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Solution of Multivariate Inverse Radiation Transport Problems

John Mattingly, Dean Mitchell, Chris Stork, and Ed Thomas

Sandia National Laboratories, Albuquerque, New Mexico, USA

Sara Pozzi, Shaun Clarke, and Eric Miller

University of Michigan, Ann Arbor, Michigan, USA

Glenn Sjoden and Ce Yi

University of Florida, Gainesville, Florida, USA

Workshop on Models and Methods of Non-destructive Assay in Nuclear Safeguards and Non-proliferation

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Inverse Radiation Transport Problems

- Objective: infer the configuration of an unknown radiation source from its measured radiation signatures

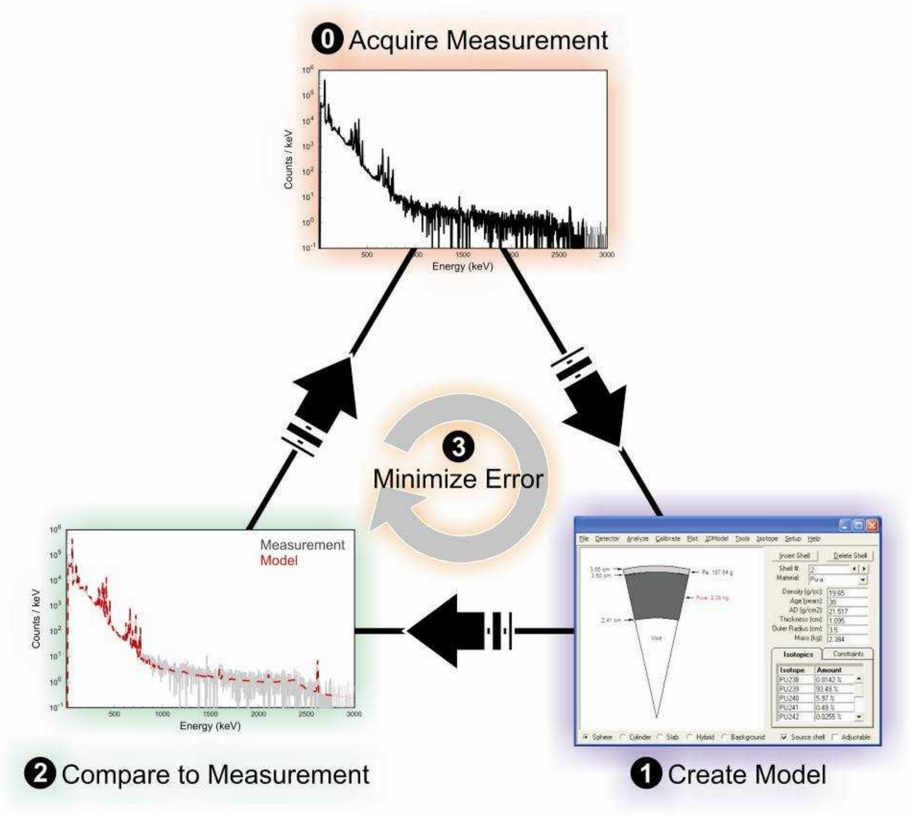
- Source features
  - Isotopic composition
  - Fissile mass & multiplication
  - Geometric arrangement of radiating and shielding materials

- Radiation signatures
  - Gamma spectrometry
  - Neutron time-correlation and multiplicity counting

- Applications
  - Non-intrusive, non-destructive inspection & interrogation
  - Nonproliferation & counterterrorism

Solution Method

- Start with an initial model of the source; treat some model parameters as variable
- Estimate the radiation field incident on the detector(s) using radiation transport calculations
- Fold the radiation field with a model of the detector response function(s) to calculate the radiation signature(s)
- Iteratively minimize the error between the calculated and measured signature(s) using nonlinear regression



Components of the Inverse Transport Framework

Radiation Transport

- Discrete ordinates transport solvers are used to compute the neutron, electron, and photon radiation fields
- Neutron transport
  - Neutron flux & leakage
  - Induced fission gammas
  - Capture & inelastic scatter gammas
- Electron transport
  - Bremsstrahlung
- Photon transport
  - Photon flux & leakage
  - Decay gammas
  - Spontaneous fission gammas
  - (α, n) gammas

Detector Response

- Point models are used to estimate the response to photons & neutrons
  - Detector material & dimensions
  - Energy calibration & resolution
  - Near- & far-field scatter
  - Shielding & collimation

Nonlinear Regression

- The Levenberg-Marquardt regression solver is used to find transport model parameters that minimize the error in the calculated detector response

Solution Requirements

- Forward computations (radiation field and detector response) must be accurate
- Minimize bias in the solution due to systematic errors in the model

- Forward computations must be fast
- Minimize the time per iteration required to find the solution

- The model must have a finite number of numeric parameters
- Minimize the degrees of freedom/dimensionality of solution

- Accuracy requires high-fidelity spectral synthesis: coupled neutron/electron/photon transport calculations
- Speed requires explicit solution of transport problem: deterministic transport
- Tractable problems do not have arbitrary geometry

Radiation Observables

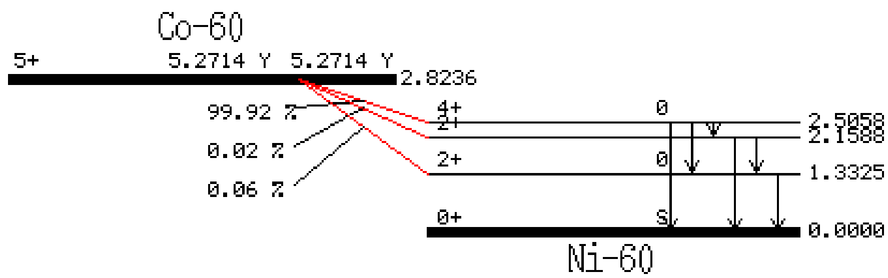
- Most externally observable radiation signatures result from gamma and neutron emissions
- Observables are usually differential over one or more independent variables (e.g., energy, position, time)
- Gamma spectrometry measures the distribution of photons versus energy
- Neutron multiplicity counting measures the distribution of neutrons versus number and counting time

