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Title: Nuclear Data Sensitivities in Fast Critical Assemblies

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Nuclear Data Sensitivities in Selected Fast Critical Assemblies

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Abstract

MCNP6 has the capability to compute *k*-eigenvalue sensitivity coefficients using continuous-energy physics. Sensitivity profiles are generated for Jezebel, Flattop, and Copper-Reflected Zeus.

Introduction

- Motivation
- Method
- Results
- Outlook

Motivation

- Nuclear data (e.g., cross sections, fission χ) are uncertain.
- Neutronics uncertainties are typically dominated by uncertainties in nuclear data.
- Questions:
  1. How well can our codes and data predict criticality of a particular system?
  2. Which nuclear data drive the criticality of that system?
  3. Which nuclear data contribute the most to its **uncertainty**?

Motivation

- Knowing what drives the uncertainty in a particular system tells us where to allocate limited resources.
- Particle accelerators conduct differential measurements, but are expensive.
- New integral experiments can also help narrow uncertainties.
  - Specific experiments can be designed that are particularly sensitive to data of interest.
  - Observing biases in multiple experiments can inform us about biases in data.

- All of these require sensitivity analysis!

Perturbation Theory in Neutronics

- Perturbation theory gives the following result:

$$\frac{dk}{k} = -\frac{\langle \psi^\dagger, (d\Sigma_t - d\mathcal{S} - k^{-1} d\mathcal{F})\psi \rangle}{\langle \psi^\dagger, k^{-1}\mathcal{F}\psi \rangle}.$$

- k = multiplication factor.
- ψ = neutron (angular) flux.
- $\psi^\dagger$ = adjoint function.
- Σ_t = total interaction cross section.
- $\mathcal{S}$ = scattering source.
- $\mathcal{F}$ = fission source.

Connection to Uncertainty Quantification

- The uncertainty in k because of uncertain parameters x_i is estimated by:

$$(\Delta k)^2 = \sum_{i=1}^{N} (\Delta x_i)^2 \left(\frac{\partial k}{\partial x_i} \right)^2$$

- Uncertainties in nuclear are typically given as $\Delta x / x$.
- Define a useful quantity called a sensitivity coefficient:

$$S_{k,x} = \frac{dk}{k} \frac{x}{dx} = -\frac{\left\langle \psi^\dagger, (\Sigma_x - \mathcal{S}_x - k^{-1} \mathcal{F}_x) \psi \right\rangle}{\left\langle \psi^\dagger, k^{-1} \mathcal{F} \psi \right\rangle}.$$

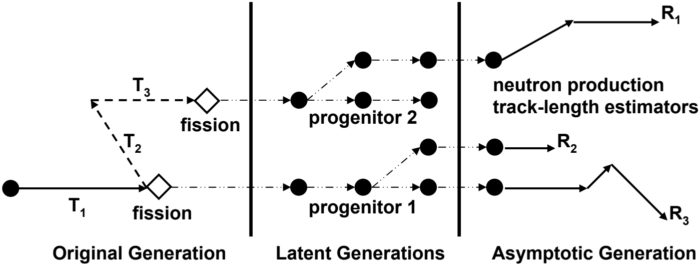
Solution Technique

$$S_{k,x} = -\frac{\langle \psi^{\dagger}, (\Sigma_x - \mathcal{S}_x - k^{-1}\mathcal{F}_x)\psi \rangle}{\langle \psi^{\dagger}, k^{-1}\mathcal{F}\psi \rangle}.$$

- Accurate solutions to this equation for can readily be obtained by continuous-energy Monte Carlo.
- Can get energy-resolved sensitivity profiles for cross sections, fission ν, fission χ, and scattering distributions.
- **New capability in MCNP6!**

Iterated Fission Probability Method

- Divide active cycles of eigenvalue calculation into "blocks" of some size (default 10).
- First cycle: accumulate scores and tag neutrons.
- Follow neutrons through generations, preserving tags.
- Last cycle: multiply scores by neutron production of corresponding progeny.



Constraining Sensitivities

- Fission χ and scattering laws are normalized in outgoing energies E and angles μ.
- An increase somewhere must result in decrease(s) elsewhere to preserve normalization.
- Common technique is to increase the distribution in some energy interval and renormalize.
- The sensitivity is constrained by the following relation:

$$\hat{S}_{k,x}(E,\mu|E_i) = S_{k,x}(E,\mu|E_i) - x(E,\mu|E_i)S_{k.x}(E_i).$$

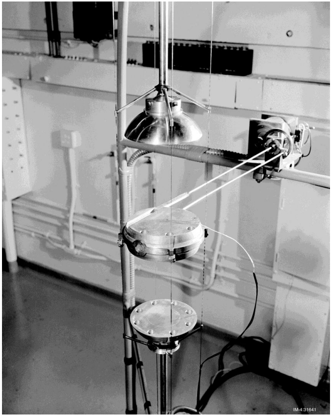
- Note: Because of normalization, the sensitivity integrated over all outgoing energies and angles is zero.

