GEANT4 SIMULATION OF IRRADIATION FACILITIES AND NEUTRON SOURCES AT UNIVERSITY OF UTAH TRIGA FOR NUCLEAR FORENSICS AND DETECTION

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Advanced Radiation Simulation Laboratory

Presented at 2nd National Conference in Advancing Tools and Solutions for Nuclear Material Detection
Salt Lake City, UT, 2 May 2011

Nuclear Engineering
THE UNIVERSITY OF UTAH

Andrew Voyles

Major: Chemical Engineering
Minors: Nuclear Engineering, Chemistry

As a young child, my only wish for my future was to someday be in a history textbook. Now, I have the opportunity to be able to actually succeed in this effort: I want to be able to improve the world through nuclear technologies, and my current dream is to be able to help develop sustainable fusion as a viable power source for the future.

Goals for Project:

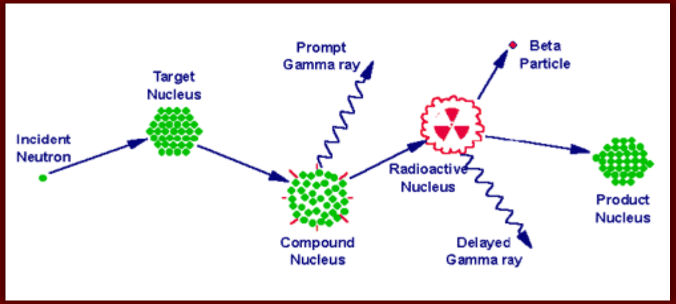
- Model UUTR irradiation facilities, using GEANT4 simulation toolkit
- Calculate dose from irradiated samples at various distances
- Provide method of benchmarking experiments at irradiation facilities
- Simulate shielding of neutron source
  - THEREFORE, create nuclear signatures for nuclear forensics involving UUTR

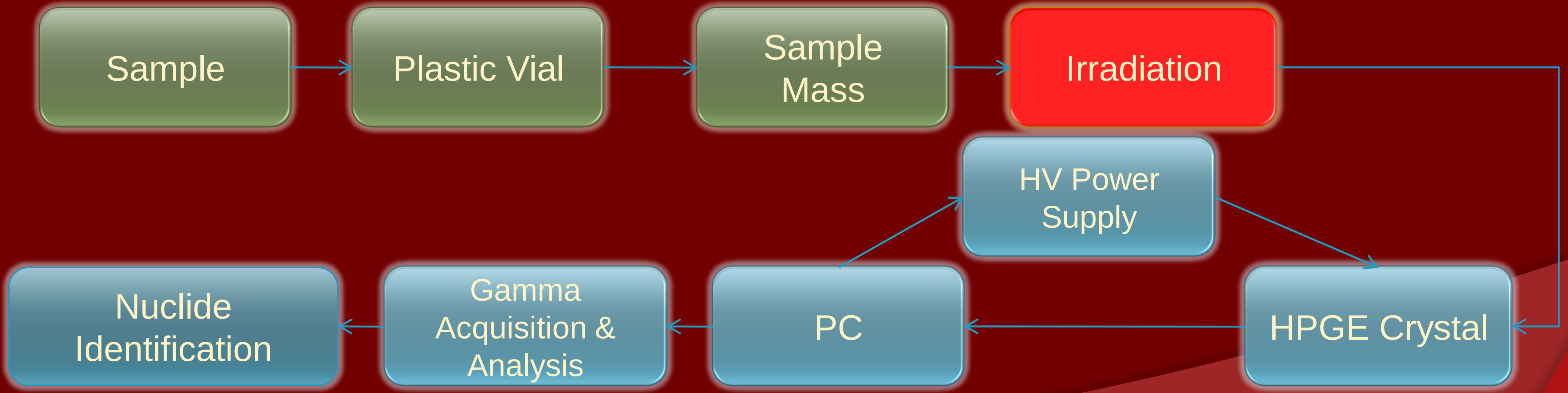
GEANT4 (GEometry ANd Tracking)

- "Toolkit for the simulation of the passage of particles through matter" (http://geant4.cern.ch)
  - Developed at CERN for studying particle interactions
- Utilizes Monte Carlo methods for simulations
- Freely distributed open source code
- Written in C++
  - All Object-Oriented Programming concepts are utilizable
- Application areas include:
  - High energy physics
  - Nuclear experiments
  - Nuclear medicine studies
  - Particle accelerator studies
  - Space physics studies

Neutron Activation Analysis

- Nondestructive method to find
  - Sample composition and concentrations
- Sample is exposed to neutrons
  - Becomes activated
  - Isotopes decay to become more stable
  - Decay emission paths used to determine the composition of the sample





Neutron Activation at UNEP

Canberra HPGE Detectors used for NAA at UNEP

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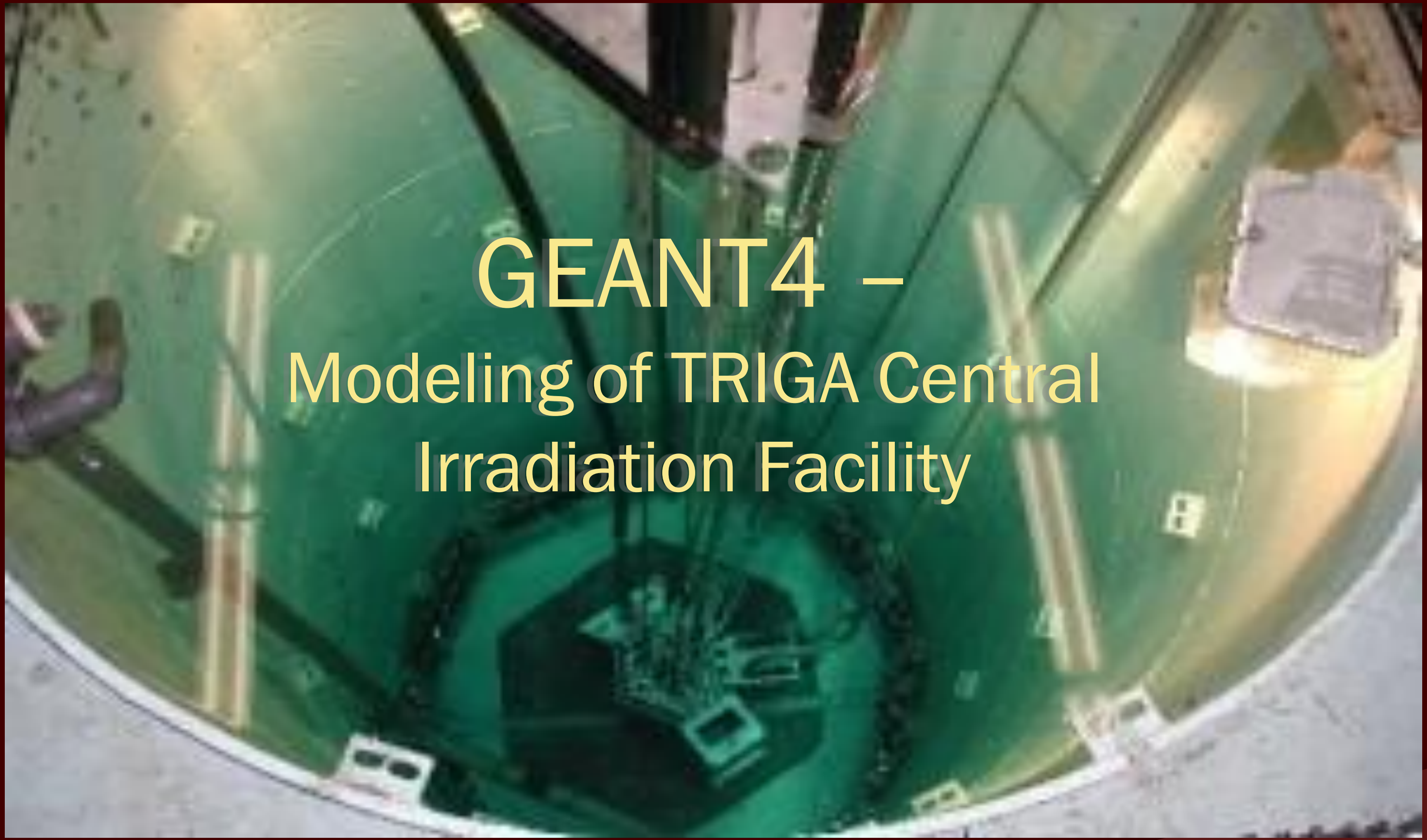
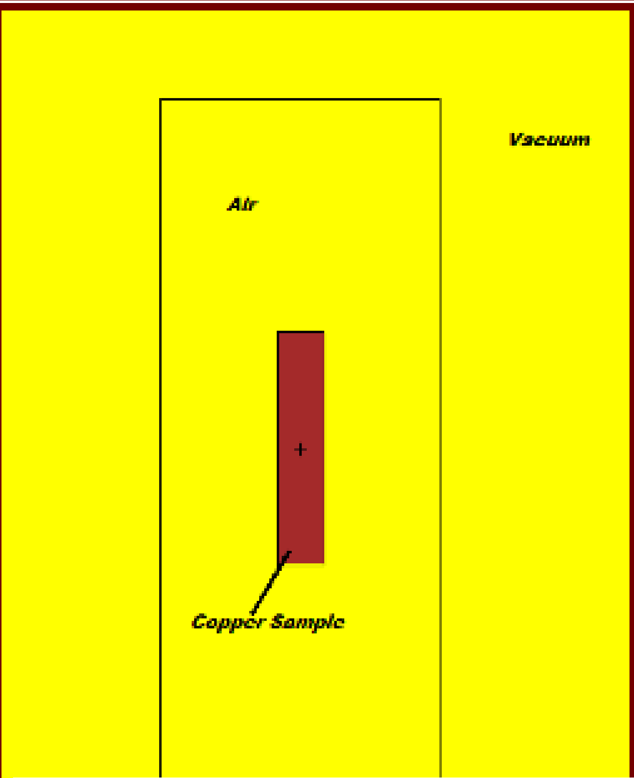