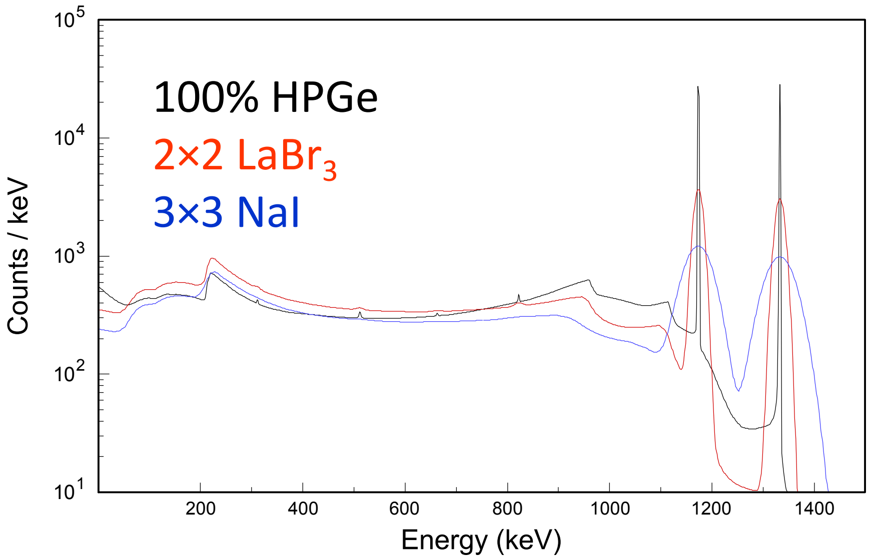
Gamma Spectrometers

Neutron Multiplicity Counters

Gamma Spectrometry

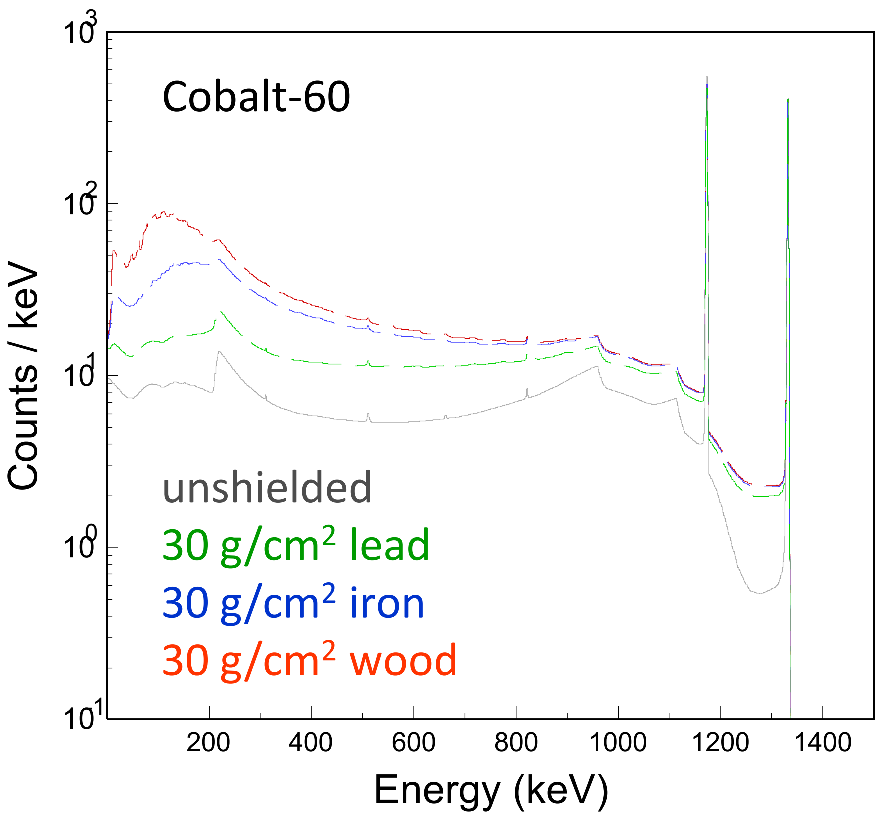
- A radionuclide decays from its unstable state through a series of discrete energy levels
- Decay between levels of a single daughter nucleus is achieved via emission of discrete energy gammas
- The gammas are characteristic of the daughter level scheme
- Gamma spectrometers measure the distribution of photon energies
- The gamma spectrum can be used to identify radionuclides and shielding