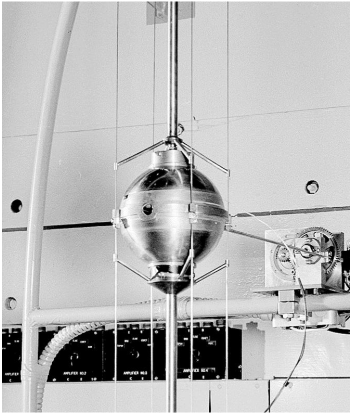
Results

- Three fast-critical experiments were analyzed:
    1. Jezebel
    2. Flattop
    3. Copper-Reflected Zeus

Jezebel

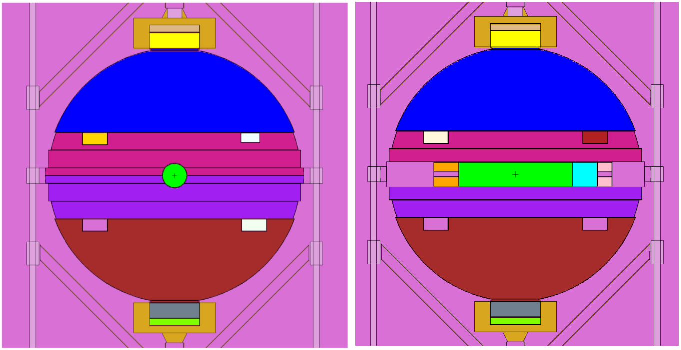
- Plutonium critical experiment at LASL in 1950's:





Jezebel

- Detailed MCNP model by R. Brewer and J. Favorite:



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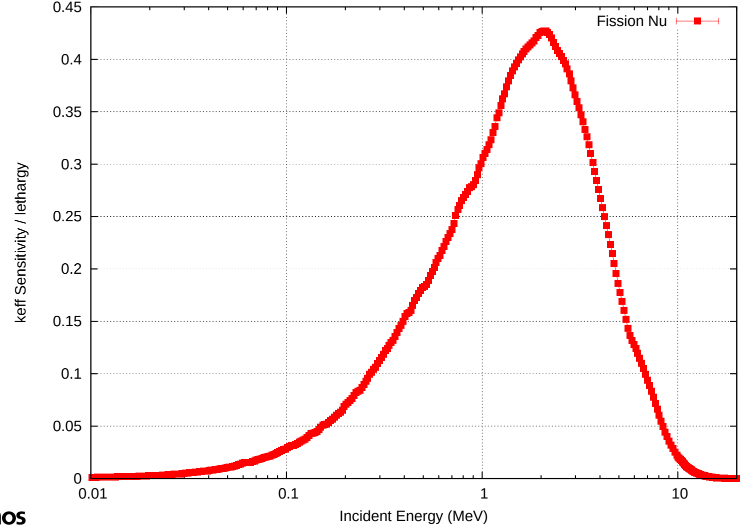
Jezebel: Top Sensitivities

Isotope	Data	$S_{k,x}$
Pu-239	ν	+9.662E-01 ± 0.00%
Pu-239	Fission	+7.274E-01 ± 0.02%
Pu-239	Elastic	+6.200E-02 ± 0.20%
Pu-240	Fission	+2.291E-02 ± 0.03%
Pu-239	n,n' Continuum	+1.008E-02 ± 0.34%
Pu-239	n,n' Level 2	+9.487E-03 ± 0.31%
Pu-239	n,n' Level 1	+8.906E-03 ± 0.32%
Pu-239	n,γ	−7.673E-03 ± 0.08%
Pu-240	Elastic	+3.268E-03 ± 0.55%
Pu-241	ν	+2.905E-03 ± 0.02%
Ni-58	Elastic	+2.435E-03 ± 0.48%
Pu-241	Fission	+2.185E-03 ± 0.03%
Pu-239	n,n' Level 3	+1.829E-03 ± 0.54%

