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# Neutron Flux Characterization of the Kansas State University TRIGA Mark II's Northeast Beam Port

John Boyington
Advisor: Dr. Jeremy Roberts

Department of Mechanical and Nuclear Engineering
Kansas State University

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# Objective Statement

To do a multi-dimensional, high resolution, high fidelity characterization of the neutron beam departing from the Northeast Beam Port (NEBP)

- Energy, Angle, Space
- Fine group structures
- Minimize errors

# Motivational Significance

- Detector Characterization
- Model Validation
- Safety

# Hypotheses

- Predominately Fast
- Monodirectional

# Outline

- Neutron Spectrometry and Deconvolution
- Simulated Work
- Experimental Work
- Conclusions and Future Work

# Neutron Spectrometry

How do we measure neutrons?

# Bonner Sphere Spectrometers

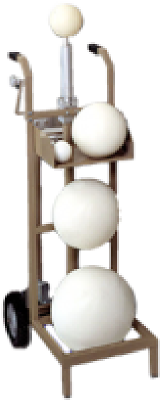

Figure: Bonner Sphere Spectrometer

- Active detection through $^{6}$Li($n$, $\alpha$)t [1]
- Thermally sensitive crystal
- Increasing HDPe sphere sizes provide different (faster) responses.

# Foil-based Spectrometers

- Passive detection through various reactions, [($n$, $\gamma$), ($n$, $\alpha$), etc.]
- Secondary $\gamma$-ray actually what is measured
- Multi-foil experiment can span entire spectrum [2]
- Gold (thermally sensitive) can be used in conjunction with Bonner Spheres [3]

# Problem Formulation

$$N_k + \epsilon_k = \sum_i R_{ki}\phi_i, \quad k = 1, \ldots, m. \tag{1}$$

$N_k$ Measured response of detector $k$
$\epsilon_k$ (Unknown) error of detector $k$ response
$R_{ki}$ Response function of detector $k$ at energy $i$
$\phi_i$ (Unknown) Flux in energy $i$

Ill posed - much more energy groups than detectors!
Infinite solutions!

# How to Solve

How do we arrive at one acceptable solution in a domain of infinite solutions?

- Default Spectrum - becomes a 'tuning' problem
- Maximum Entropy - neutrons behave like gases

# Unfolding Methods

Doroshenko Directed Divergence [4]

- Minimize Directed Divergence
- Iterative

Gravel [5]

- Modified Sand-II [6]
- Iterative
- Works by applying correction factors to a weighting function

MAXED [7]

- Maximized Skilling entropy, a function of both the default and solution spectrum

# Simulated Work

Simulation of the NEBP flux

# Modeling Overview

- Added NEBP to existing model
- Tallied fission rates within core to produce SDEF
- Applied ADVANTG variance reduction software to speedup tally convergence
- Tallied flux at NEBP aperture

# Existing Model

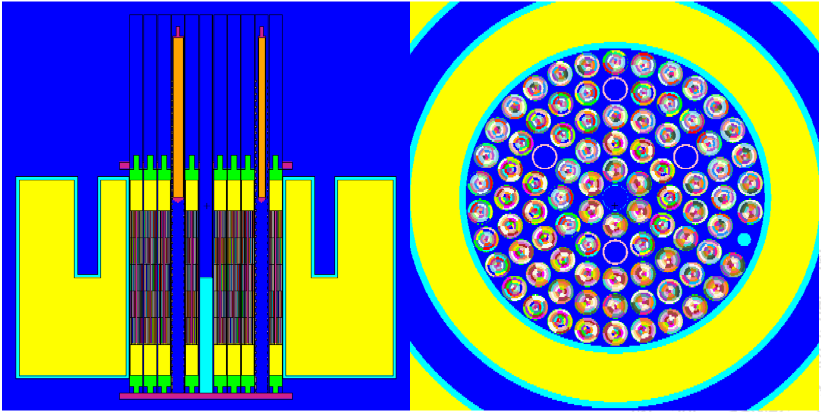

Figure: YZ (left) and XY (right) views of the existing core model with discretized fuel, control rods, graphite reflector, etc.