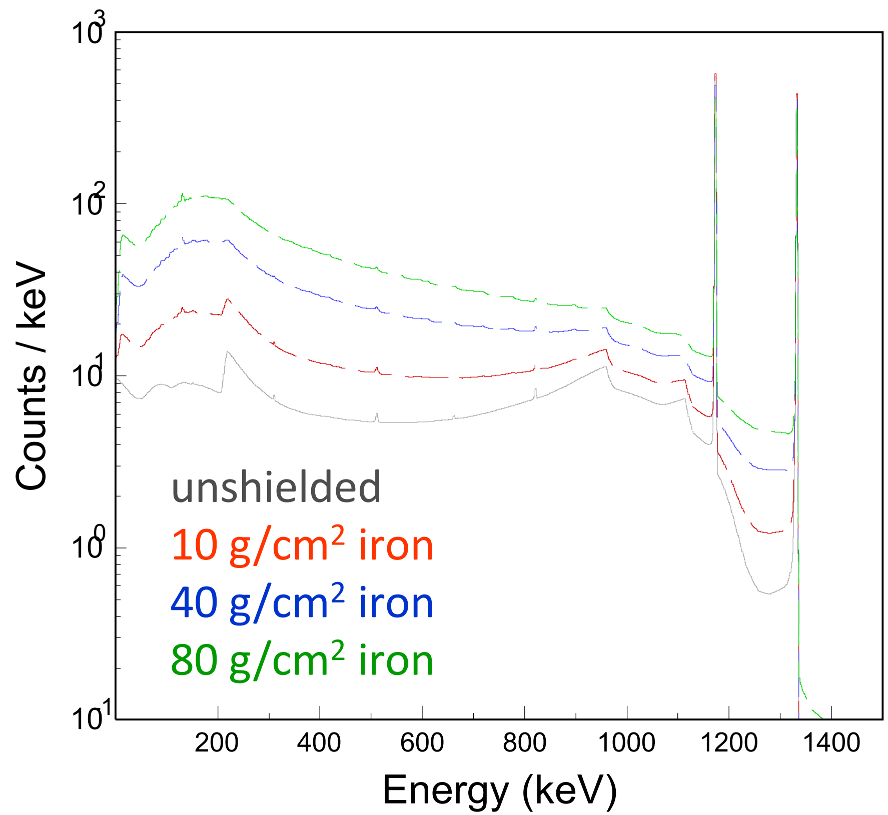




Photopeaks and Compton Continua

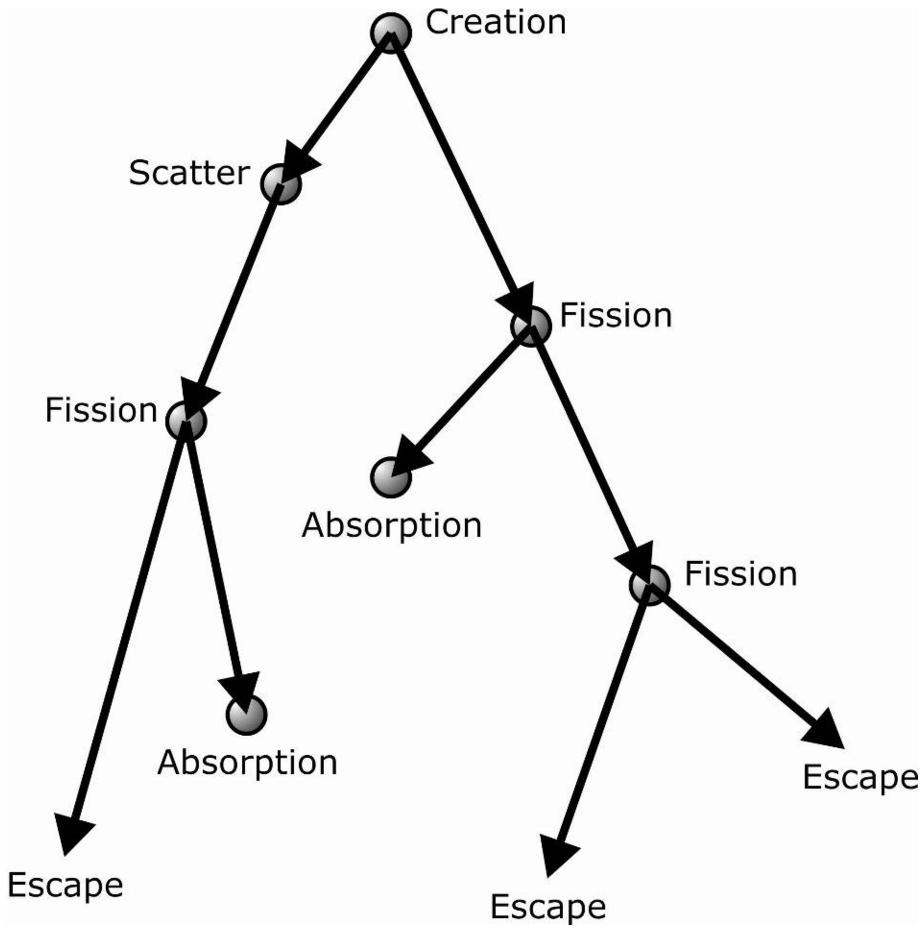
- Photopeak positions identify source
- Differential attenuation of photopeaks and Compton continua identify shielding
- Fitting the full spectrum enables the source and shielding to be characterized





Fission Chain-Reactions

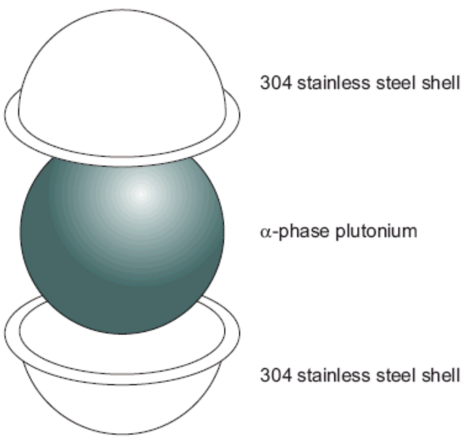
- Fission chain reactions multiply the number of neutrons in fissile transport medium
- Chain reaction characteristics:
  - Number of neutrons made during the chain reaction: neutron multiplication
  - Speed of chain reaction evolution: neutron generation time
- Neutron multiplicity measurements are sensitive to both characteristics
- Neutron multiplicity counting can be used to estimate kinetics properties of the source
  - Source strength
  - Multiplication
  - Neutron lifetime
  - Leakage probability