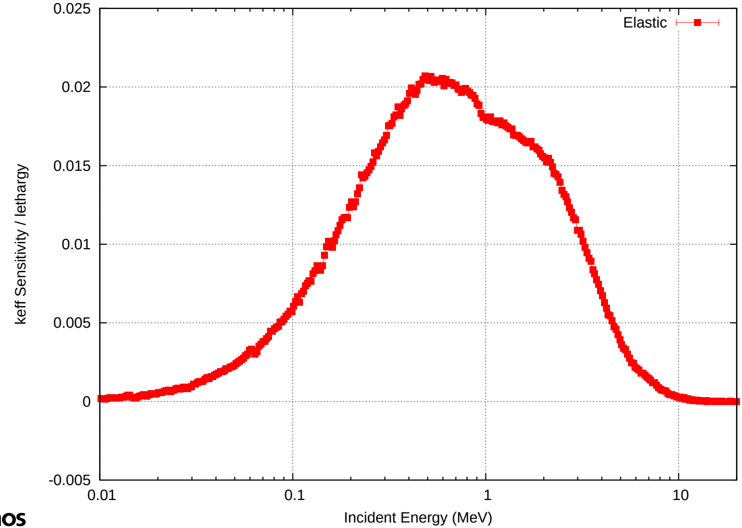
Pu-239 Uncertainties 1 MeV

- Fission ν: 0.2%
- Fission: 1%
- Elastic: 4%
- Inelastic: 10-20%
- Capture: 10%

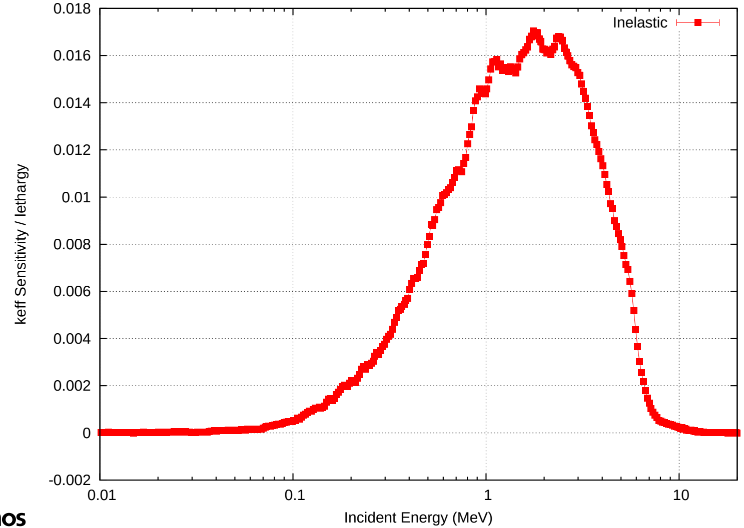
Jezebel: Pu-239 Fission-ν Sensitivity



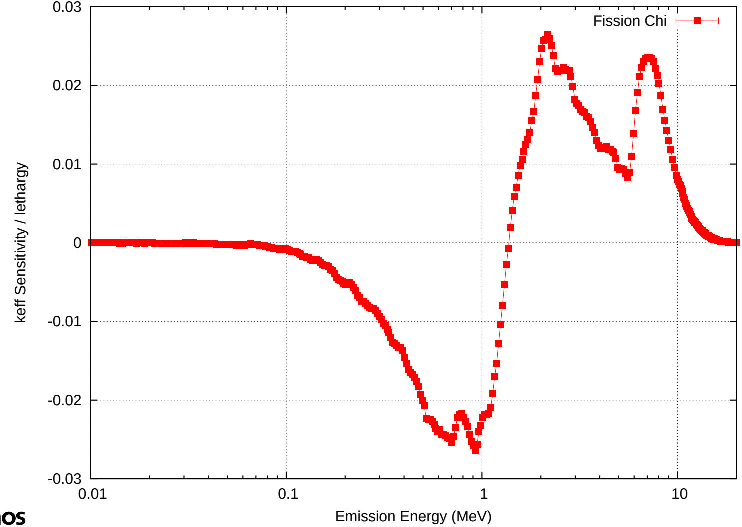
Jezebel: Pu-239 Elastic Cross-Section Sensitivity



