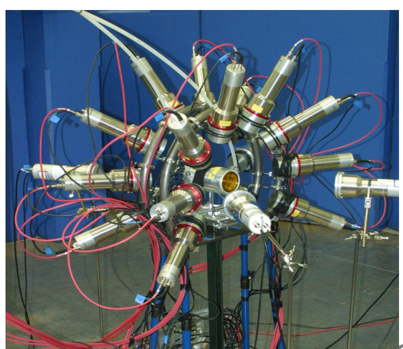
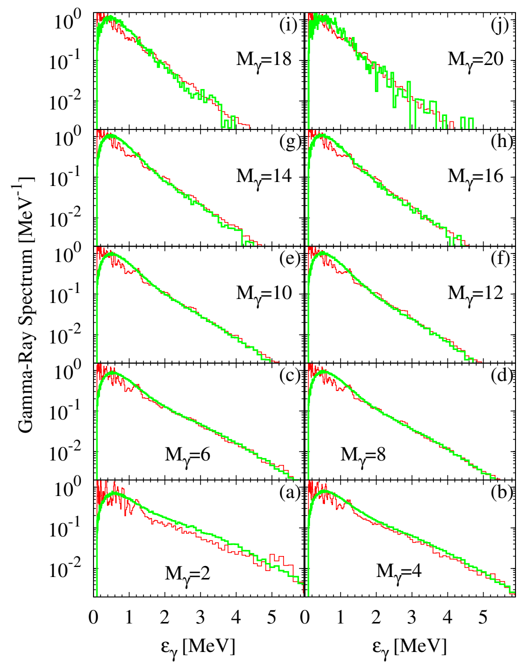
Future: In Addition to Synthesizing Cross Section & Integral Data, Future Evaluations Grounded in Full Correlations of Fission Data & Model Calculations

- **Ongoing NA-22 project: CGMF & FREYA in MCNP6**
  "Developing Accurate Simulations of **Correlated Data in Fission Events**"

- **Advances include:**
  - Predicting correlations and distributions of prompt neutrons and photons on an event-by-event basis (CGMF- Talou, Stetcu, Kawano; FREYA- Vogt, Randrup)
  - New and unique experimental data to benchmark model predictions
    - Univ. Michigan, **S.Pozzi** et al., MCNPX-PoLiMi
    - DANCE, **M.Jandel** et al.
  - Series of validation measurements at NNSS/DAF





UNCLASSIFIED

Backup

Fission Never Ends …

Plus Ultra **: there is more beyond**

(motto of the great scientific pioneers of the 16th & 17th Century)

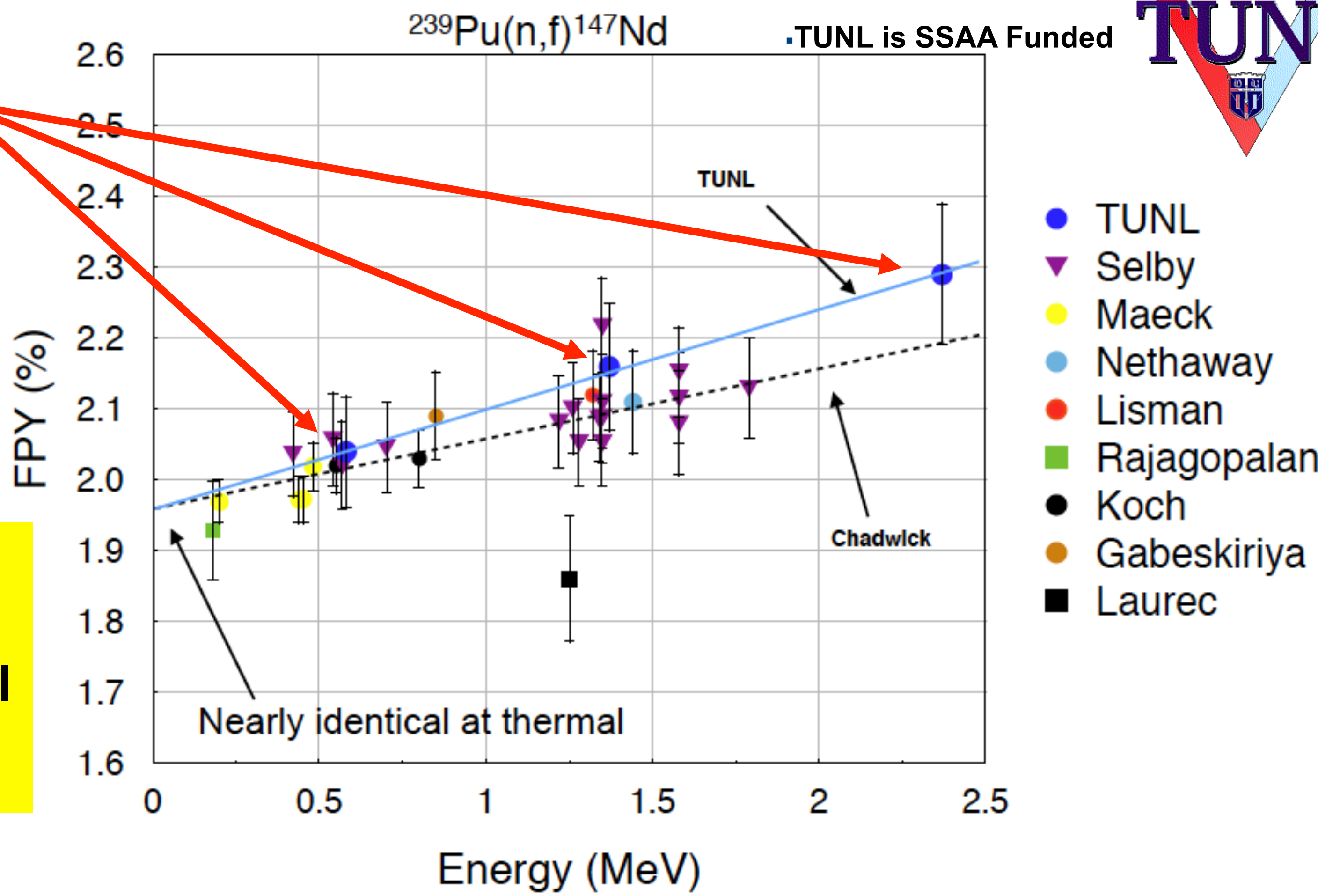
Francis Bacon's *Novum Organum* (1620): Straits of Gibraltar flanked by the colossal pillars of Hercules.