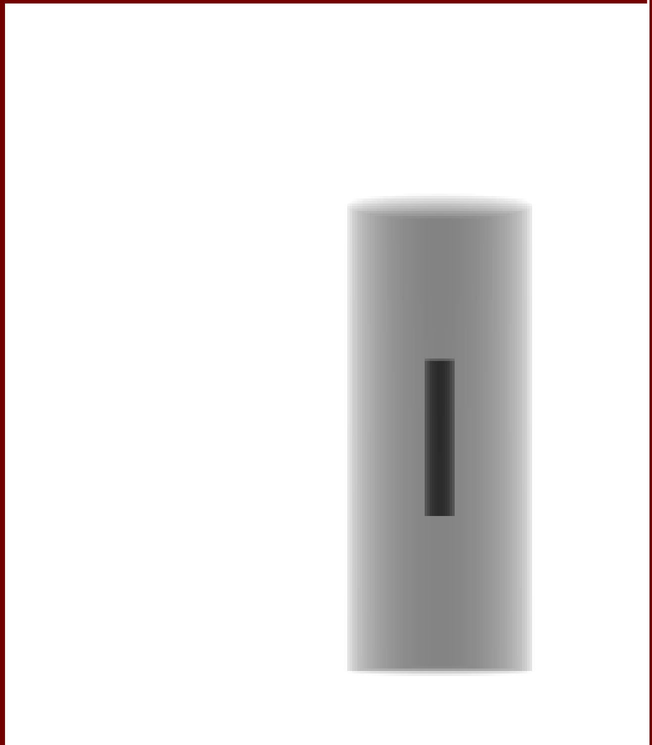
GEANT4 –

Modeling of TRIGA Central Irradiation Facility

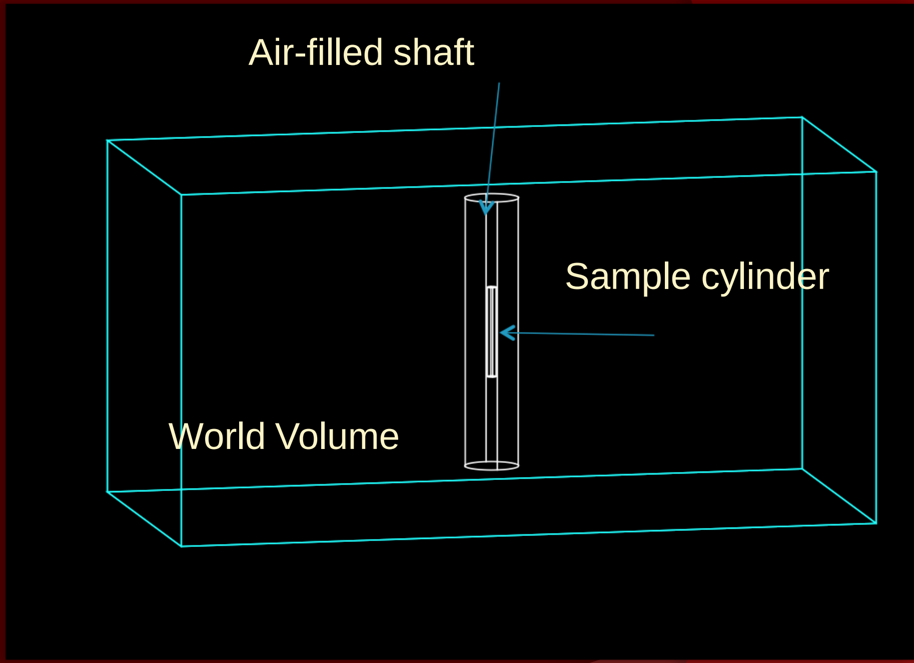
MCNP5 & GEANT4 Synergism for TRIGA Central Irradiator Model



Schematic of central irradiator



MCNP5 model of central irradiator



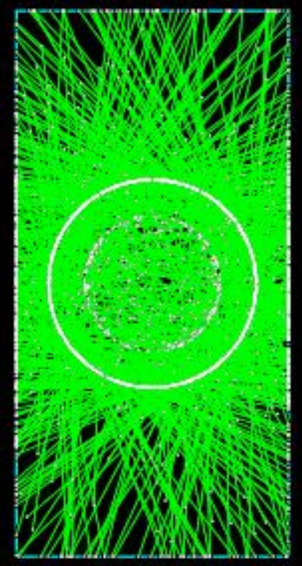
To calculate flux-per-source-neutron, for scaling results to actual flux values for TRIGA

MCNP5 to GEANT4 Scaling of Flux

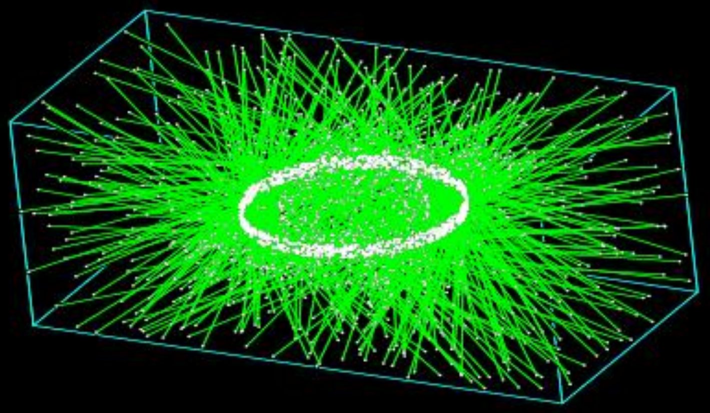
- In GEANT4, a homogeneous flux is simulated by selecting massive number of particles
- MCNP5 simulation of irradiator used to calculate flux per source particle
  - Central facility →1.07745 * 10^{-3} neutrons / cm^2 * sec per particle
  - Dividing known flux for irradiator by flux per particle yields number of particles necessary for GEANT4 modeling