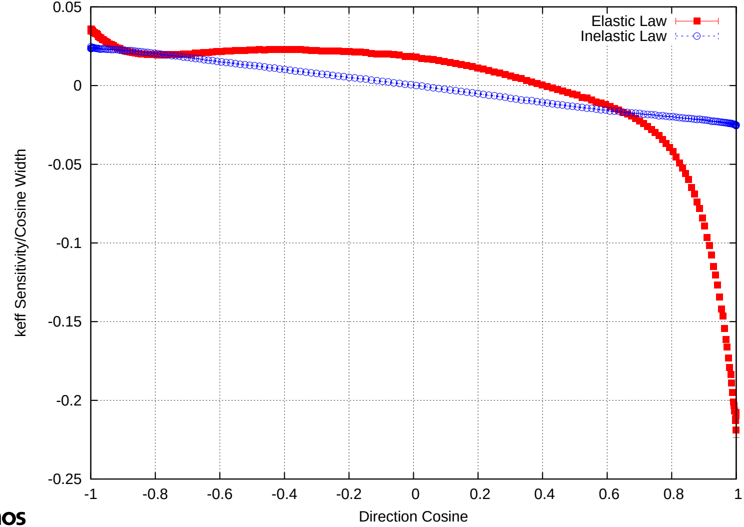
Jezebel: Pu-239 Inelastic Cross-Section Sensitivity



Jezebel: Pu-239 Fission-χ Sensitivity



Jezebel: Pu-239 Scattering Law Sensitivity



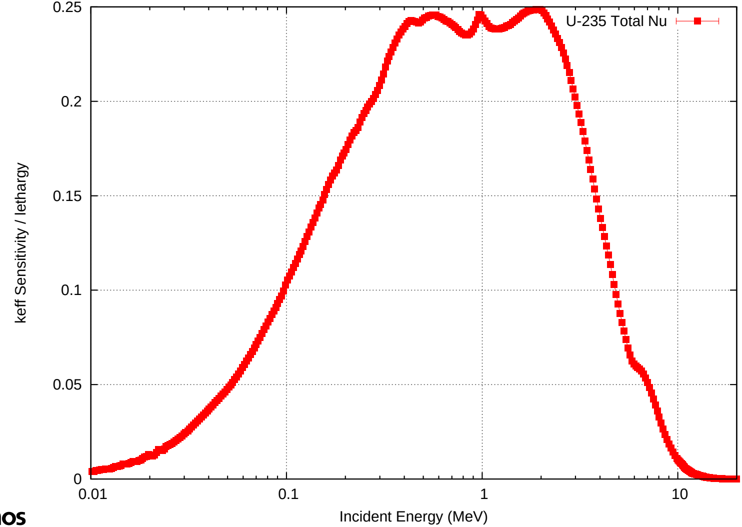
Flattop

- HEU sphere reflected by natural uranium:

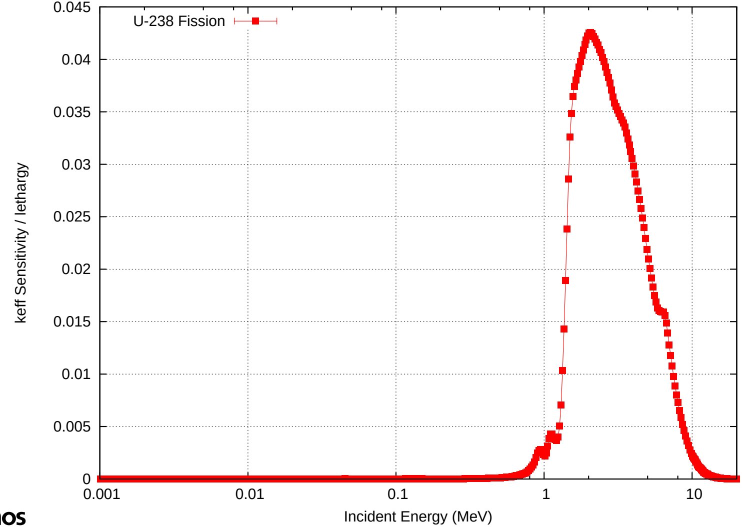
Flattop: Top Sensitivities

Isotope	Data	$S_{k,x}$
U-235	ν	$+9.149$E-01 $\pm$ 0.01%
U-235	Fission	$+5.937$E-01 $\pm$ 0.02%
U-238	Elastic	$+1.430$E-01 $\pm$ 0.12%
U-238	ν	$+7.857$E-02 $\pm$ 0.05%
U-238	Fission	$+5.567$E-02 $\pm$ 0.06%
U-235	n,γ	-4.810E-02 $\pm$ 0.03%
U-238	n,γ	-4.806E-02 $\pm$ 0.05%
U-238	n,n' Level 1	$+3.560$E-02 $\pm$ 0.15%
U-235	Elastic	$+3.261$E-02 $\pm$ 0.26%
U-235	n,n' Continuum	$+1.144$E-02 $\pm$ 0.25%
U-238	n,n' Level 2	$+8.036$E-03 $\pm$ 0.21%
U-238	n,n' Continuum	$+7.793$E-03 $\pm$ 0.25%
U-234	ν	$+6.579$E-03 $\pm$ 0.02%