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# NEBP Additions

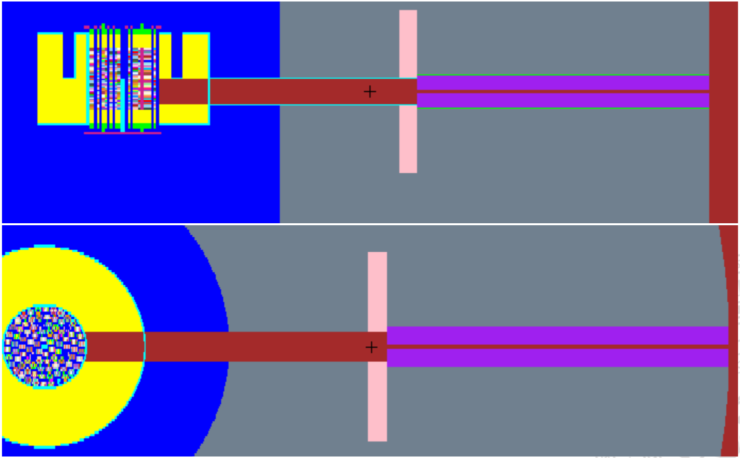

Figure: XZ (top) and XY (bottom) views of the NEBP additions with reflector penetration, lead shadow shield, and collimator.

# Fission Tallies

- 40 Axial Segments
- 5 Radial Segments
- Used to create PDFs for steady-state problem

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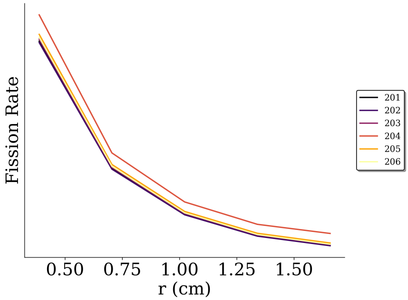
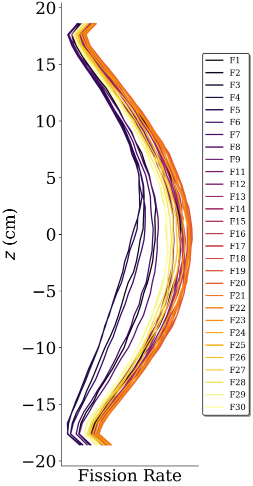
# Fission Tally Results

Example results from fission tallies within core fuel, B-ring radial (left), fuel element slice (middle), F-ring axial (right).







# Fission Tally Results

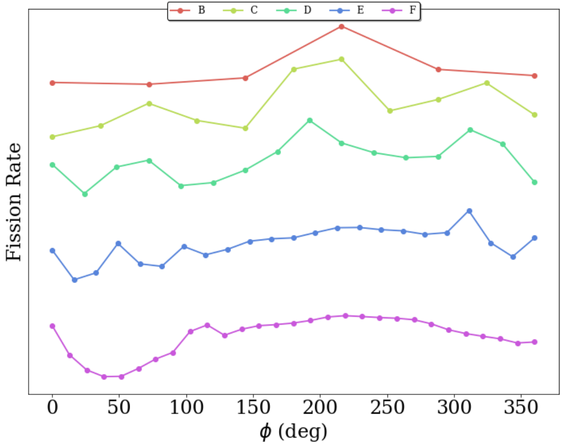



Figure: Integrated fission rates as a function of core azimuthal position.