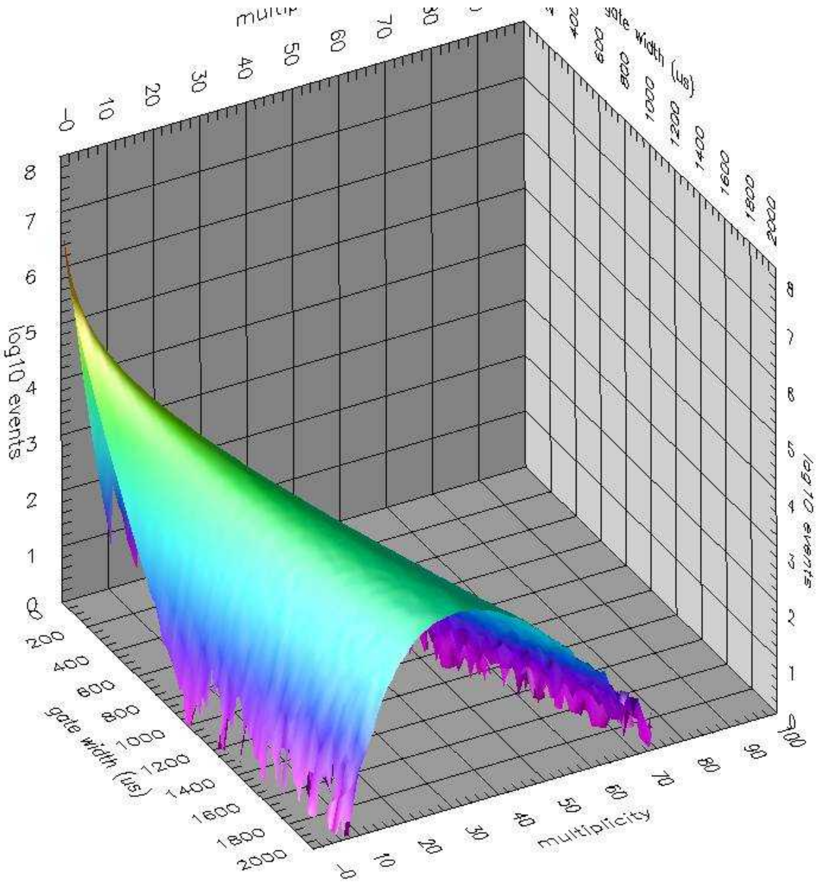
Neutron Multiplicity Counting

- Neutron multiplicity counting measures the frequency of neutron detection versus:
  - Counting time, a.k.a. coincidence gate width, usually on order of microseconds
  - Number of coincident counts, a.k.a. multiplicity, usually between 10’s and 100’s of coincident neutrons

LANL BeRP Ball

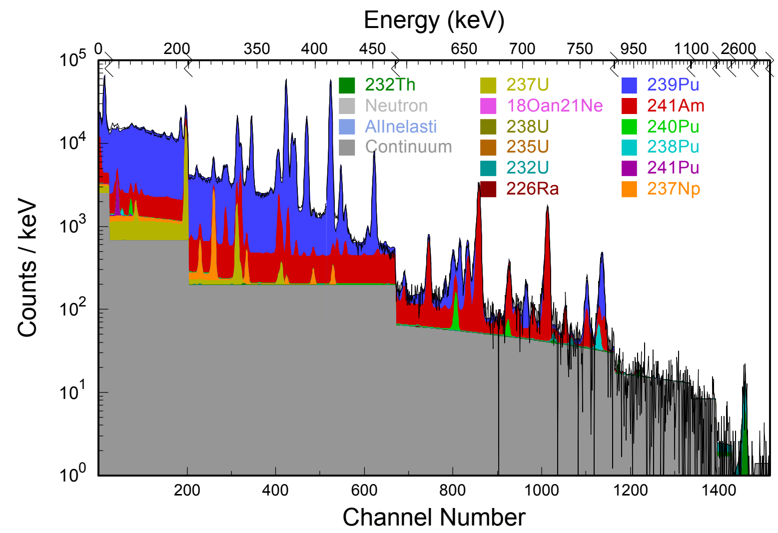


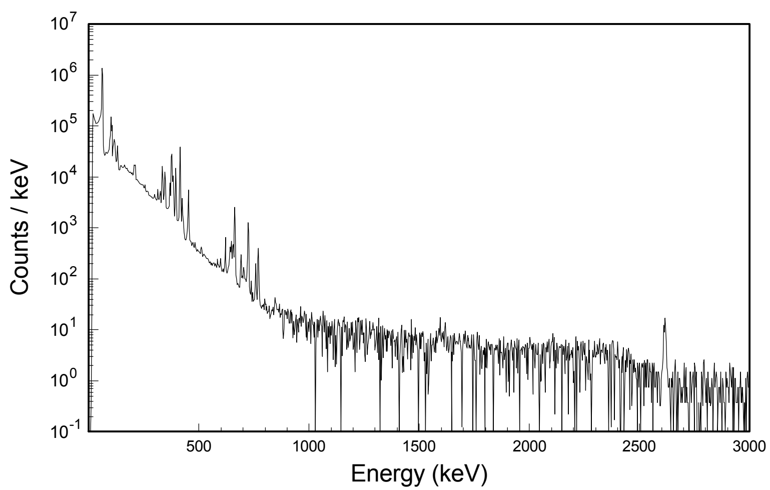
LANL BeRP Ball / 3.8 cm Poly Reflector



Example Problem

- The gamma spectrum below exhibits features consistent with plutonium
- The spectrum can be fit (top-right) via nonlinear regression using variable isotopics, volume, shielding, and age
- The regression analysis (bottom-right) provides approximate model of source



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Plutonium wt.% (@ 33 +/-  1 years) _________ @ t=0 _________

Pu-236:    2.69E-12  +/-  1.19E-12      8.98E-09  +/-  4.75E-09
Pu-238:       0.014  +/-     0.008         0.019  +/-     0.010
Pu-239:      94.205  +/-     0.603        94.295  +/-     0.604
Pu-240:       5.279  +/-     1.157         5.298  +/-     1.161
Pu-241:       0.095  +/-     0.006         0.513  +/-     0.038
Pu-242:    [  0.010]                    [  0.010]
Am-241:       0.396  +/-     0.008
Np-237:       0.017  +/-     0.002
U-237:     2.94E-09  +/-  1.92E-10
U-232:     8.98E-09  +/-  3.97E-09