TRIGA Central Irradiator GENAT4 Model

Side view, 1000 neutrons

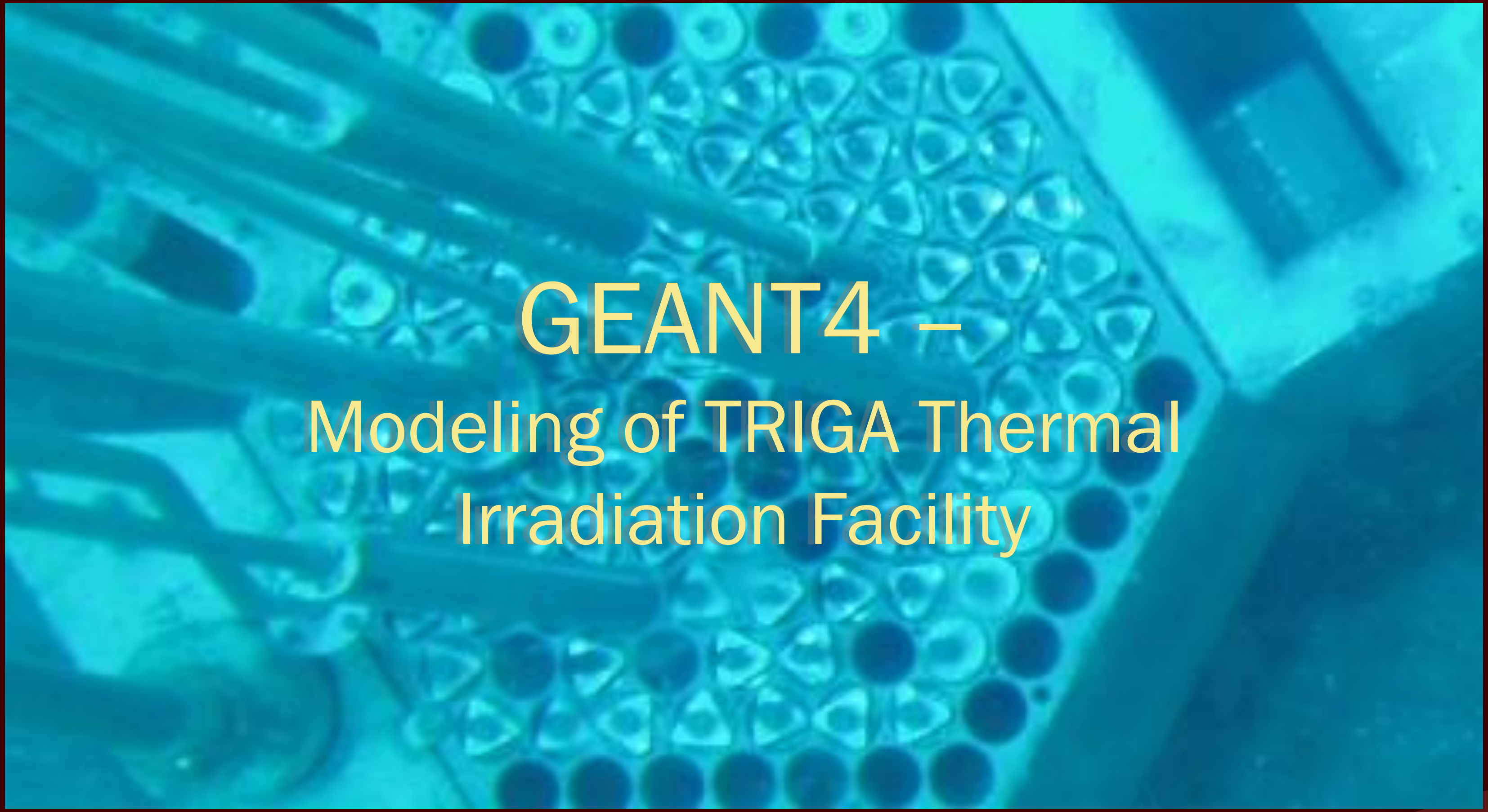


Top view, 1000 neutrons

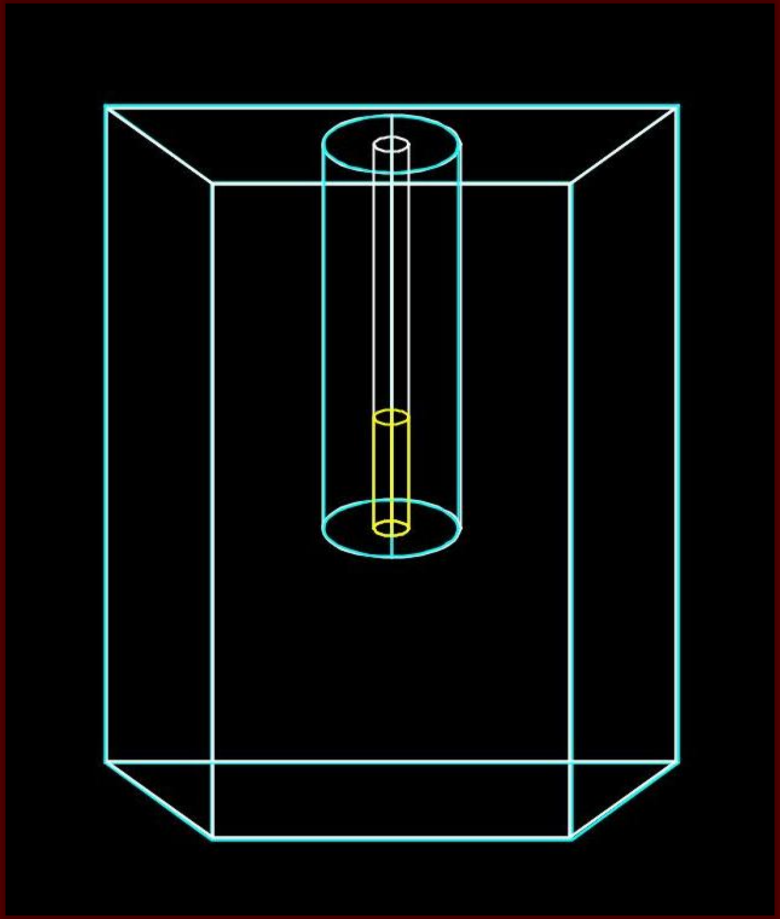


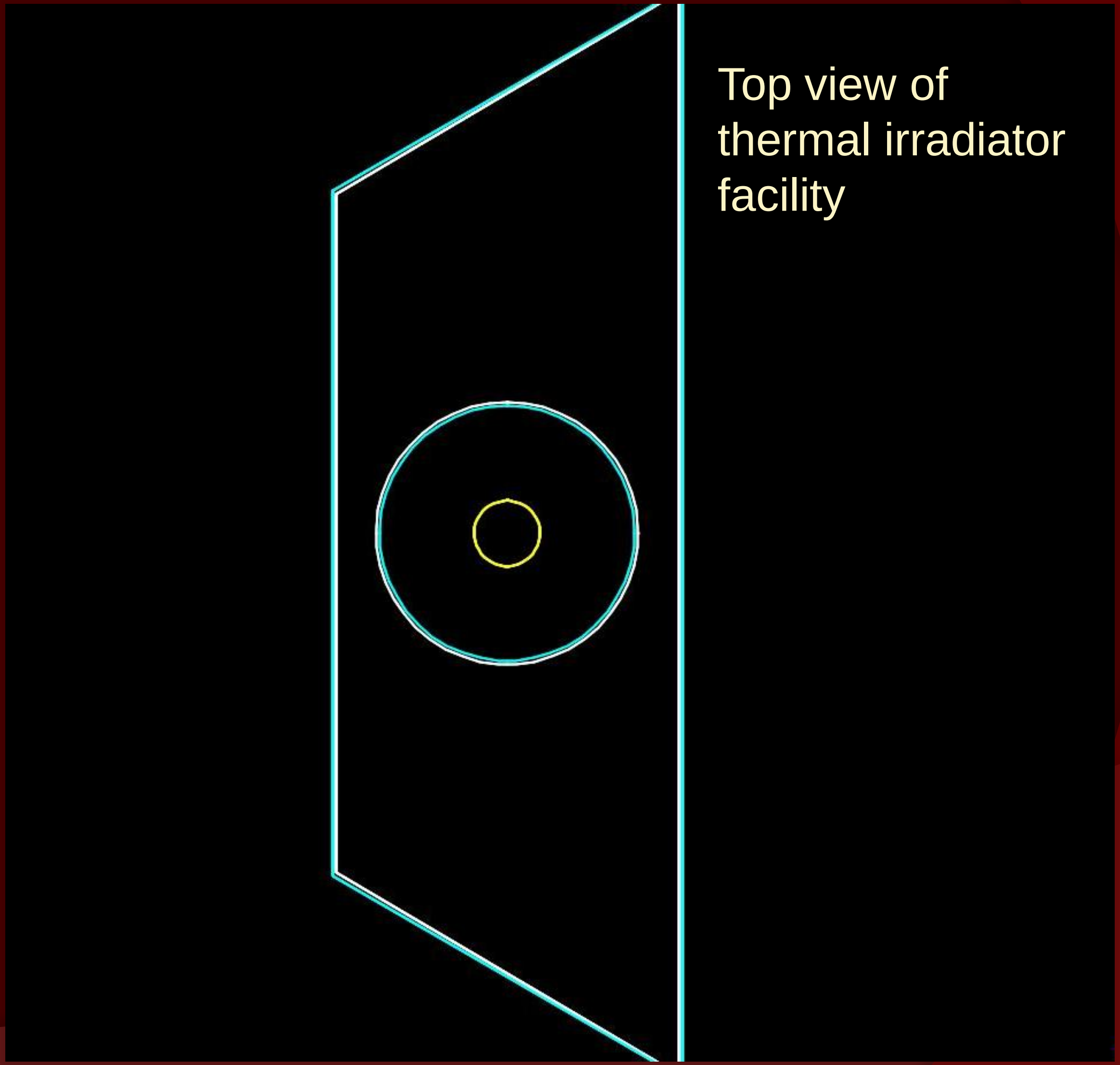
Isometric view, 1000 neutrons

University of Utah TRIGA



TRIGA Thermal Irradiator Facility - GEANT4 Model





TRIGA Thermal Irradiator Facility - GEANT4 Model

Particle Tracks

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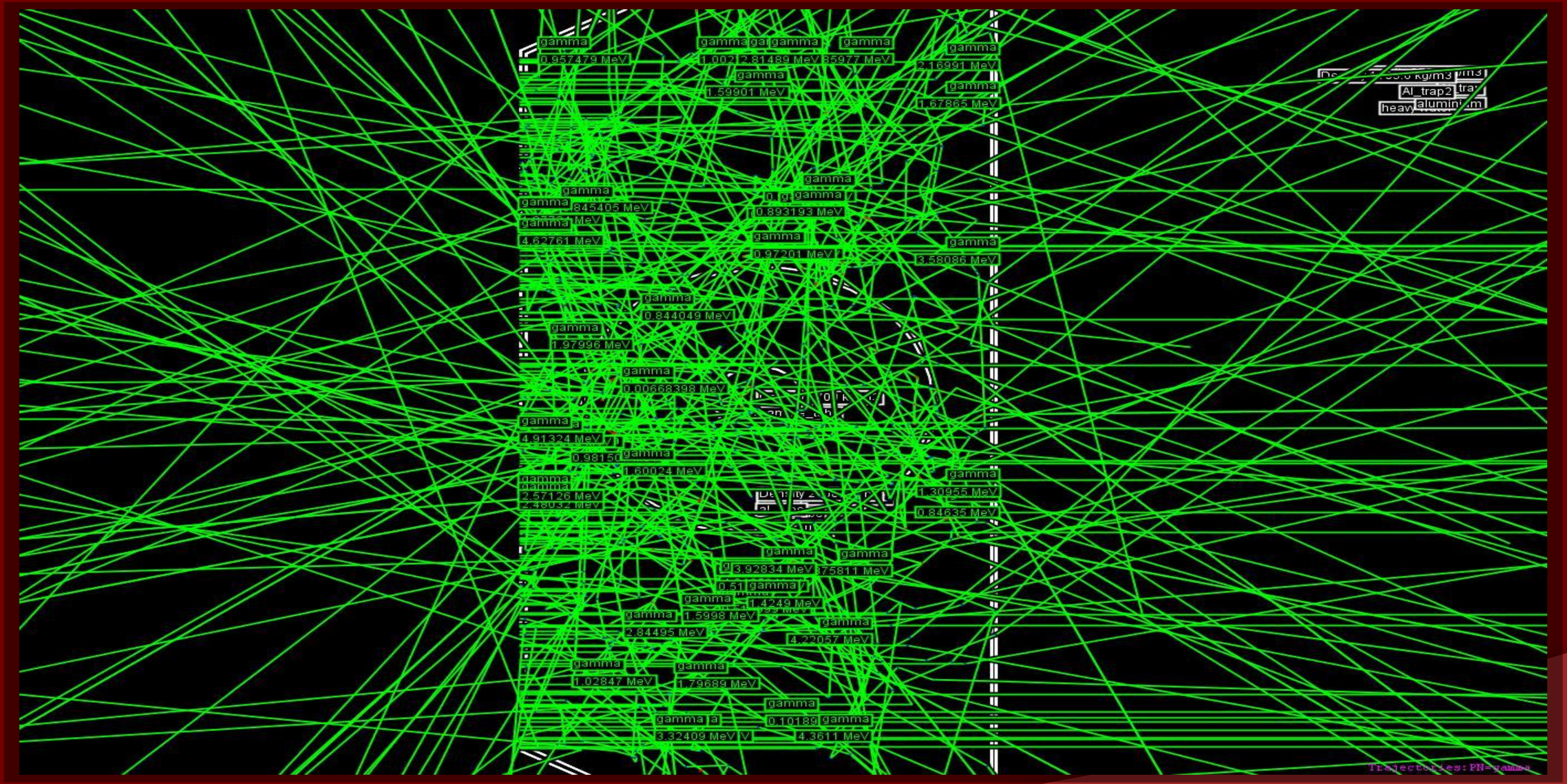
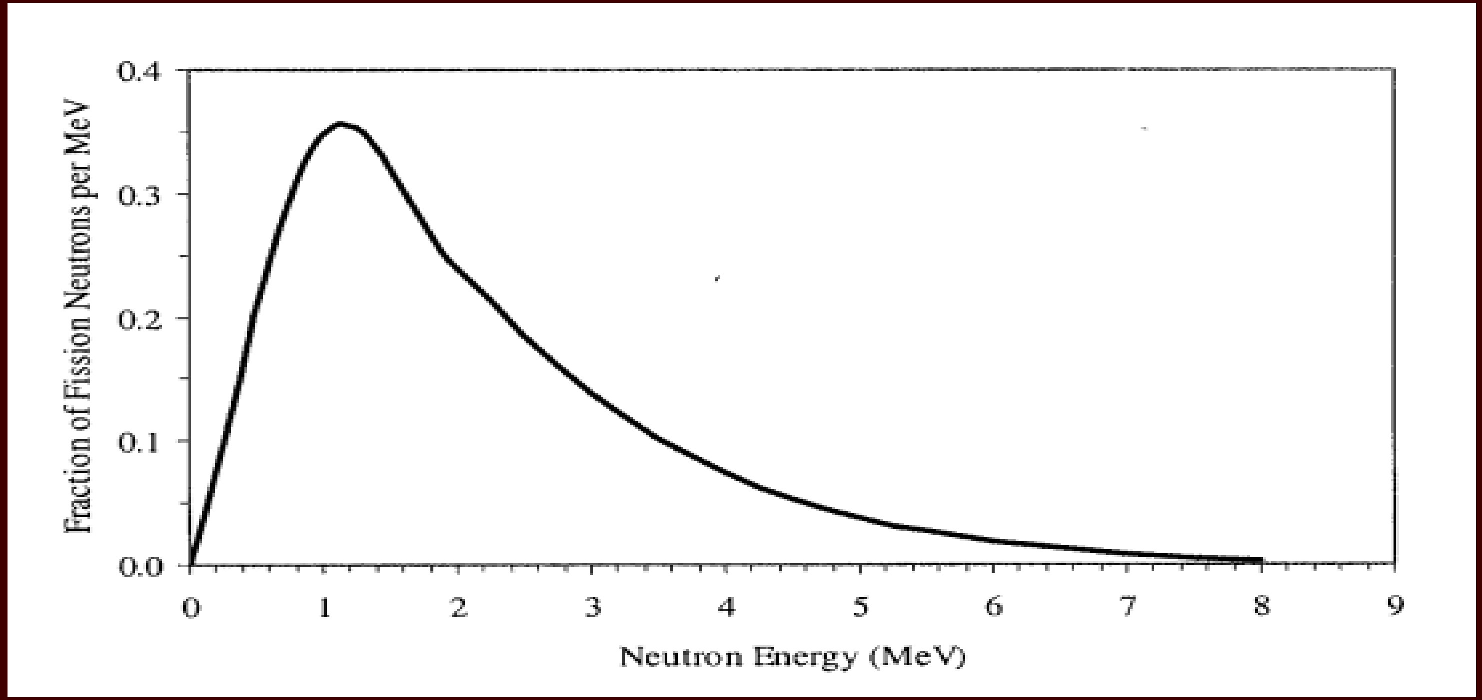