# ADVANTG

The AutomateD VAriaNce reducTion Generator [8], generates weight window parameters for a fixed-source, continuous-energy MCNP problem

- Used Denovo discrete ordinates solver
- Produces weight windows to speed tally convergence
- Also adds source biasing parameters to MCNP input

# Applying ADVANTG

- Model rotated so beam was on $x$-axis
- 1,570,624 voxels
- Parallelized for 64 cores

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# Spectral Flux

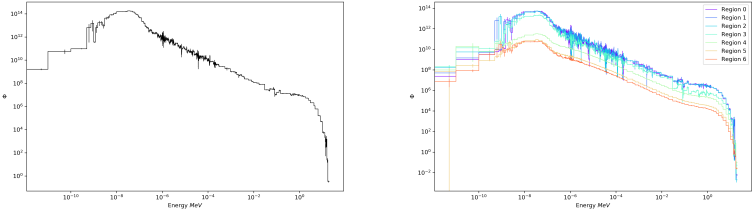


Figure: The spectral flux distribution integrated (left) and separated by radial region (right)

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# Angular Flux

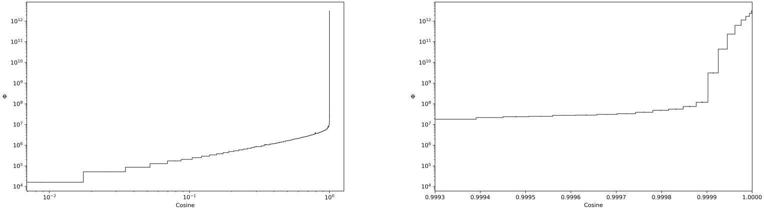


Figure: The angular flux (left) and a zoomed-in view of the angular flux (right).

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# Angular Flux

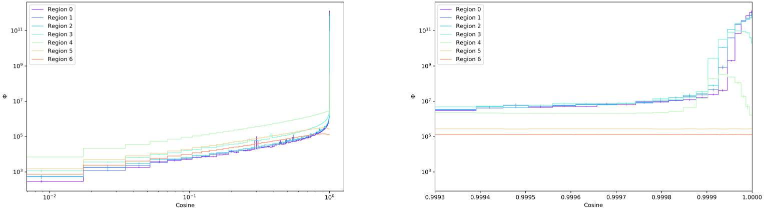


Figure: The angular flux, broken into radial regions (left) and a detail view of the same spectra (right).

# Radial Flux

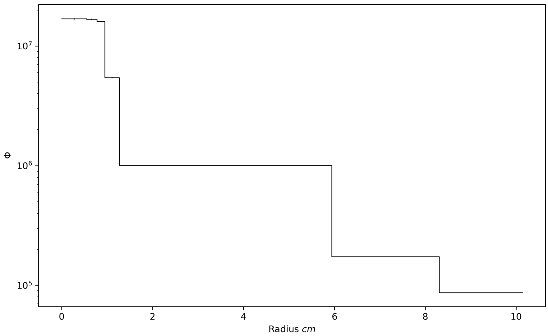


Figure: The energy- and angle-integrated radial flux.

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# Experimental Work

The effort to experimentally determine the spectral flux of the NEBP.