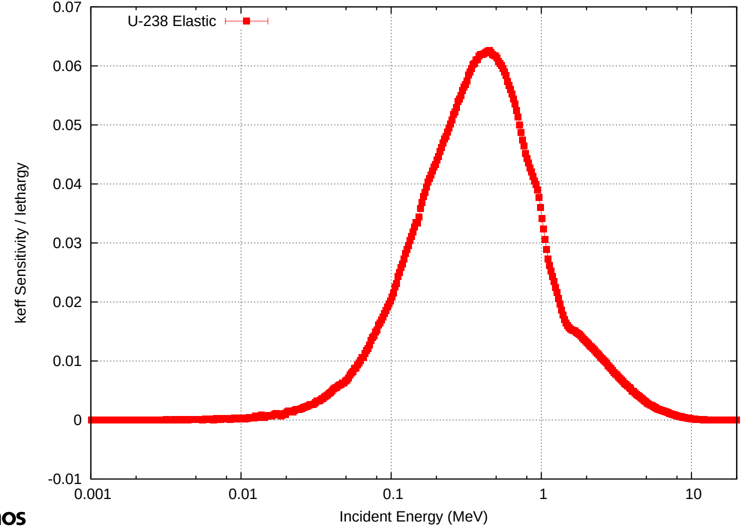
Flattop: U-235 Fission-ν Sensitivity



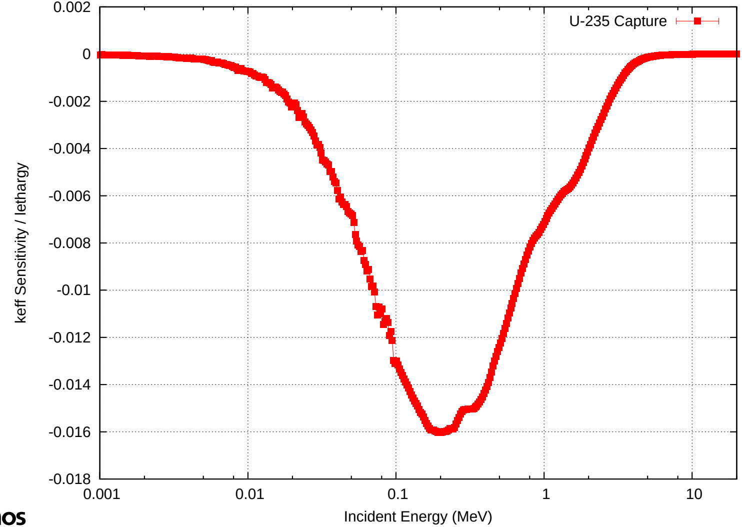
Flattop: U-238 Fission Cross-Section Sensitivity



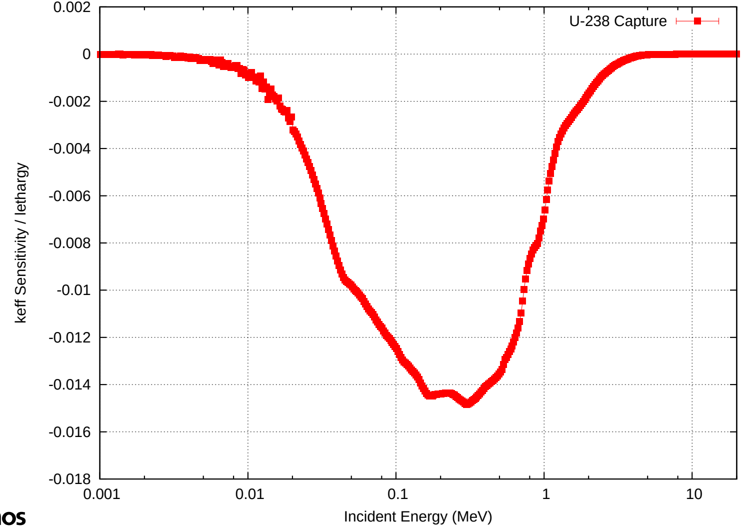
Flattop: U-238 Elastic Cross-Section Sensitivity