Achieved planar neutron source

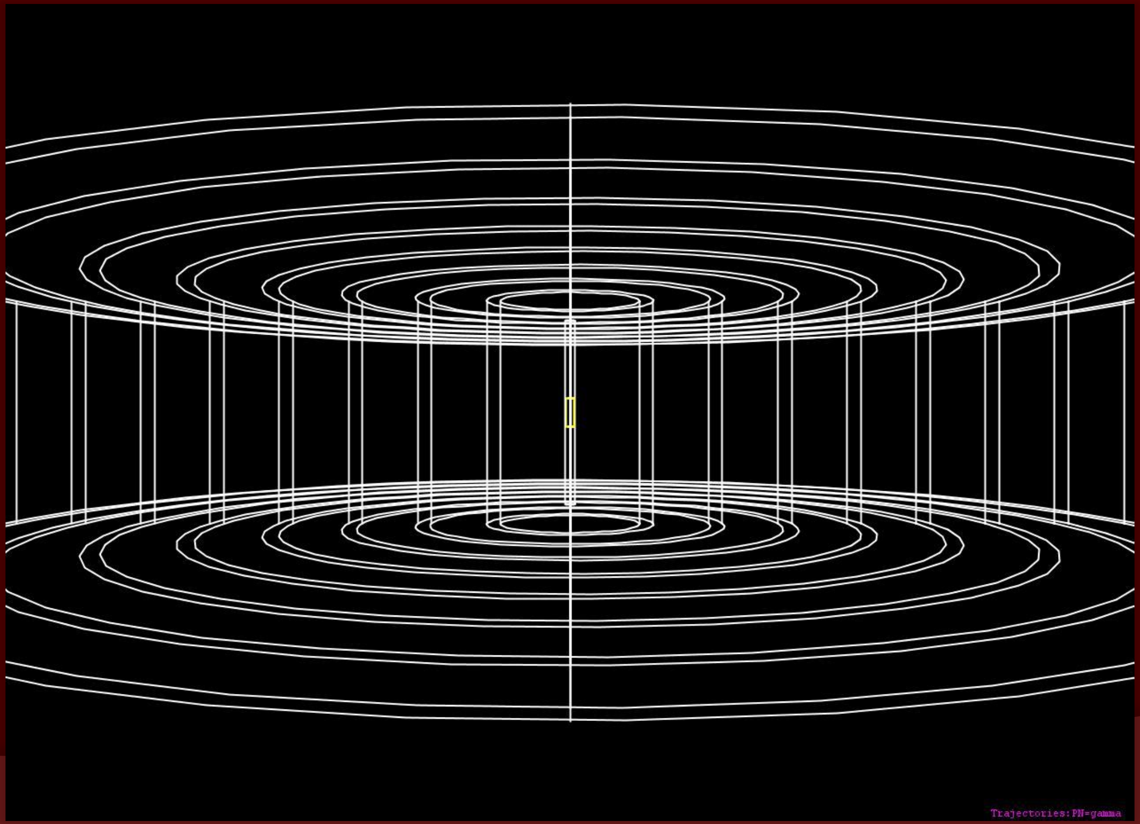
Neutron Energy Distributions in GEANT4 Models for CI and TI in TRIGA



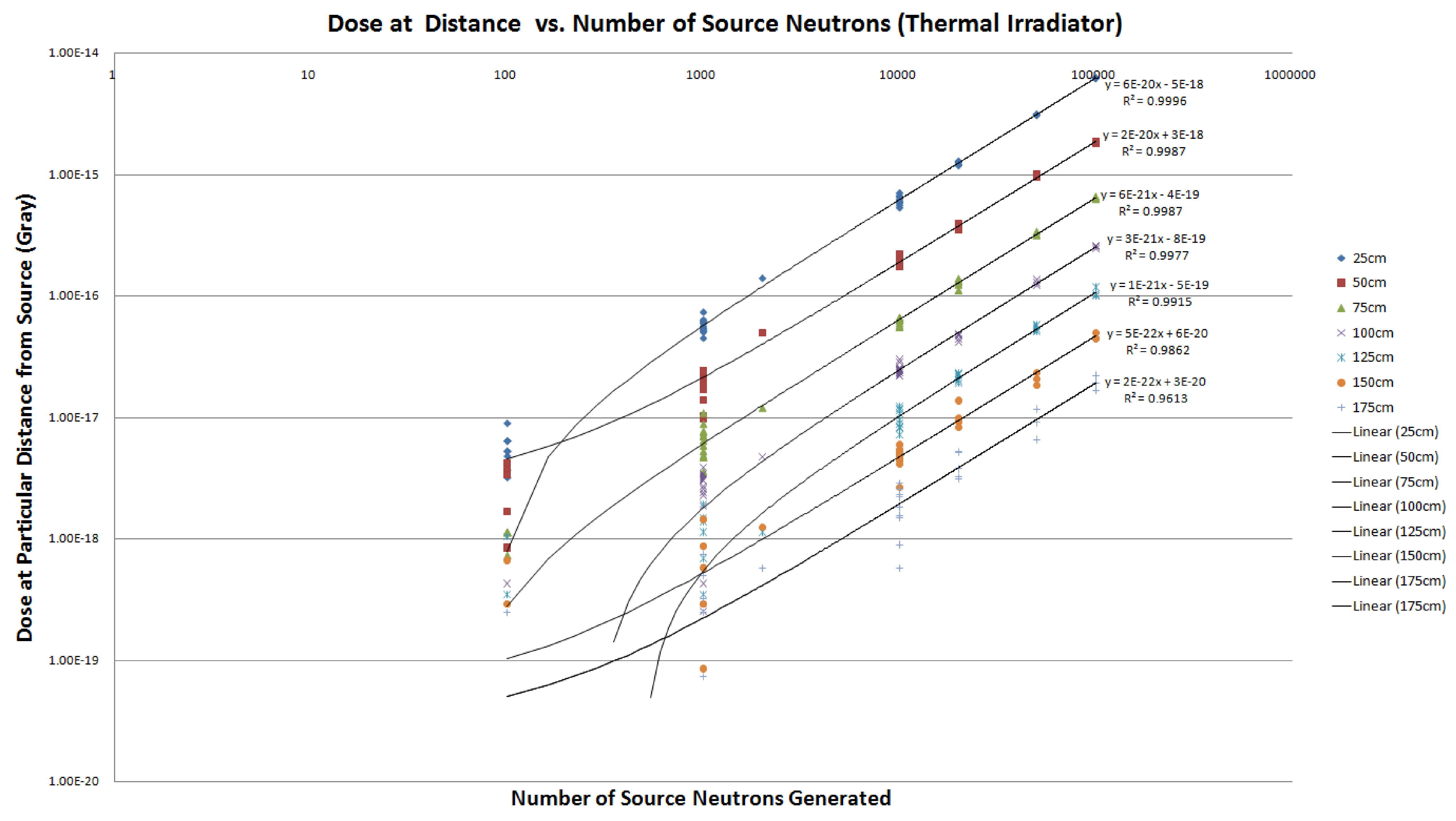
Watt model of thermal fission neutron energy spectrum.
Source: Tatjana Jevremovic, “Nuclear Principles in Engineering”

GEANT4 Detectors: Scoring / Dose Deposition

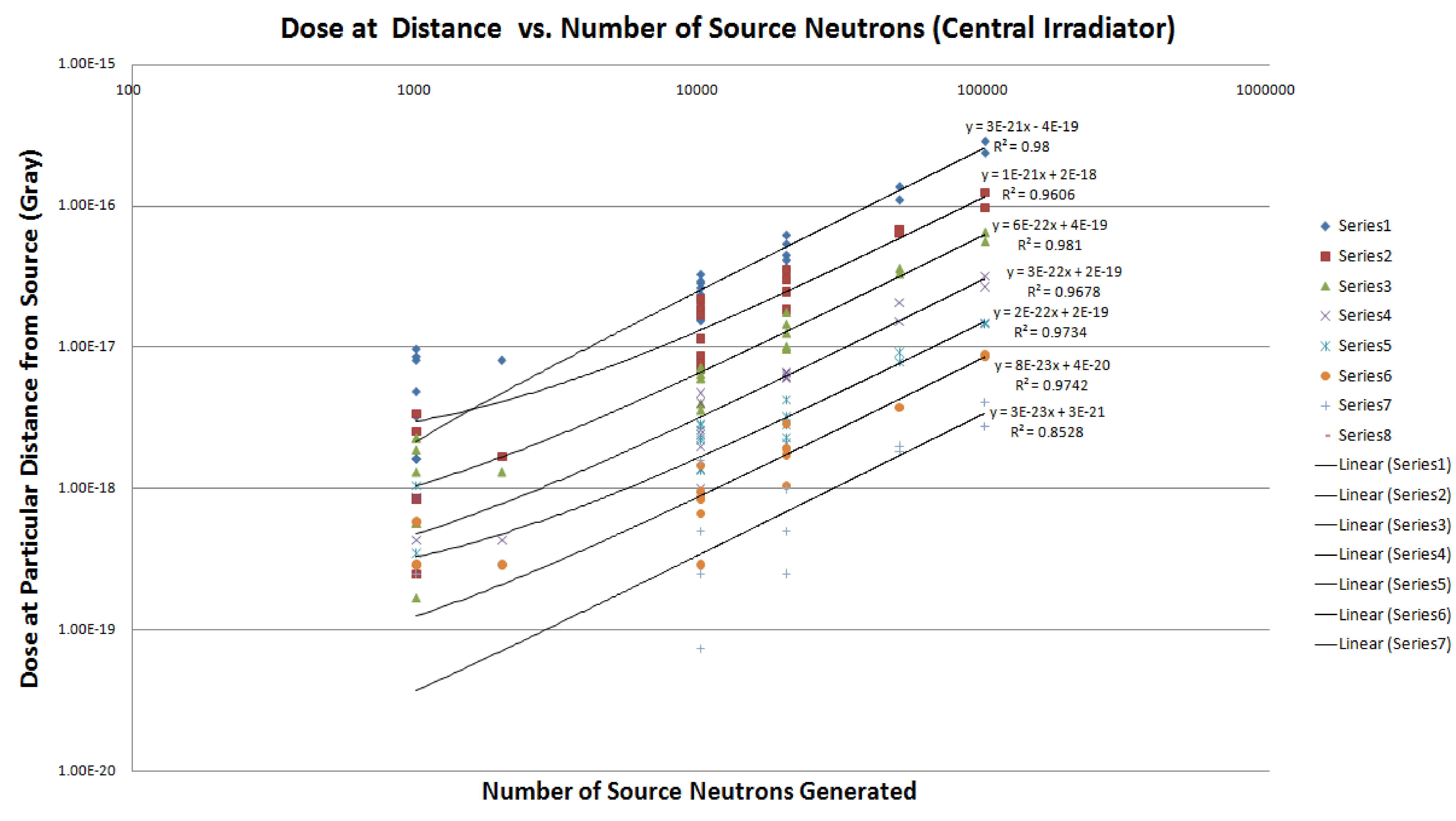
- Using sensitive detectors (sensitive to only gammas) to calculate dose deposition at various distances from sample
- Set up concentric tube detectors at various distances from center of sample, to calculate dose at various distances