Inscription: Many shall pass too and fro and knowledge shall be increased

Resolution of Fission Yield Basis, for Plutonium. Confirmation of Energy-Dependence in Neodynium-147 Fission Product Yield

- LANL-LLNL-TUNL
- TUNL is SSAA Funded

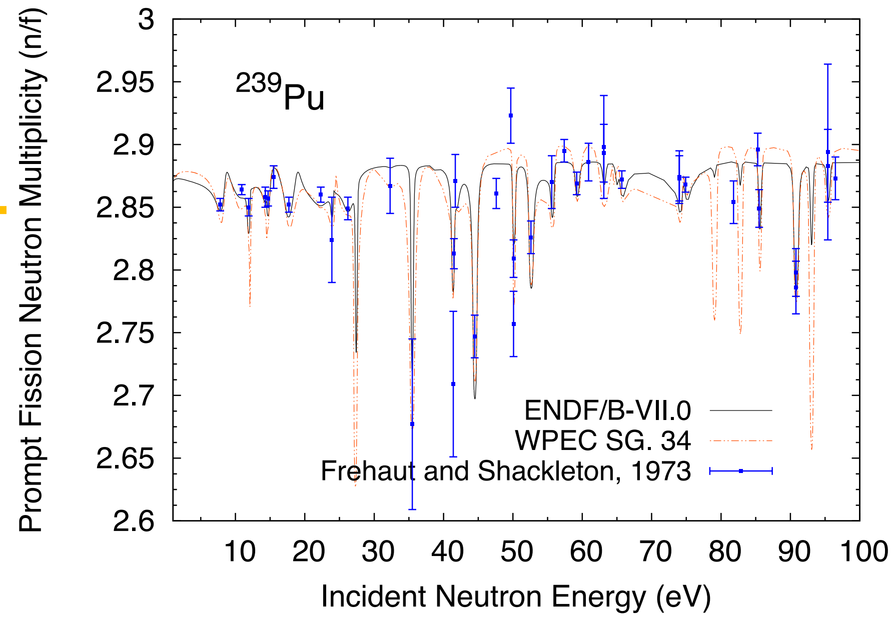
- New TUNL Data

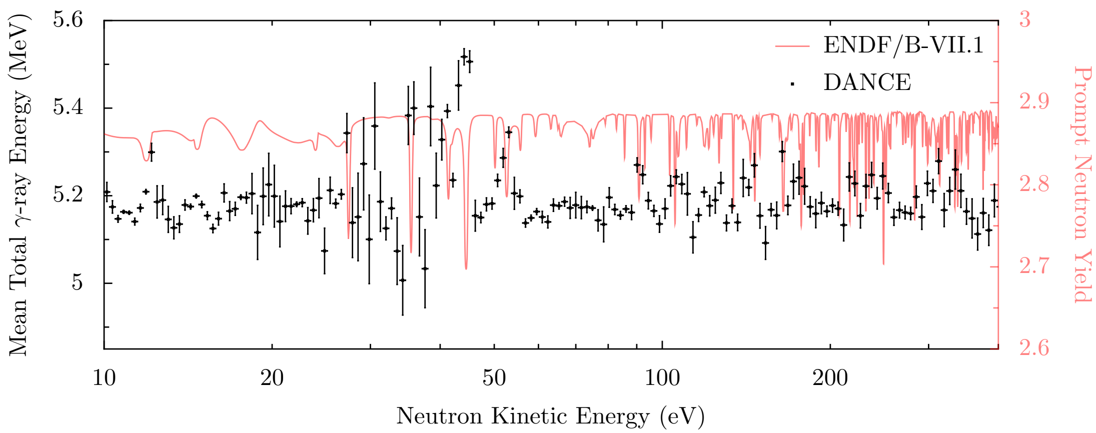


- **Remaining open questions will be solved by the SPIDER detector**

The (n,γf) process

- Fluctuations of <ν_p> in RRR
- New DANCE measurements (Mosby, Couture), showing fluctuations of <E_γ^{tot}> in RRR





(n,γf) would increase <N_γ> by ~1, and reduce E* available for prompt neutron emission by ~1 MeV, hence reduce <ν_p>

Early studies: J.E.Lynn, Phys. Lett. **18**, 31 (1965);
Stavinsky, V. and Shaker, M.O., Nucl. Phys. **62**, 667 (1965).

Fission Fragment Angular Distributions

- Original idea of **A. Bohr** (1959) following the experimental observation of strong anisotropies in fission fragment angular distributions

$$d\sigma_f(\theta) = \sum_J \sum_{M=-J}^{J} \sigma(JM) \sum_{K=0}^{J} \frac{\Gamma_f(JK)}{\Gamma(J)} \frac{2J+1}{4} \left(\left|\mathcal{D}^J_{MK}(\theta)\right|^2 + \left|\mathcal{D}^J_{M-K}(\theta)\right|^2 \right) sin\theta d\theta$$

s-wave neutrons on even target: $W(KI) = \frac{1}{4}(2I+1)\left[|d^I_{1/2,K}(\theta)|^2 + |d^I_{-1/2,K}(\theta)|^2\right]$