# Gold Foil Tube

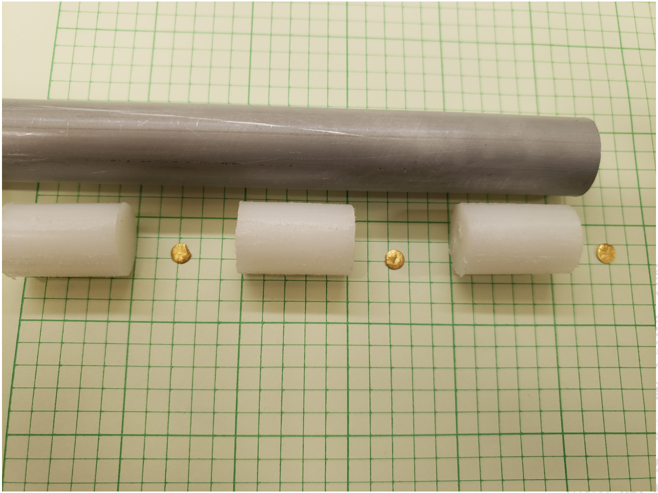

Figure: The disassembled gold foil tube

# Response Function Generation

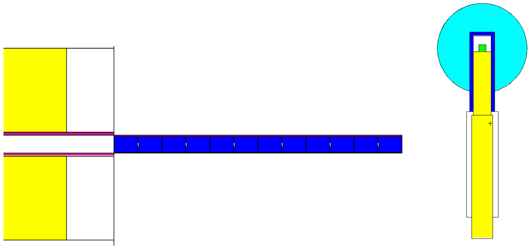

Figure: The foil tube model (left) and the bonner sphere model (right).

- Decoupled MCNP model used to generate response functions

# Foil Tube Response Functions

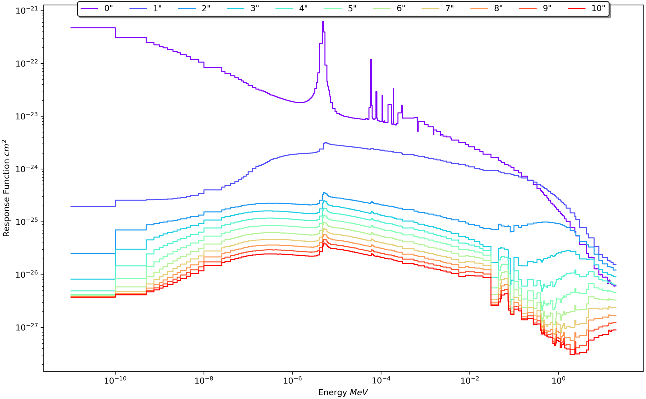


Figure: The MCNP-generated response functions for the gold foil tube detector.

# Bonner Sphere Response Functions

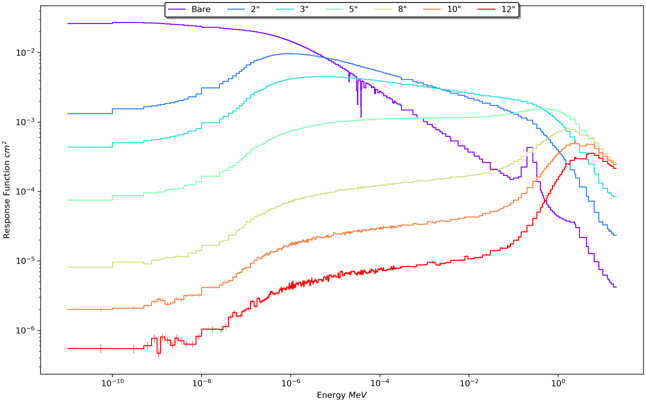


Figure: The MCNP-generated response functions for the bonner sphere spectrometer.

# Experimental Procedures

Gold foil tube

- Tube inserted into NEBP collimator.
- Reactor brought to 100 kW(th).
- Irradiated for approximately 2.5 hours.
- Reactor powered off, foils removed from tube, bagged and labeled.
- Foils counted with HPGe

Bonner Sphere Spectrometer

- Reactor powered to 1 kW(th).
- Bare detector placed directly in front of beam 28" from aperture.
- Shutter opened
- Acquired counts for 300s live time (600s for 12" sphere).
- Shutter closed
- Repeated for different spheres (2", 3", 5", 8", 10", 12").

# Foil Tube Postprocessing

$$A_{sat} = A_{meas} \frac{R_{meas}}{R_{sat} n_a K I_{rel}}, \tag{2}$$

$A_{meas}$ is the measured activity
$R_{meas}$ corrects for decay during measurement
$R_{sat}$ is the ratio between the radiation at measurement and the saturation activity
$n_a$ is the number of sample atoms
$K$ is the isotopic abundance
$I_{rel}$ is the relative gamma intensity

# Capturing Flux Transients

$$\frac{R_{sat}(t)}{dt} = \lambda(P_f(t) - R_{sat}(t)) \tag{3}$$

$\lambda$ is the decay constant
$P_f(t)$ is the power at time $t$ relative to nominal power

Allows for *transient* power data to be used when calculating saturation activities!