- Example detector array, for central irradiator model
  - Array is same for thermal model, other than geometry of the actual irradiation facility



Dose at Distance vs. Number of Source Neutrons (Thermal Irradiator)
Dose at Particular Distance from Source (Gray)
Number of Source Neutrons Generated
1.00E-14
1.00E-15
1.00E-16
1.00E-17
1.00E-18
1.00E-19
1.00E-20
1
10
100
1000
10000
100000
1000000
y = 6E-20x - 5E-18
R² = 0.9996
y = 2E-20x + 3E-18
R² = 0.9987
y = 6E-21x - 4E-19
R² = 0.9987
y = 3E-21x - 8E-19
R² = 0.9977
y = 1E-21x - 5E-19
R² = 0.9915
y = 5E-22x + 6E-20
R² = 0.9862
y = 2E-22x + 3E-20
R² = 0.9613
25cm
50cm
75cm
100cm
125cm
150cm
175cm
Linear (25cm)
Linear (50cm)
Linear (75cm)
Linear (100cm)
Linear (125cm)
Linear (150cm)
Linear (175cm)
Linear (175cm)



Dose at Distance vs. Number of Source Neutrons (Central Irradiator)
Dose at Particular Distance from Source (Gray)
Number of Source Neutrons Generated
1.00E-15
1.00E-16
1.00E-17
1.00E-18
1.00E-19
1.00E-20
100
1000
10000
100000
1000000
y = 3E-21x - 4E-19
R² = 0.98
y = 1E-21x + 2E-18
R² = 0.9606
y = 6E-22x + 4E-19
R² = 0.981
y = 3E-22x + 2E-19
R² = 0.9678
y = 2E-22x + 2E-19
R² = 0.9734
y = 8E-23x + 4E-20
R² = 0.9742
y = 3E-23x + 3E-21
R² = 0.8528
Series1
Series2
Series3
Series4
Series5
Series6
Series7
Series8
Linear (Series1)
Linear (Series2)
Linear (Series3)
Linear (Series4)
Linear (Series5)
Linear (Series6)
Linear (Series7)

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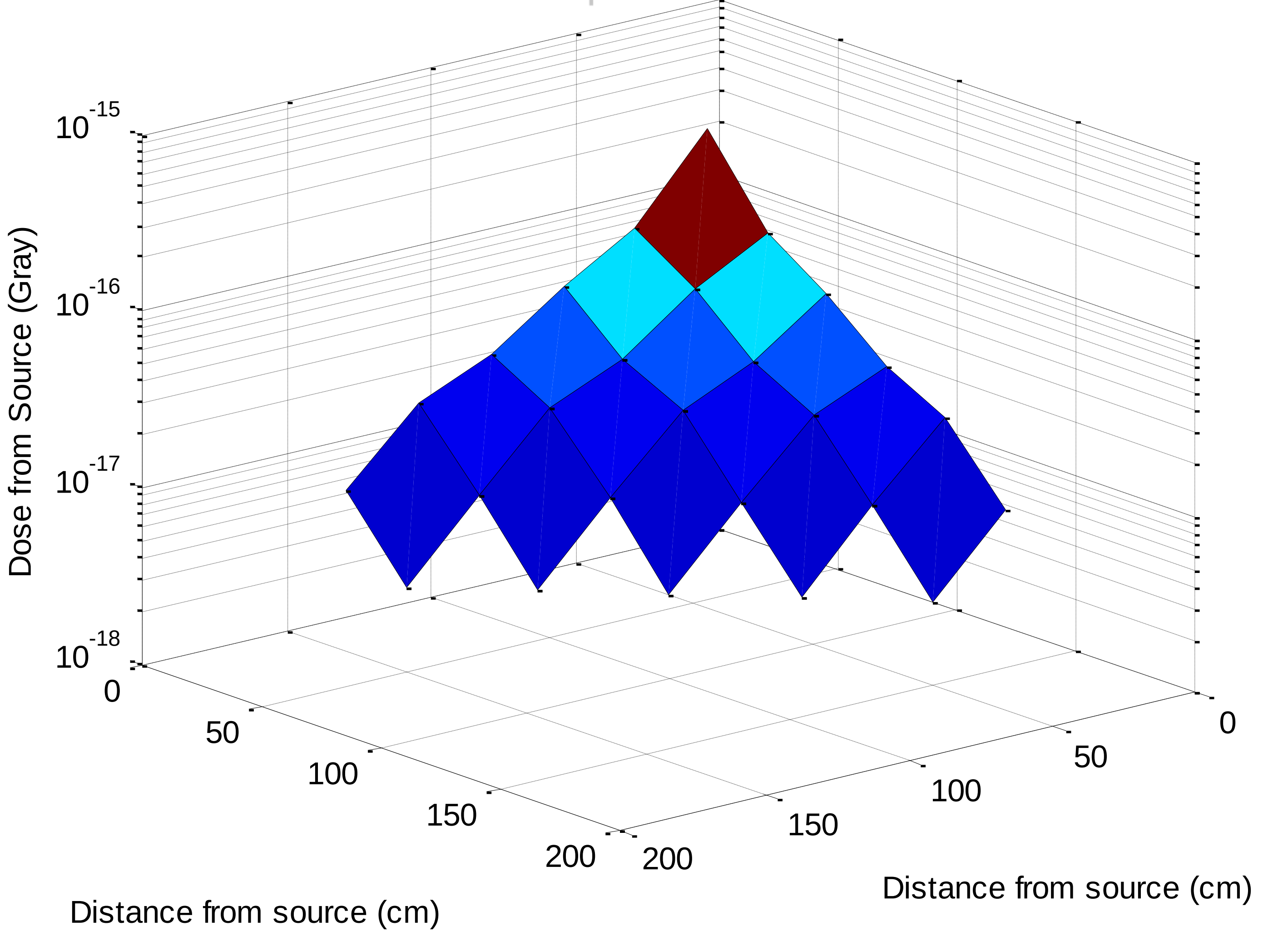
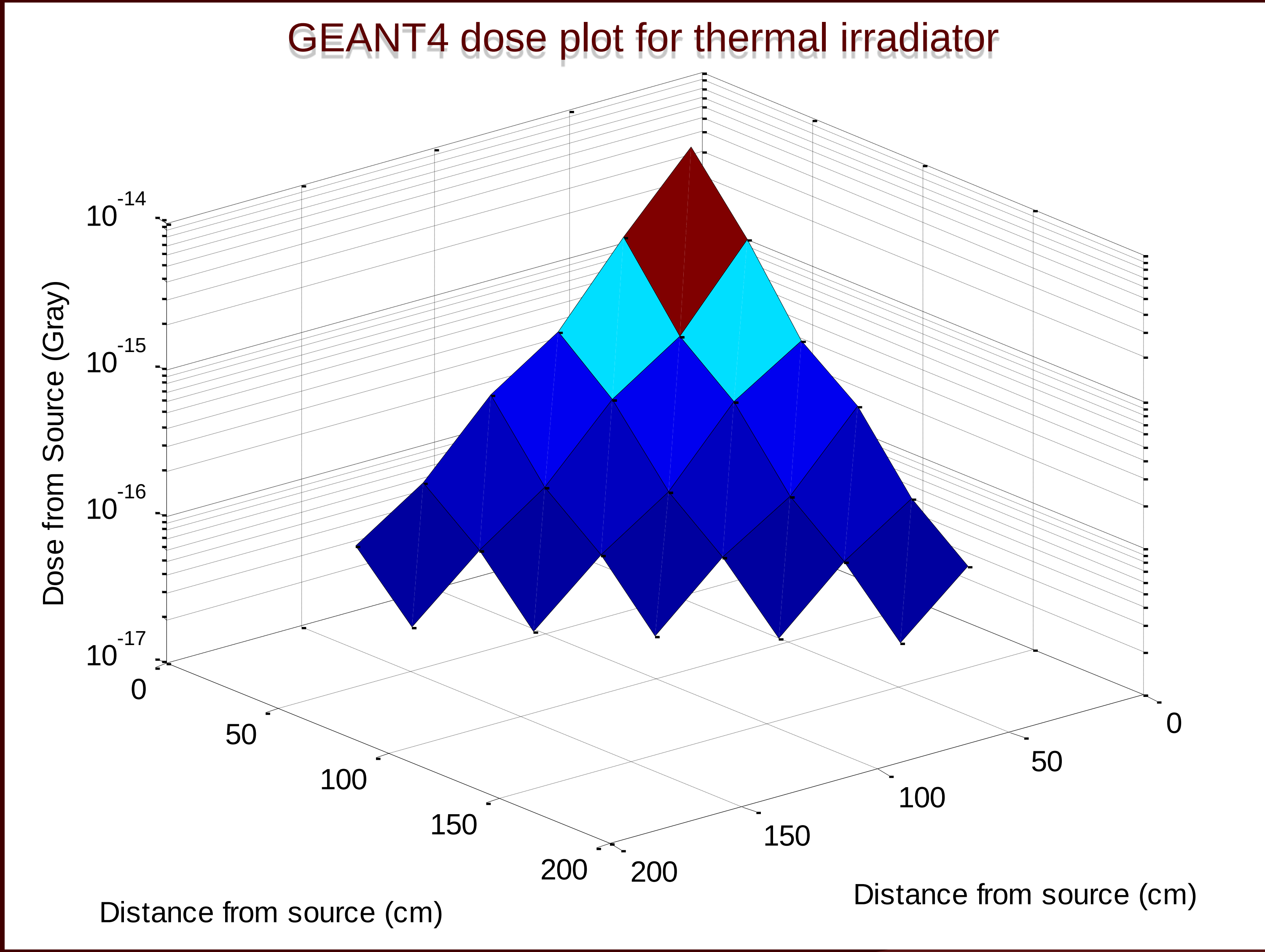
GEANT4 Dose plot for central irradiator