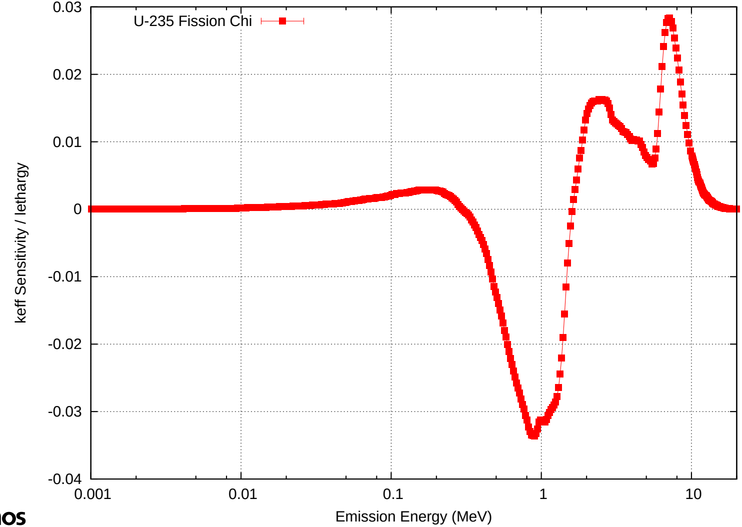
Flattop: U-235 Capture Cross-Section Sensitivity



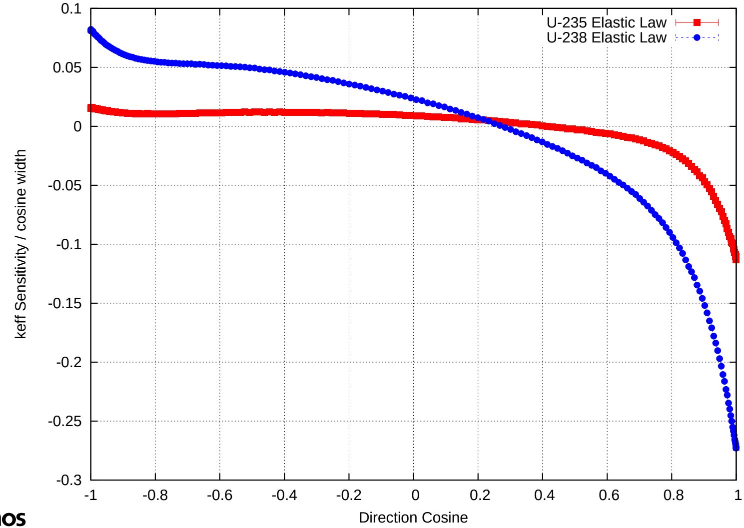
Flattop: U-238 Capture Cross-Section Sensitivity



Flattop: U-235 Fission-χ Sensitivity



Flattop: Elastic Scattering Law Sensitivity



Copper-Reflected Zeus

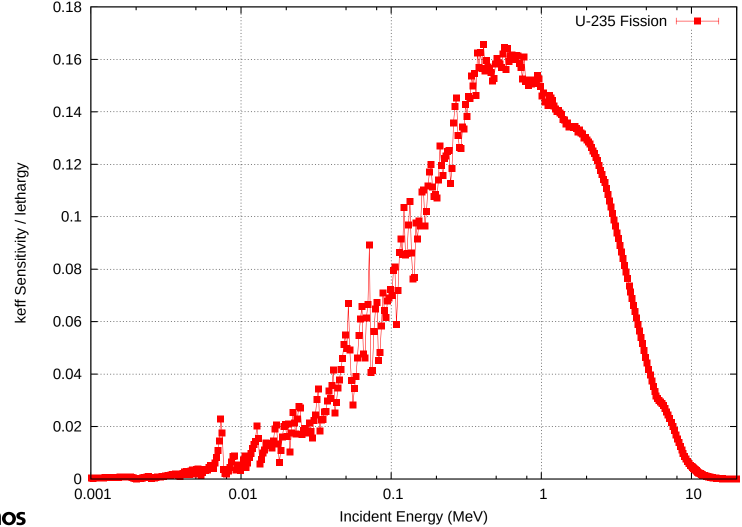
- HEU plates surrounded by a copper reflector:

04-GA50001-183

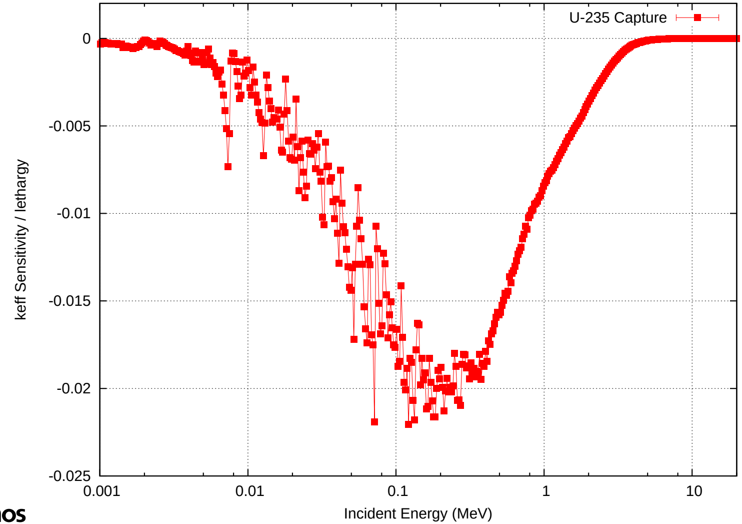
Copper-Reflected Zeus: Top Sensitivities