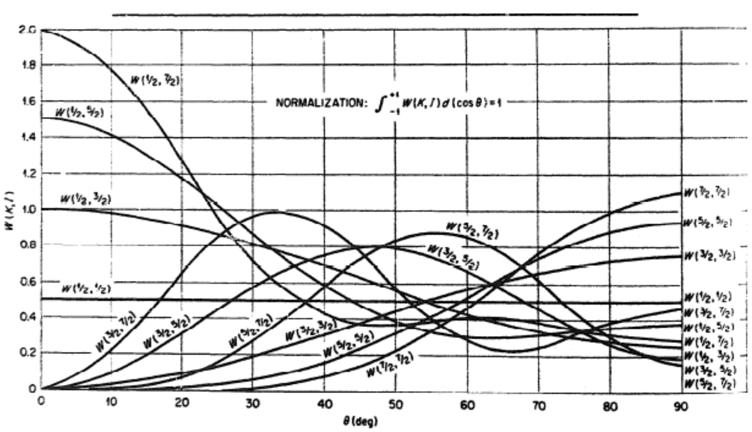
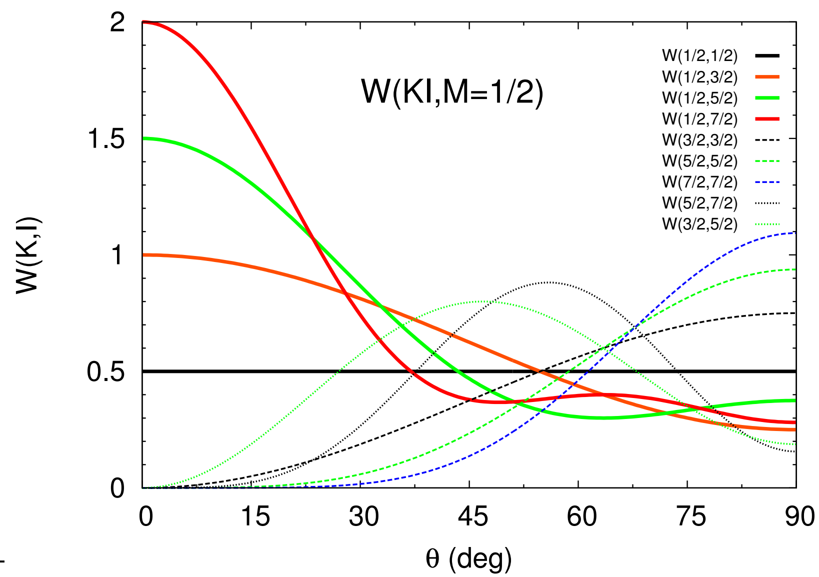
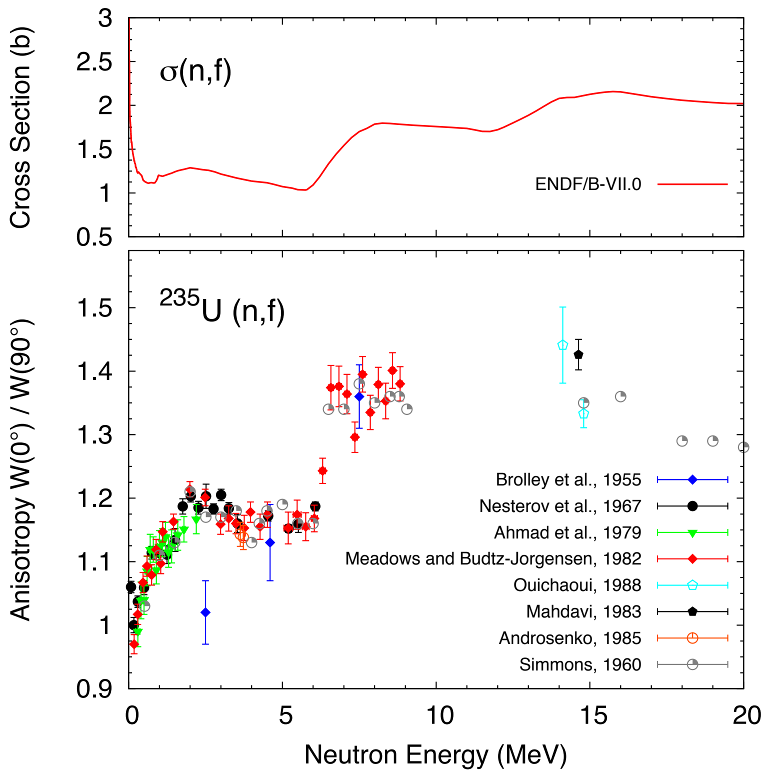