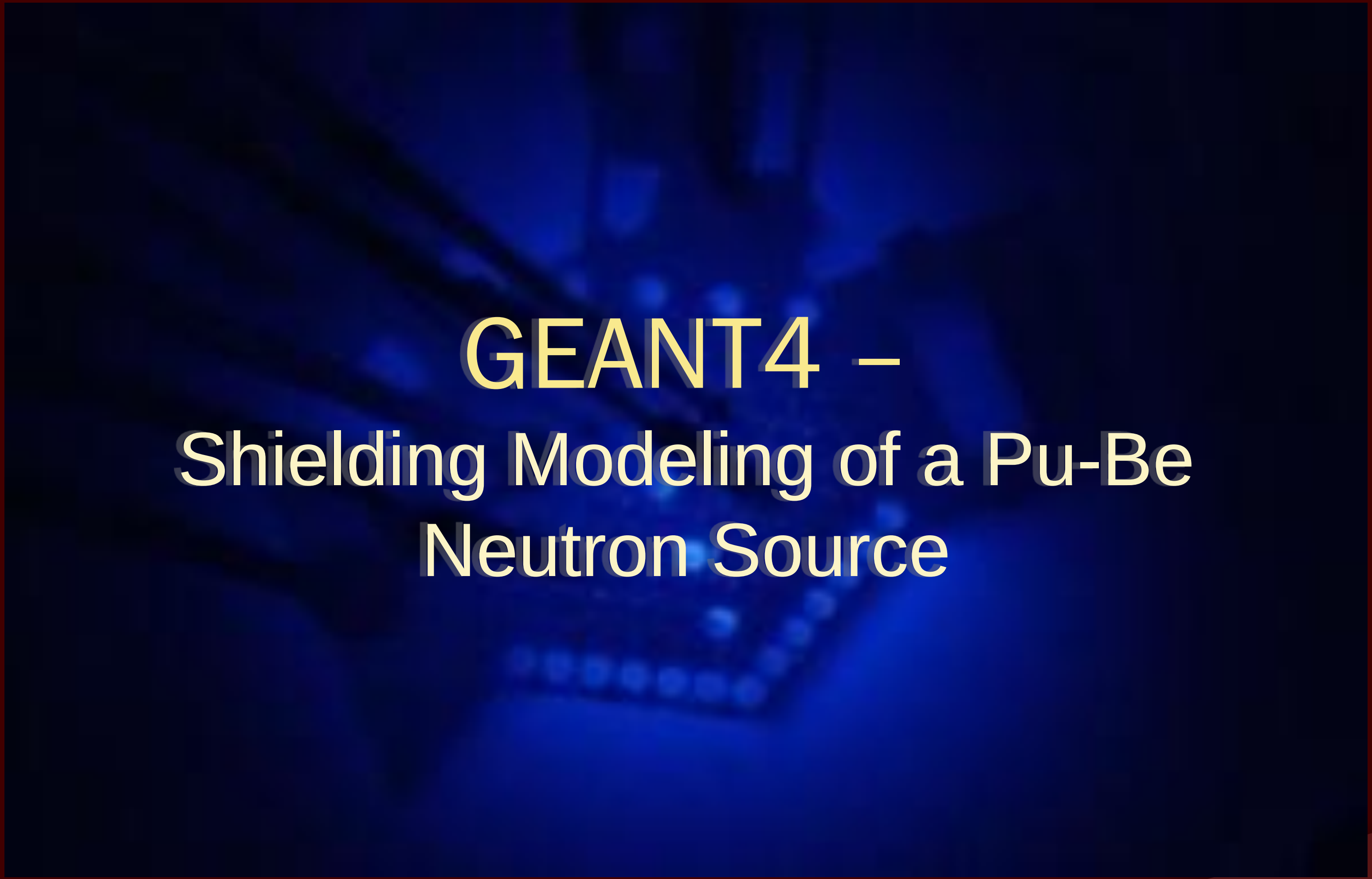

GEANT4 dose plot for thermal irradiator
Dose from Source (Gray)
10^-14
10^-15
10^-16
10^-17
0
50
100
150
200
Distance from source (cm)
0
50
100
150
200
Distance from source (cm)

Example Dose Results

- At 25cm from the irradiated sample, absorbed dose for 0.154 μs irradiation time of aluminum sample from thermal irradiator is $5.995 \cdot 10^{-15}$ Gray.
- For a 2 hour irradiation time common for NAA, this equals a dose rate of $0.139\ ^{Sv}/_{hr} = 1.39 \cdot 10^{4}\ ^{mrem}/_{hr}$.

- At University of Utah TRIGA, Area Radiation Monitors SCRAM reactor for detection of > 10 $^{mrem}/_{hr}$ dose rates
  - In this case, samples are suspended at half depth in reactor pool to cool until < 10 $^{mrem}/_{hr}$
  - For 1 $^{mrem}/_{hr}$ < dose rates < 10 $^{mrem}/_{hr}$, samples are cooled inside 4”-thick lead box until < 1 $^{mrem}/_{hr}$
  - Samples < 1 $^{mrem}/_{hr}$ are deemed safe

University of Utah TRIGA



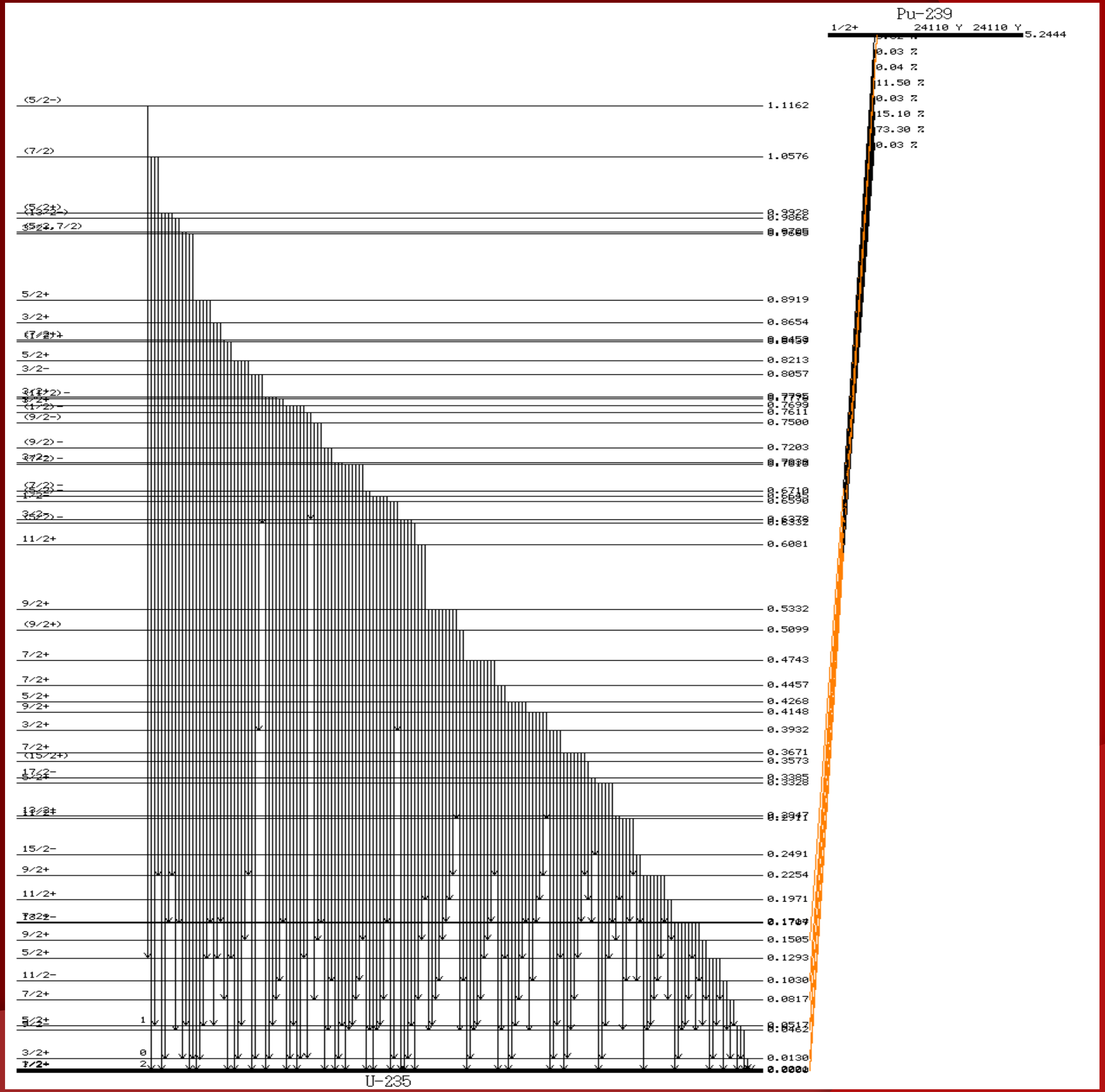
GEANT4 –
Shielding Modeling of a Pu-Be Neutron Source

Pu-Be Source

- Pu-Be neutron source at UNEP exhibits three different neutron flux values:
  - $6.700 \cdot 10^{6}$ neutrons / $_{\text{cm\^{}2 * sec}}$
  - $3.350 \cdot 10^{6}$ neutrons / $_{\text{cm\^{}2 * sec}}$
  - $1.675 \cdot 10^{6}$ neutrons / $_{\text{cm\^{}2 * sec}}$
- The simulation is performed for each of these flux values, and the resulting absorbed doses are reported.

Pu-Be Source (cont.)

$^{239}Pu \rightarrow\, ^{235}U + \alpha$



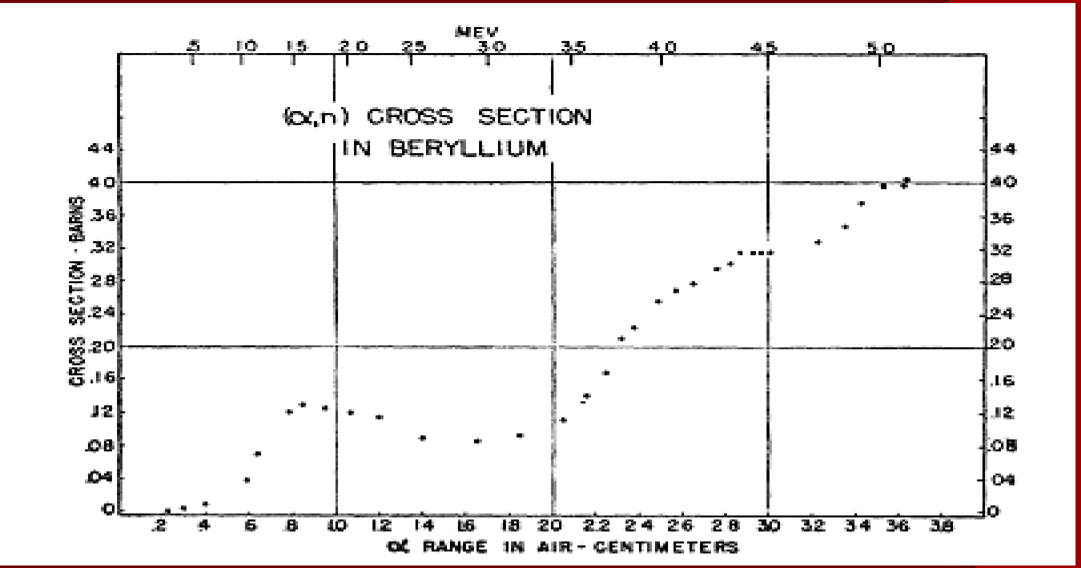
^{239}Pu α decay diagram, $T_{1/2}$ = 24110 years

Source: http://atom.kaeri.re.kr/cgi-bin/decay?Pu-239%20A

Pu-Be Source (cont.)