Confidence for measured 18O-an-21Ne gammas:          -1.6 sigma
Measured (a,n) relative to expected for oxide:       -3.0 sigma
Aluminum-inelastic peak:              1011.7 keV @   2.3 sigma
Chemical form:                                        METALLIC
External shielding:            AN = 30 +/- 1;   AD = 3.9 +/- 0.1
Outer radius if plutonium is spherical:              3.8 cm
Estimated void radius:                               3.3 cm
Estimated mass if delta-phase plutonium:             1.3 kg

There is no evidence that uranium is present.
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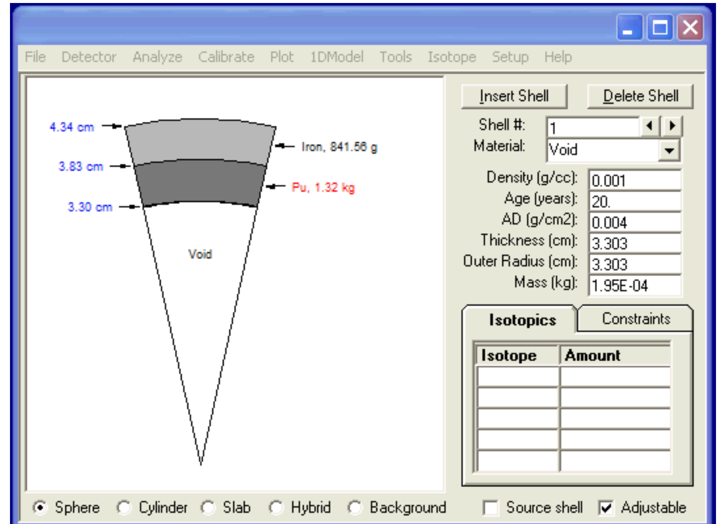
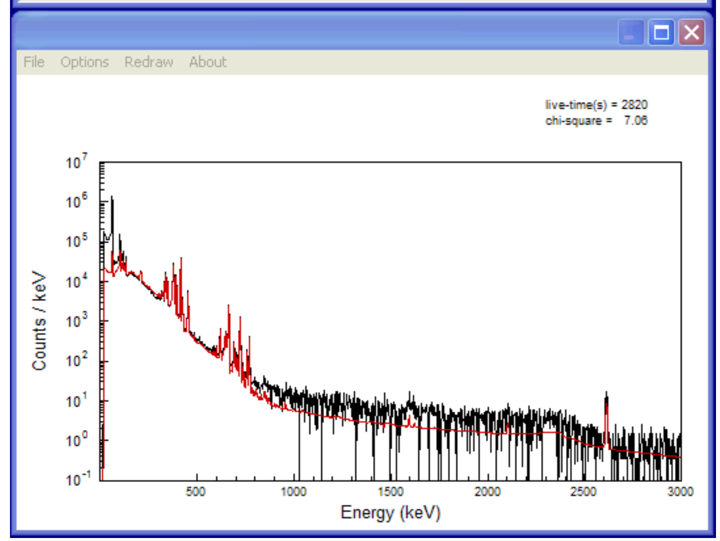
Example Problem

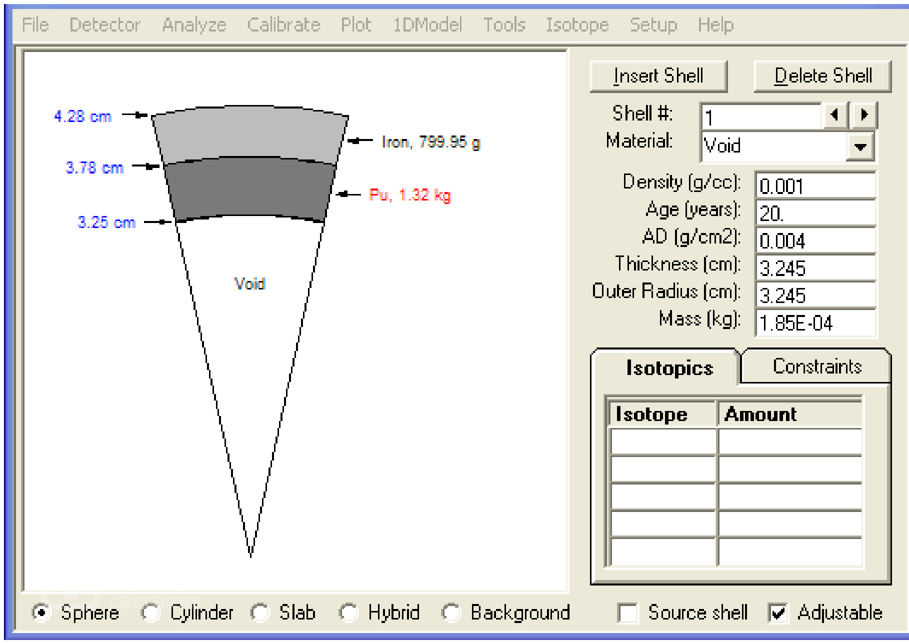
- A one-dimensional transport model (top) can be generated from regression analysis
  - The model is displayed as a section of sphere with the center at the bottom and outer surface at the top
  - The dimensions of the model layers are treated as variables for nonlinear regression
- An initial estimate of the gamma spectrum (bottom) is generated from coupled neutron/electron/photon transport calculations
- Nonlinear optimization procedures are used to find the model dimensions that minimize the error in the calculated spectrum