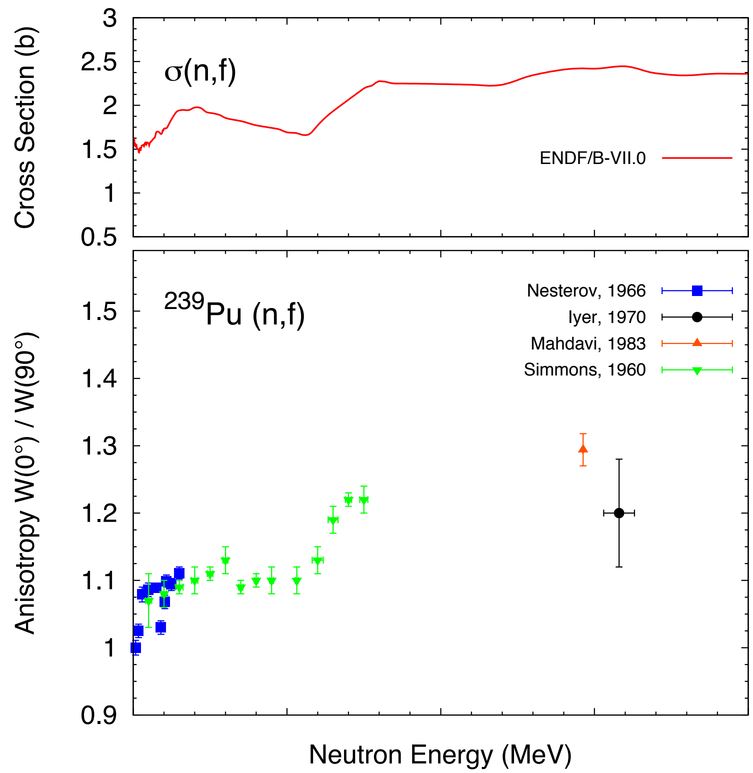
Fig. 6. Theoretical fission fragment angular distributions for fission through pure rotational states, W(KI).