$^{9}Be + \alpha \rightarrow {}^{12}C + n + \gamma$

- C-12 and Be-9 are stable isotopes, and produce no decay products.
  - Decay products from original Pu-Be source include all isotopes in U-235 decay chain, as well as neutrons and gammas.
- Both Plutonium and Beryllium, as well as many of the decay products are both chemically toxic (Beryllium and Plutonium when inhaled deposit in the lungs and cause severe respiratory inflammation and pneumonia-like symptoms due to exposure), and many can cause cancer.



Source: The (α, n) cross sections of Beryllium, Magnesium, and Aluminum, I. Halpern, Phys. Rev., Vol 76.2, 1949.

U-235 Decay Chain

Uranium^{235} Decay Chain (Actinium Series)

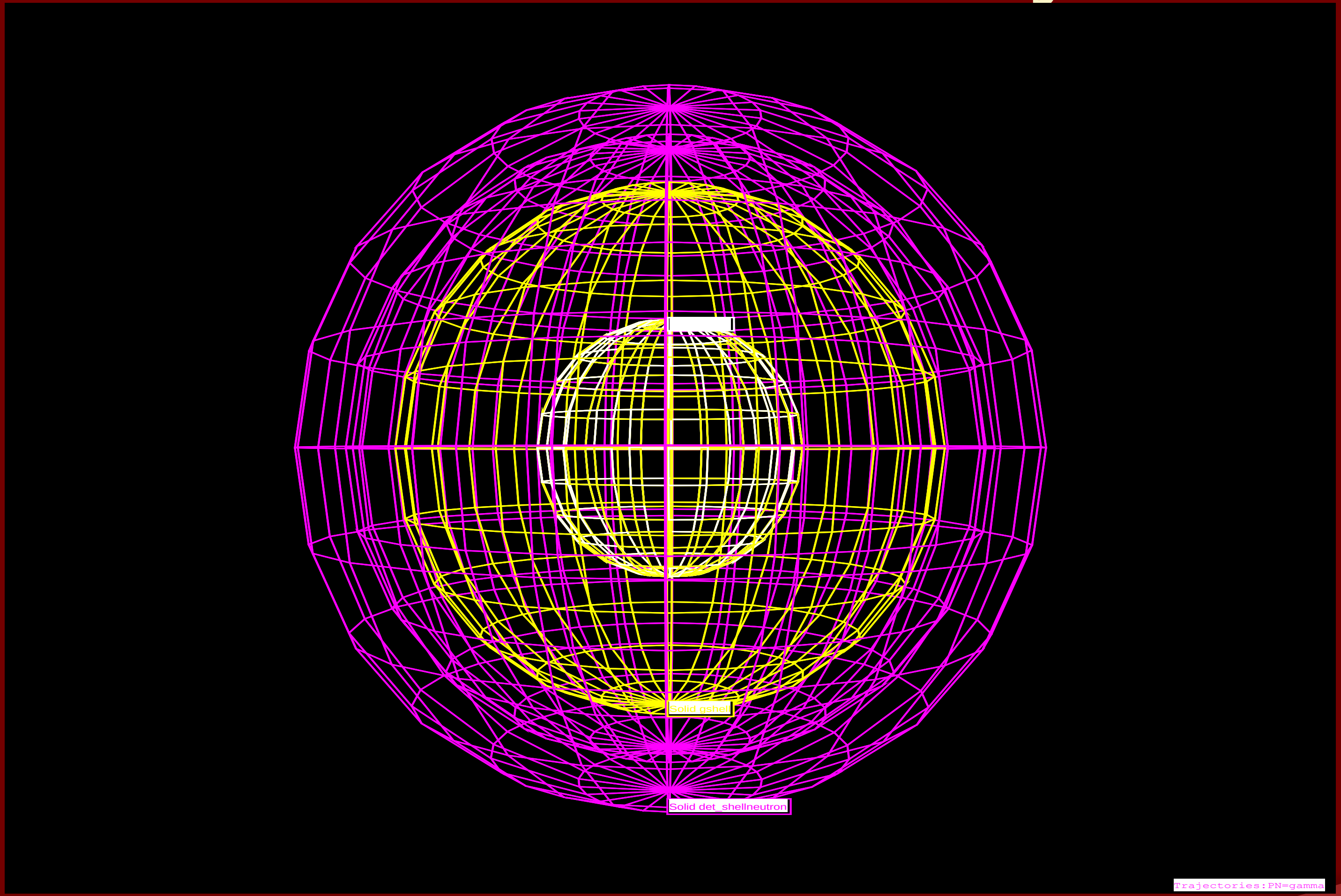
RE: www.periodictable.com

The 4n+2 chain of U^{235} is commonly called the "Actinium Series"

Nuclide	Element Name	Historic Name	Decay Mode	Half Life	MeV	Product of Decay
$_{92}U^{235}$	Uranium - 235	*Pitchblende, Actin Uranium*	α	7.04 x 10^8 yrs	4.67826	$_{90}Th^{231}$
$_{90}Th^{231}$	Thorium - 231	*Uranium Y*	$β^-$	1.06331 d	0.39156	$_{91}Pa^{231}$
$_{91}Pa^{231}$	Protactinium - 231	*Brevium*	α	32,788 yrs	5.14987	$_{89}Ac^{227}$
$_{89}Ac^{227}$	Actinium - 227	*Emanium*	$β^-$ 98.62% α 1.38%	21.7865 yrs	0.044765 5.04219	$_{90}Th^{227}$ $_{87}Fr^{223}$
$_{90}Th^{227}$	Thorium - 227	*Radioactinium*	α	18.681 d	6.1466	$_{88}Ra^{223}$
$_{87}Fr^{223}$	Francium - 223	*Eka-Caesium, Actinium-K*	$β^-$ 99.994% α 0.006%	21.7 min	1.149171 5.56187	$_{88}Ra^{223}$ $_{85}At^{219}$
$_{88}Ra^{223}$	Radium - 223	*Actinium X*	α	11.431 d	5.97899	$_{86}Rn^{219}$
$_{85}At^{219}$	Astatine - 219	*Eka-Iodine, Dakin*	α 97% $β^-$ 3%	0.933 min	6.3236 1.5663	$_{83}Bi^{215}$ $_{86}Rn^{219}$
$_{86}Rn^{219}$	Radon - 219	*Actinon*	α	3.96 sec	6.94612	$_{84}Po^{215}$
$_{83}Bi^{215}$	Bismuth - 215		$β^-$	7.667 min	2.1888	$_{84}Po^{215}$
$_{84}Po^{215}$	Polonium - 215	*Actinium A*	α 99.99977% $β^-$ 0.00023%	1.781 msec	7.52626 0.71484	$_{82}Pb^{211}$ $_{85}At^{215}$
$_{85}At^{215}$	Astatine - 215		α	100 μsec	8.17838	$_{83}Bi^{211}$
$_{82}Pb^{211}$	Lead - 211	*Actinium B*	$β^-$	31.167 min	1.36697	$_{83}Bi^{211}$
$_{83}Bi^{211}$	Bismuth - 211	*Actinium C*	α 99.724% $β^-$ 0.276%	2.14 min	6.75033 0.57409	$_{81}Tl^{207}$ $_{84}Po^{211}$
$_{84}Po^{211}$	Polonium - 211	*Actinium C'*	α	516 msec	7.59448	$_{82}Pb^{207}$
$_{81}Tl^{207}$	Thallium - 207	*Actinium C''*	$β^-$	4.767 min	1.41824	$_{82}Pb^{207}$
$_{82}Pb^{207}$	Lead - 207		—	Stable	—	—

Source: http://www.periodictable.com/Isotopes/092.235/index.p.full.html

Simulation Geometry



HepRApp wireframe rendering of simulation geometry. Innermost shell (white) is paraffin shell, next outer shell (yellow) is lead shell, next outer shell (purple) is sensitive gamma and neutron detector