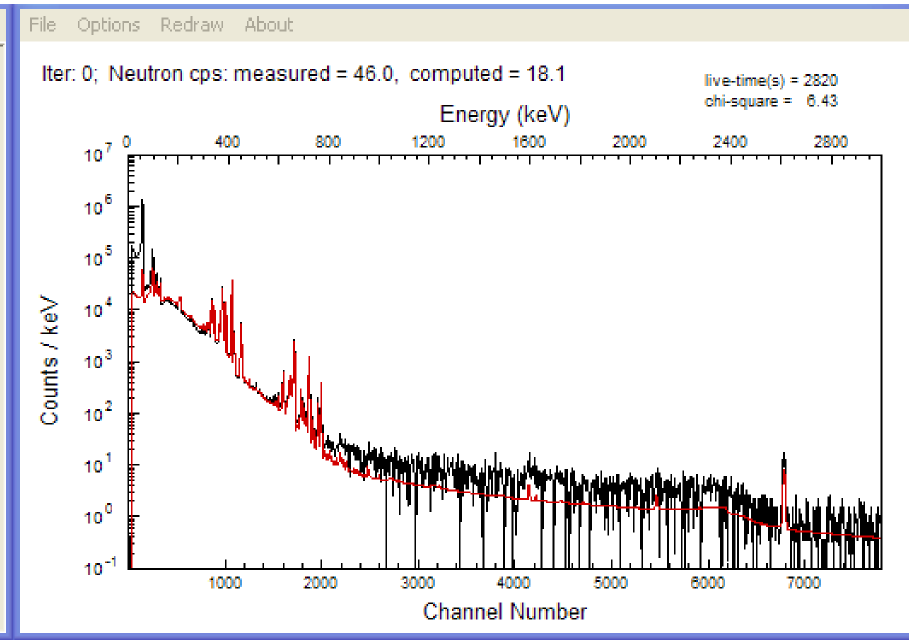


Solution Optimization

Transport Model

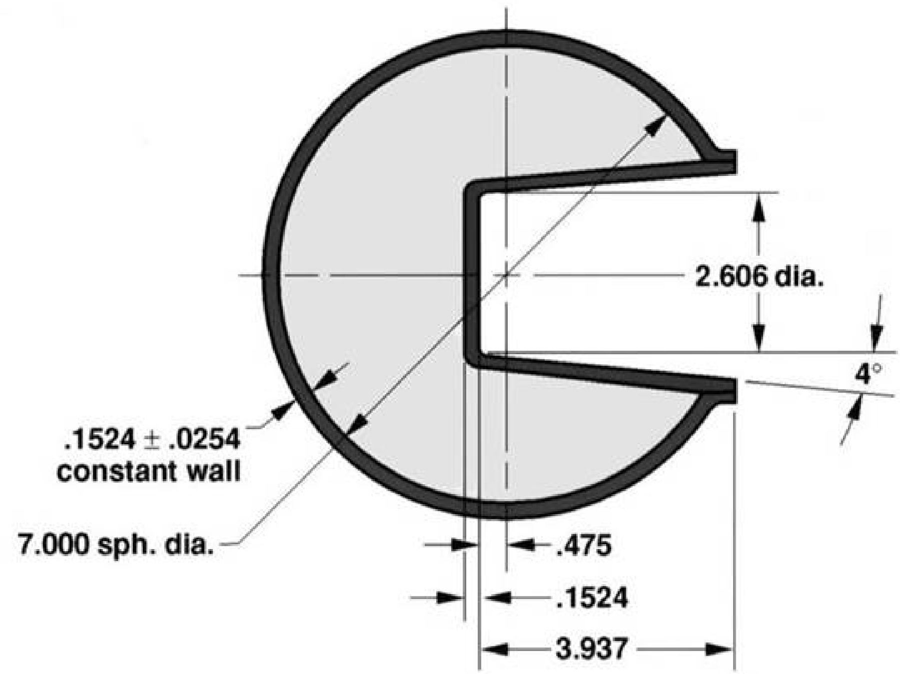


Measurement vs. Calculation

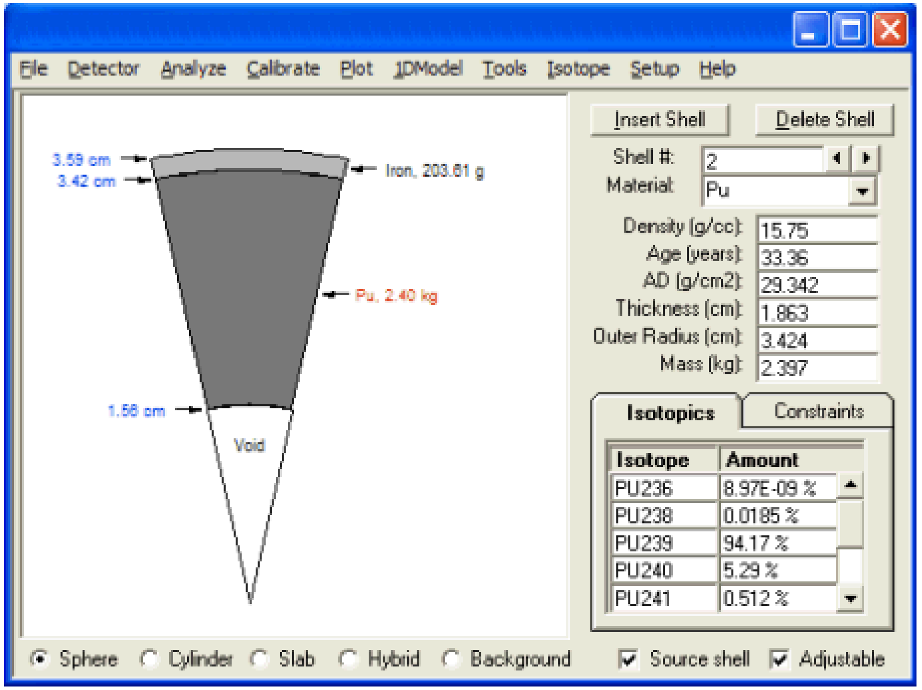


Actual Source

Plutonium Sphere

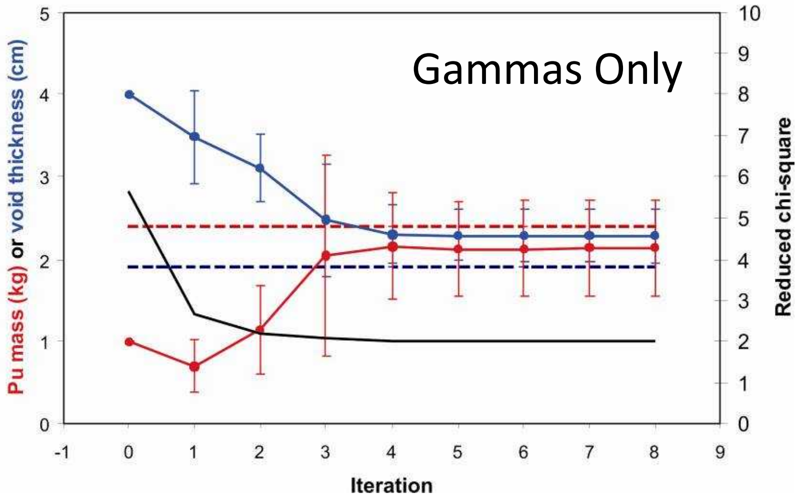


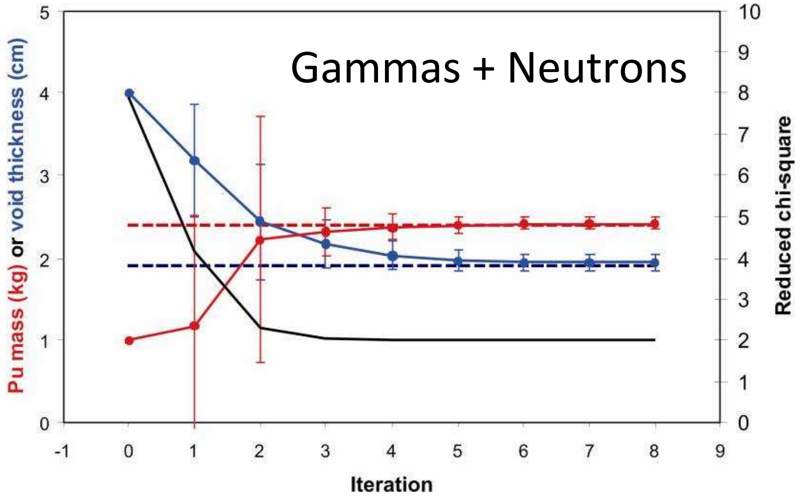
Optimized Transport Model



Solution using Gammas and Neutrons

- The gamma spectrum is primarily sensitive to the outer surface of source
- The solution based on the gamma spectrum alone is weakly constrained
- Neutron measurements (e.g., count rate) are more sensitive to the entire volume of source
- A solution based on the simultaneous analysis of gamma and neutron signatures is better constrained
- Neutron multiplicity counting provides a fairly rich signature of the neutron field



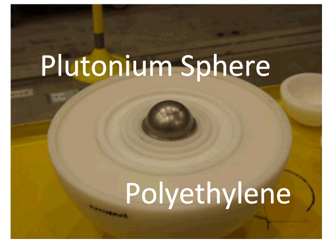


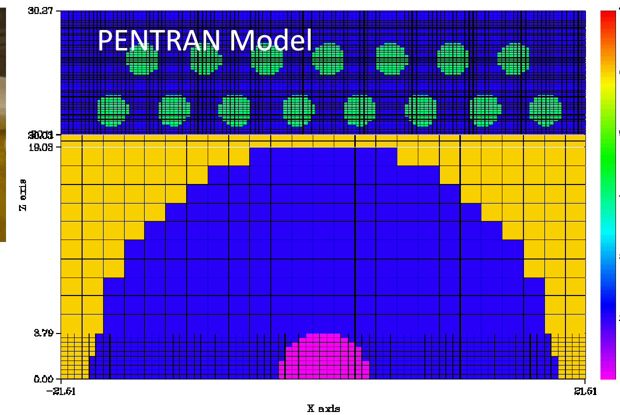
Challenges to Solving Multivariate Inverse Radiation Transport Problems

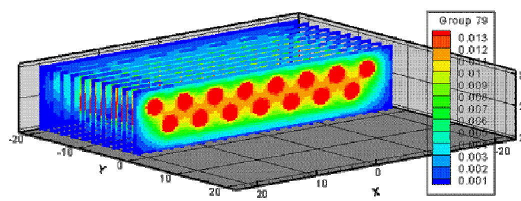
- Need to accelerate deterministic transport calculations
  - Typical computational time for neutron multiplicity statistics can be as much as 10 – 20 seconds
  - Need to investigate collapsed cross-section libraries and other approximations to speed the transport calculations
- Need to validate deterministic transport calculations
  - Approximations used to accelerate the calculations can introduce systematic errors
  - Need to validate approximations against measurements and higher fidelity (e.g., 3D Monte Carlo) simulations
- Need to develop a systematic approach to combining the analysis of complementary, correlated signatures
  - Errors in gamma spectrum and neutron multiplicity calculations are correlated
  - Need to correctly weight each signature's contribution to the error metric

Accelerating Deterministic Transport Calculations

- University of Florida (UF) is developing a platform that will be used to test alternative methods of accelerating deterministic transport calculations
- The platform is based on UF codes PENTRAN (S_N) and TITAN (hybrid S_N/ray-trace)
- UF is currently investigating contributon-weighted methods to collapse cross-sections
- So far, UF has been able to reduce the number of energy groups by a factor of 2 without introducing much error into neutron multiplicity calculations