Isotope	Data	$S_{k,x}$
U-235	ν	$+9.874$E-01 $\pm$ 0.00%
U-235	Fission	$+5.771$E-01 $\pm$ 0.03%
Cu-63	Elastic	$+1.937$E-01 $\pm$ 0.22%
Cu-65	Elastic	$+9.576$E-02 $\pm$ 0.28%
U-235	n,γ	-6.734E-02 $\pm$ 0.05%
Cu-63	n,γ	-3.555E-02 $\pm$ 0.07%
Cu-63	n,n' Level 2	$+1.012$E-02 $\pm$ 0.32%
Cu-65	n,γ	$+9.767$E-03 $\pm$ 0.08%
Al-27	Elastic	$+8.951$E-03 $\pm$ 0.43%
Cu-63	n,n' Level 1	$+8.021$E-03 $\pm$ 0.36%
U-235	n,n' Continuum	$+6.713$E-03 $\pm$ 0.57%
Cu-63	n,n' Continuum	$+6.221$E-03 $\pm$ 0.31%
U-234	ν	$+6.044$E-03 $\pm$ 0.04%

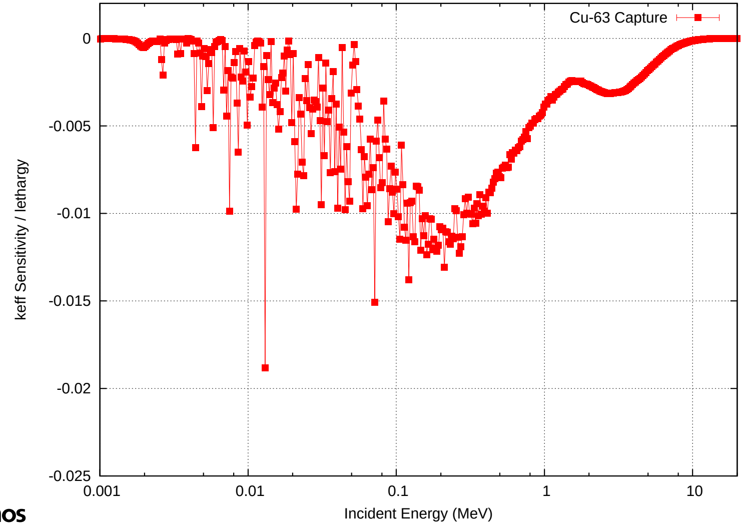
Zeus: U-235 Fission Cross-Section Sensitivity



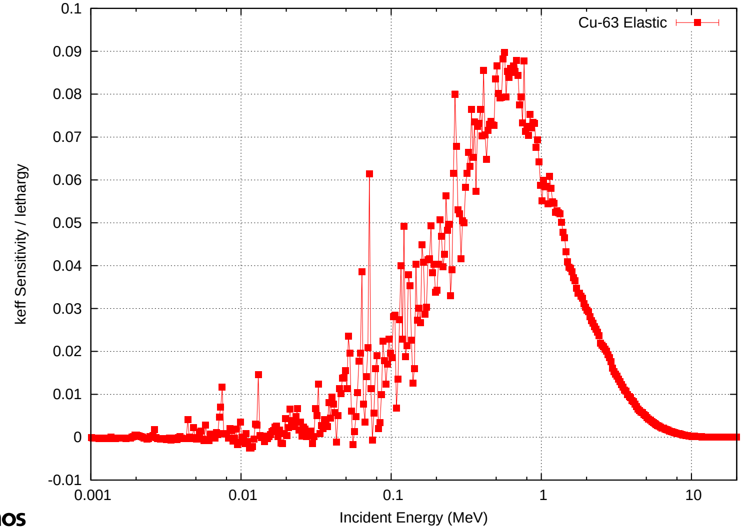
Zeus: U-235 Capture Cross-Section Sensitivity