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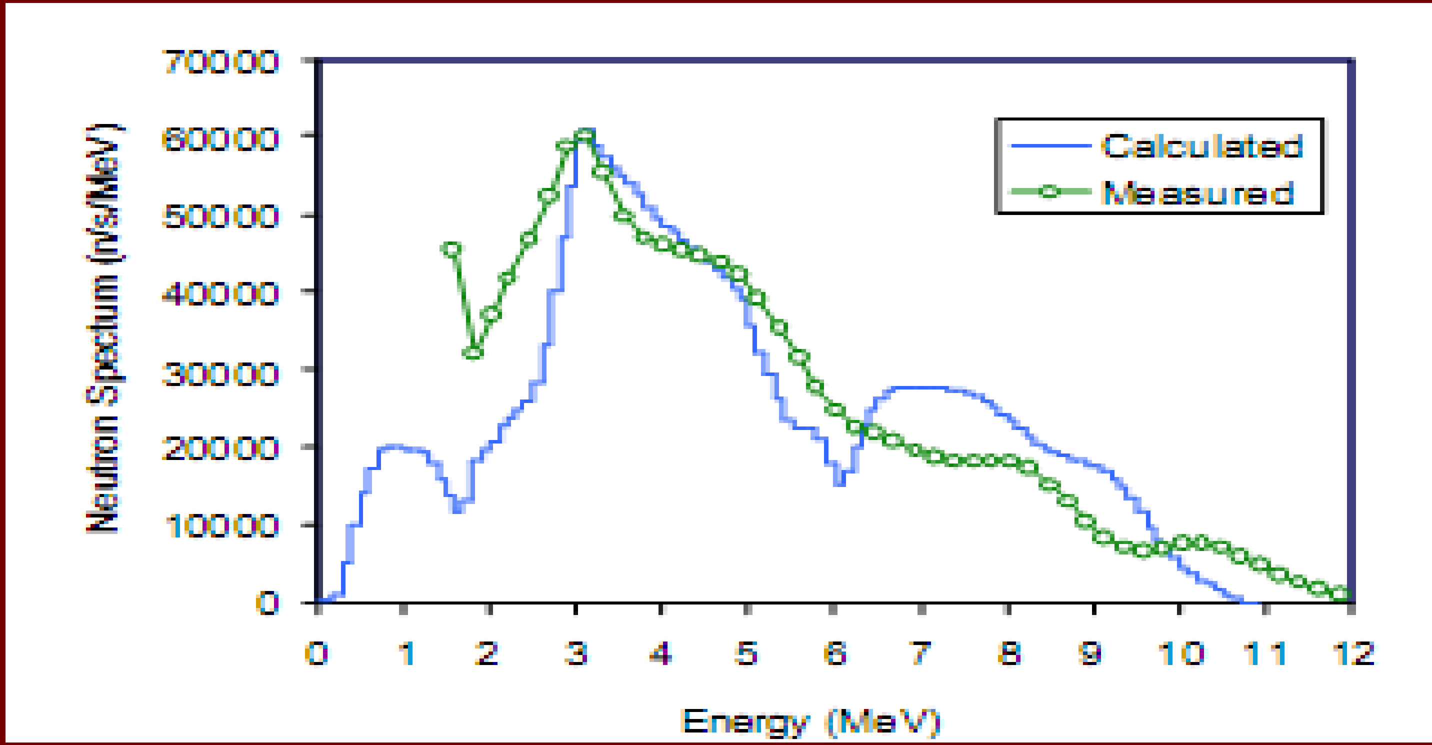
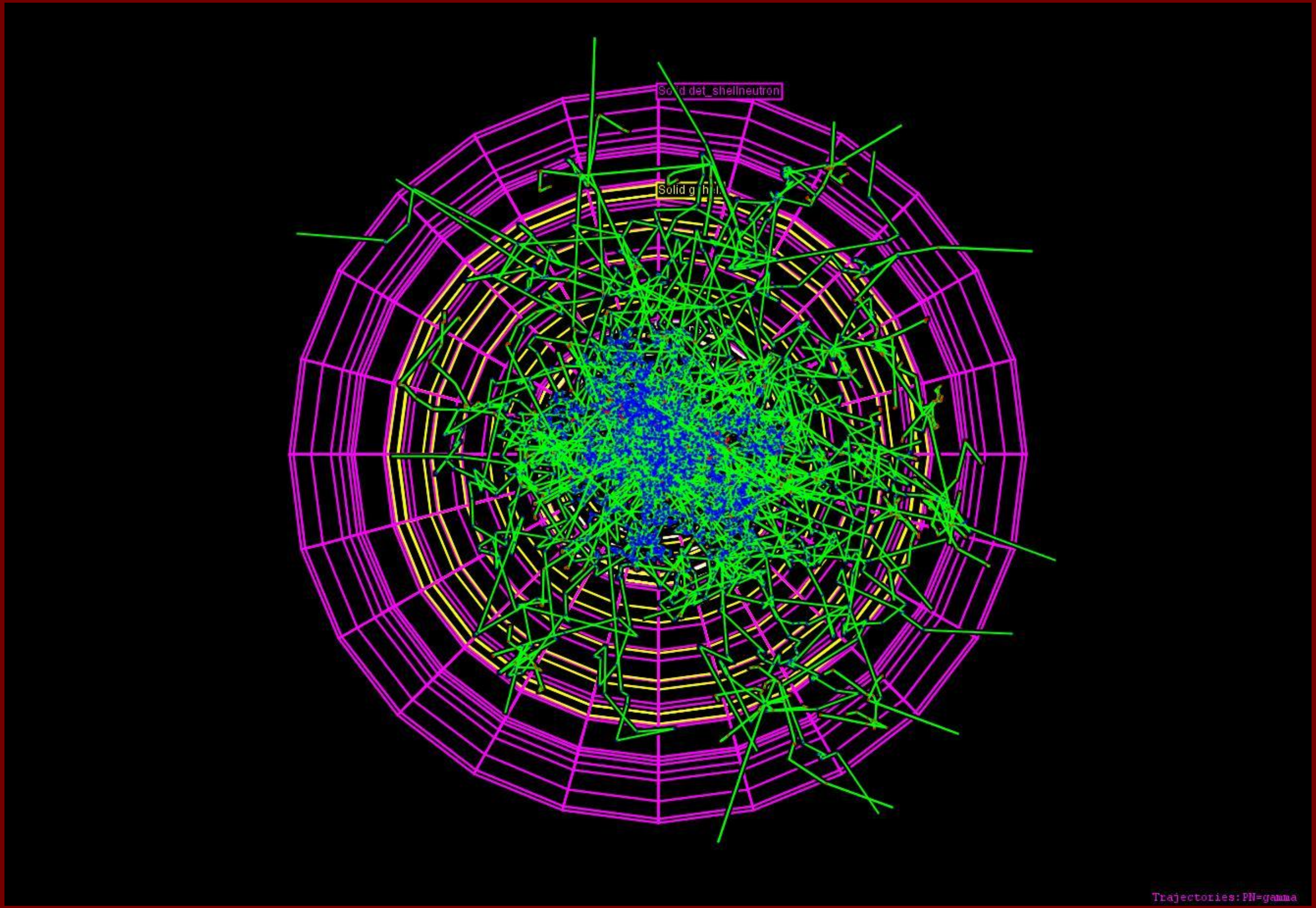
Neutron Energy Distributions



Used monoenergetic 3 MeV neutron source, as per project specifications

Pu-Be neutron energy spectrum
Source: New Neutron Source Algorithms In the ORIGEN-S Code, http://ornl.gov/sci/scale/papers/RPSD2002_Origen_Sources.pdf

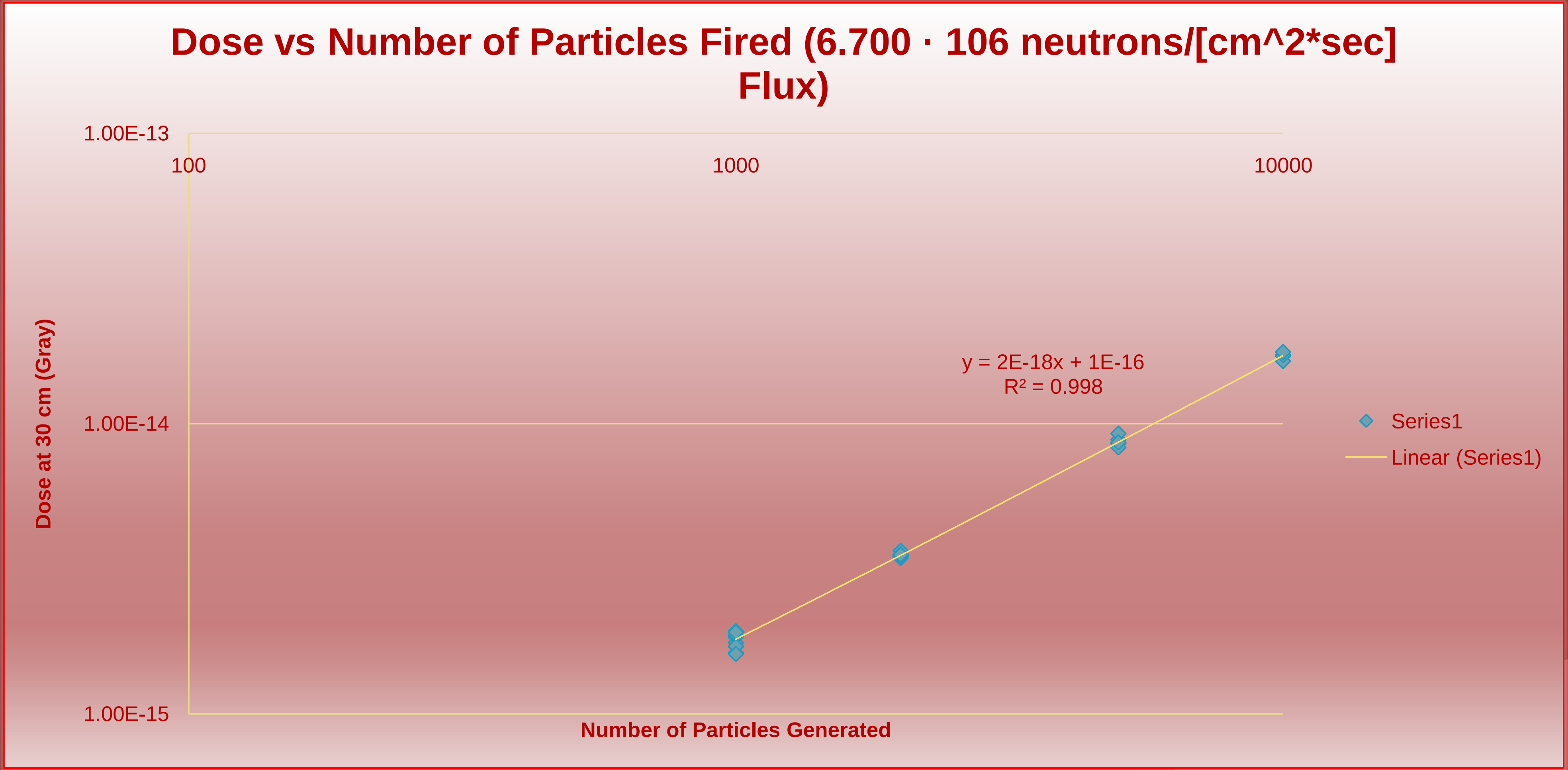
Results



- *Top-down view of experimental setup for $6.700 \cdot 10^6$, with particle tracks. Red lines indicate negatively-charged particle trajectory, green lines indicate neutrally-charged particle trajectory, blue lines indicate positively-charged particle trajectory, yellow dots indicate the actual step points used by Geant4.*

- Note how vast majority of neutrons and gammas are contained within the paraffin shell, and nearly all within lead shell.

Results (cont.)



Results (cont.)

Neutron Flux ()	Thickness of Paraffin Shell (cm)	Thickness of Lead Shell (cm)	Absorbed dose at 30 cm ()
$6.700 \cdot 10^6$	15	15	0.00183
$3.350 \cdot 10^6$	15	15	0.00091
$1.675 \cdot 10^6$	15	15	0.00046

- At University of Utah TRIGA, Area Radiation Monitors SCRAM reactor for detection of > 10 $^{mrem}/_{hr}$ dose rates
  - In this case, samples are suspended at half depth in reactor pool to cool until < 10 $^{mrem}/_{hr}$
  - For 1 $^{mrem}/_{hr}$ < dose rates < 10 $^{mrem}/_{hr}$, samples are cooled inside 4”-thick lead box until < 1 $^{mrem}/_{hr}$
  - Samples < 1 $^{mrem}/_{hr}$ are deemed safe

Future Work

- Expand the current model to include the fast neutron irradiation facility at Utah TRIGA facility.
- Benchmark simulation results against experimental results
  - Make this application suitable for export, to provide method of benchmarking experiments at irradiation facilities.
- Examine and assess assumptions and simplifications made in this first version of the simulation
  - Will make simulation as realistic and versatile as possible
  - I intend to accomplish this task this summer, and, ideally, get published when finished.
- Implement histograms of gamma energies, to deliver energy spectra of gamma energies
  - Create nuclear signatures for nuclear forensics