Lamphere, Nucl. Phys. **A38**, 661 (1962)



Incident-Energy Dependent Anisotropy

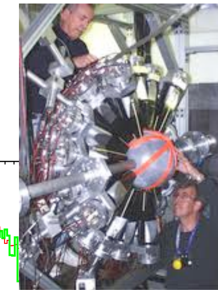


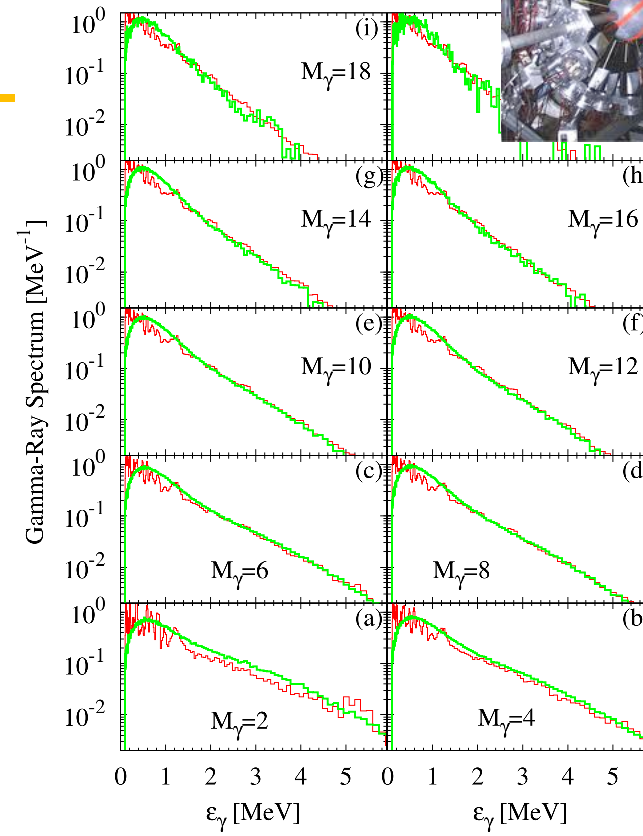


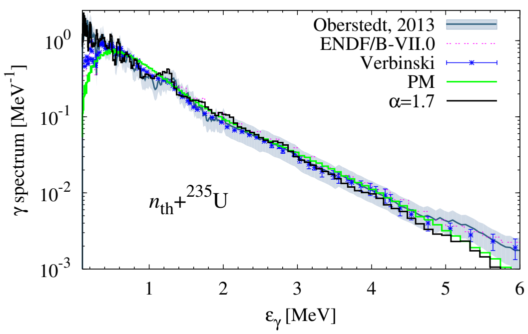
Ongoing experimental work at LANSCE, V. Kleinrath, F. Tovesson
Also, talk by L.S. Leong

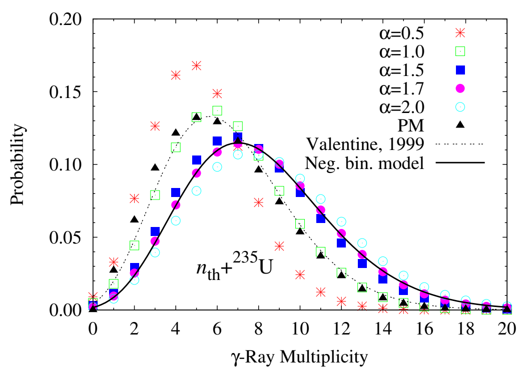
The Future is

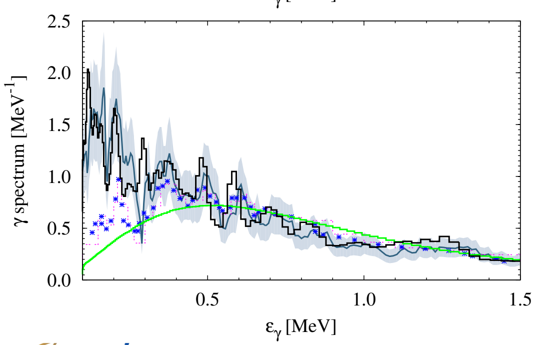
- Monte Carlo Hauser-Fesbach code CGMF
- Stetcu, Talou, Kawano, Jandel, PRC 90, 024617 (2014)
- Ullmann et al., PRC 87, 044607 (2013)











Need for accurate pre-neutron emission fission fragment yields in mass, charge and TKE as a function of excitation energy!

(many talks/posters on this at FIESTA)