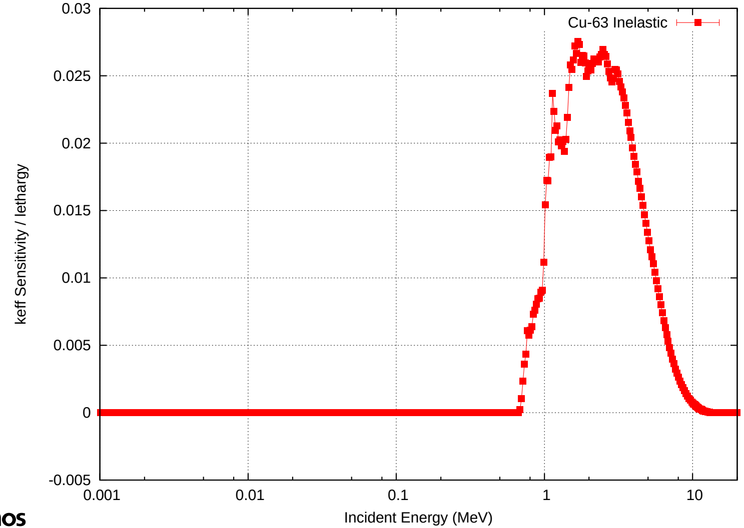
Zeus: Cu-63 Capture Cross-Section Sensitivity



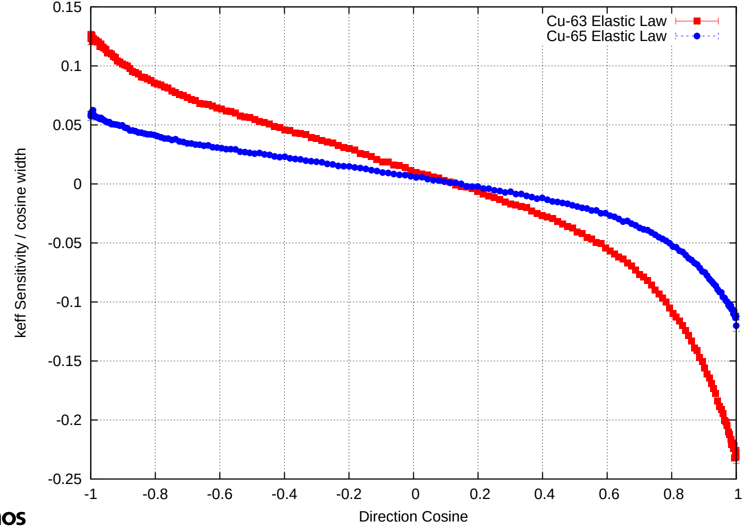
Zeus: Cu-63 Elastic Cross-Section Sensitivity



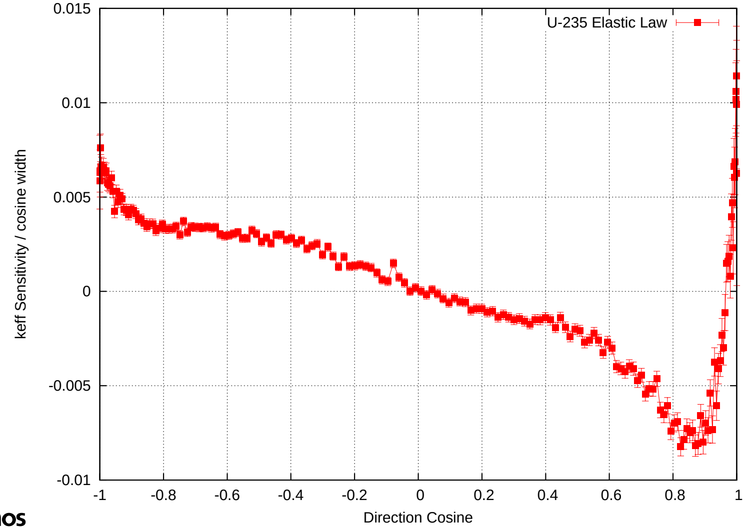
Zeus: Cu-63 Inelastic Cross-Section Sensitivity



Zeus: Cu Elastic Scattering Law Sensitivity



Zeus: U-235 Elastic Scattering Law Sensitivity



Status & Future Work

- MCNP6 can find what nuclear data most determines criticality.
- This is useful for interpreting neutronics code discrepancies and to design new experiments to address them.

- Uncertainty quantification of criticality with MCNP6 is just starting.
- Future hope is to extend to other responses: foil activation, leakage, α eigenvalue, etc.

Acknowledgments

- Funding provided by the U.S. DOE/NNSA Nuclear Criticality Safety Program.

Questions?