# Bonner Sphere Postprocessing

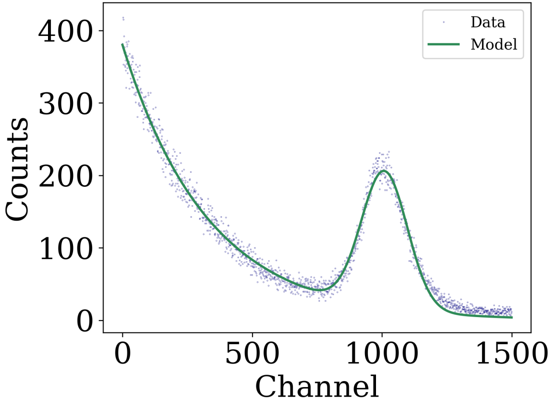


Figure: The acquired spectrum from the 8" sphere and model used to find the response.

# Response Comparison: Foil Tube

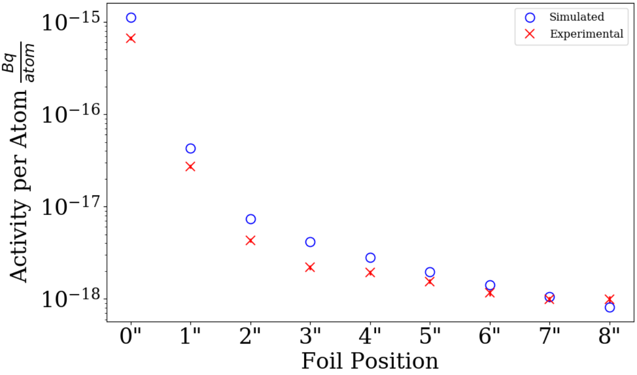


Figure: A comparison of the simulated and experimentally determined activities for the gold foil tube.

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# Response Comparison: Bonner Sphere

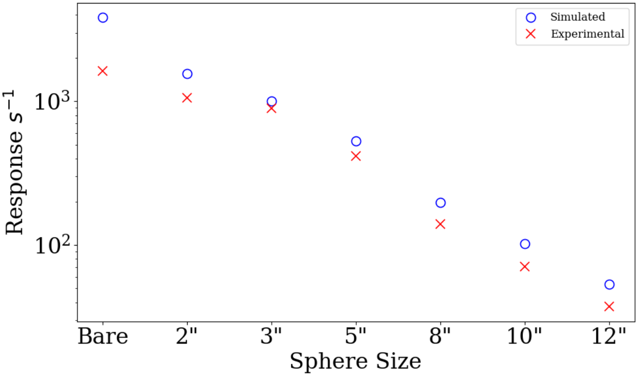


Figure: A comparison of the simulated and experimentally determined count rates for the bonner sphere spectrometer.

# Spectral Unfolding Parameters

Doroshenko Directed Divergence

- 50 iterations

Gravel

- 50 iterations

MAXED

- Omega = 9 (foil tube), 7 (BSS), 16 (combined)
- With and without pre-scaling default spectrum magnitude

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# Spectral Unfolding: Doroshenko Directed Divergence

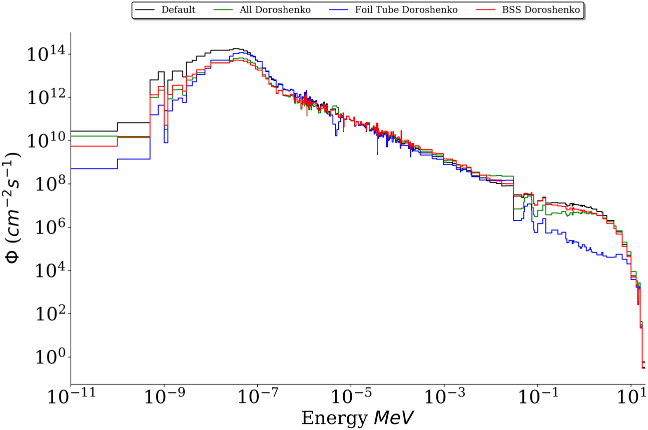


Figure: The unfolded spectra from Doroshenko Directed Divergence.

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# Spectral Unfolding: Gravel

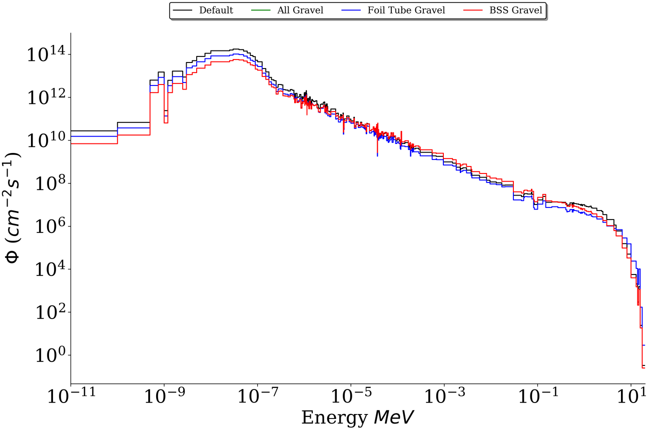


Figure: The unfolded spectra from Gravel.

# Spectral Unfolding MAXED

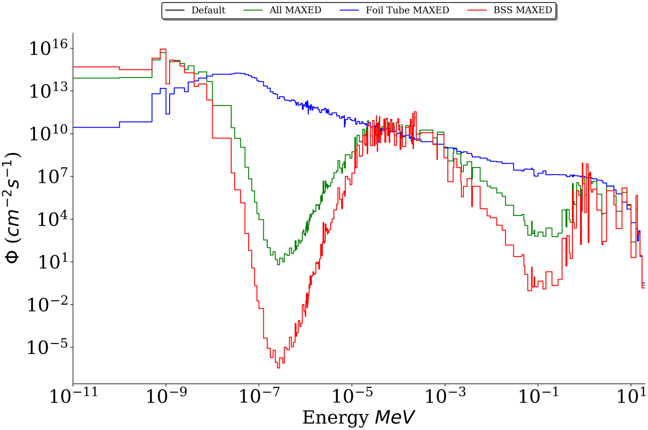


Figure: The unfolded spectra from MAXED.

# Spectral Unfolding MAXED (Scaled)

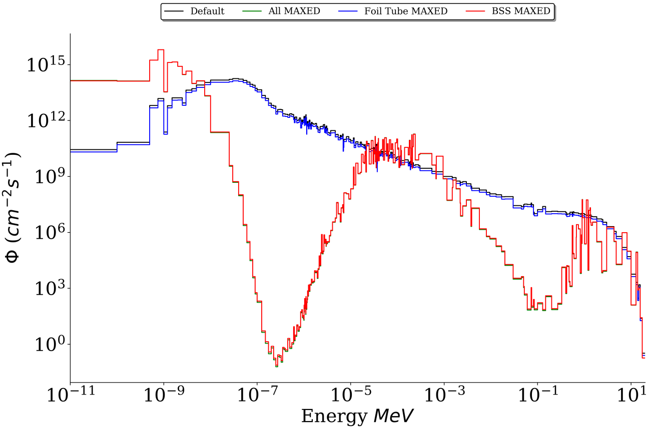


Figure: The unfolded spectra from MAXED (scaled).

# Conclusions and Future Work

Conclusions drawn from the experiment and motivation for future work

# Conclusions

- Multi-dimensional, high resolution flux simulated
- Active and passive detection experiments conducted
- Final spectra unfolded with multiple methods
- Flux was predominantly monodirectional, but not as fast as expected

# Future Work

- Characterization of other beam ports
- Continued optimization of foil tube design

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