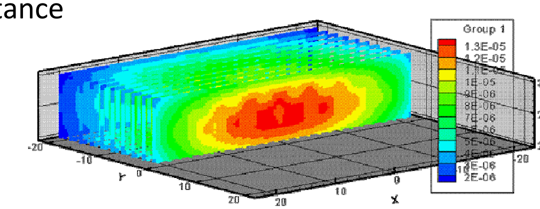






Thermal Neutron Importance

UNIVERSITY of FLORIDA



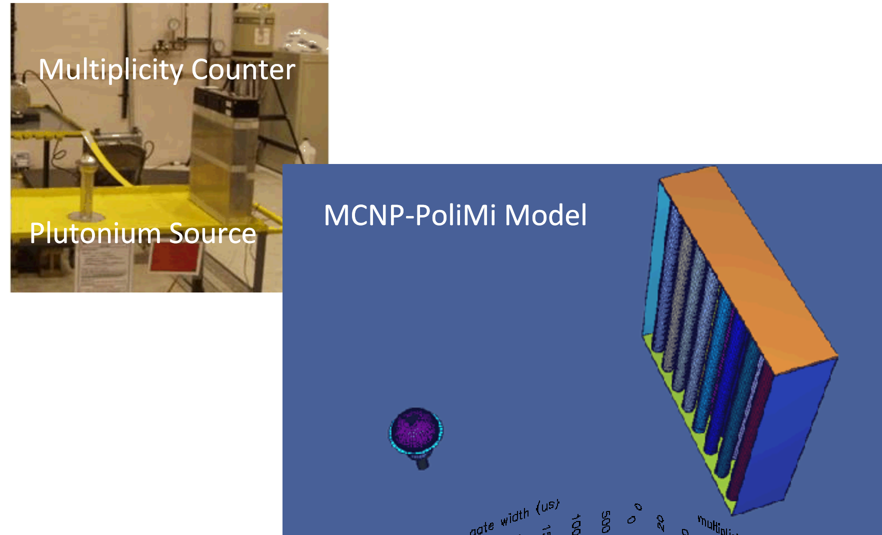
Fast Neutron Importance

National Nuclear Security Administration

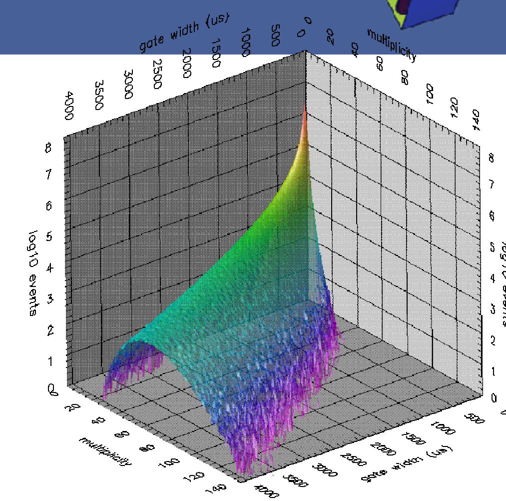
Sandia National Laboratories

Using Monte Carlo to Validate Deterministic Calculations

- University of Michigan (UM) is modifying MCNP-PoliMi and post-processing software to simulate neutron multiplicity counting experiments
- UM developed an MCNP-PoliMi post-processor that accumulates the neutron multiplicity distribution
- UM is currently validating their calculations against experiments conducted with reflected plutonium
- So far, UM has been able to match the experiments within about 15% (using the Feynman variance-to-mean statistic)



MICHIGAN



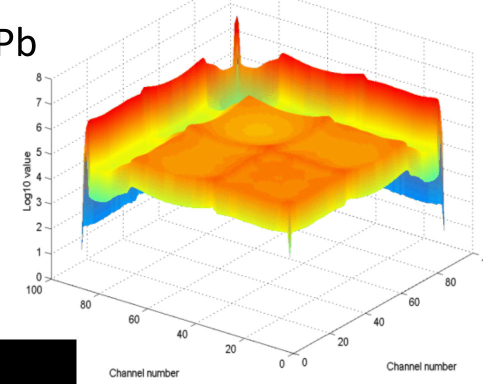
Multiplicity Distribution

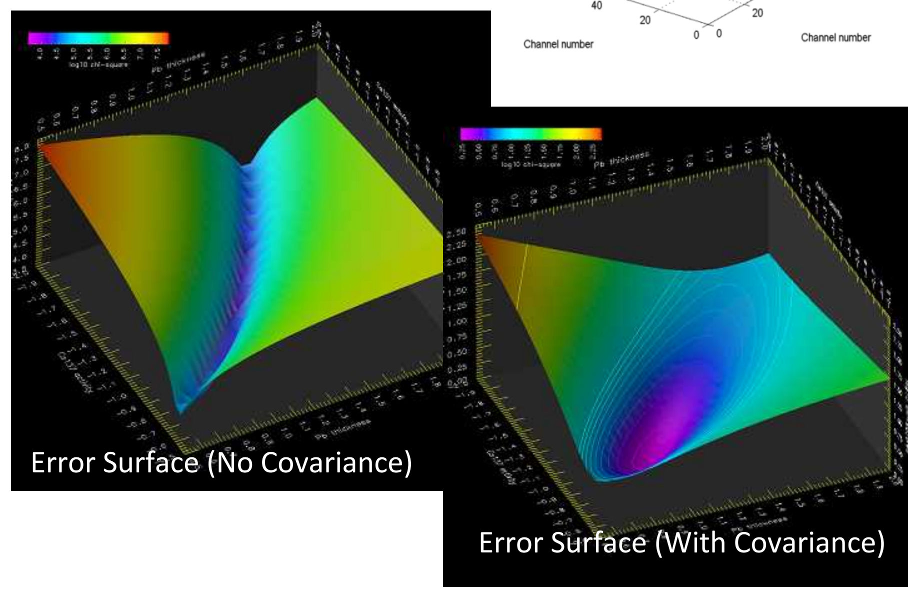
Combining Gamma Spectral and Neutron Multiplicity Analyses

- Sandia is studying alternative regression error metrics to systematically combine the analysis of gamma spectrometry and neutron multiplicity measurements
- We developed a methodology that computes the covariance between model errors – the covariance matrix is used to weight the contribution of individual model errors to the total error
- Currently, we are investigating the effect of model error covariance on the topography of the solution space

- Problem
  - Cs-137 shielded by Pb
- Variables
  - Cs-137 activity
  - Pb thickness

Covariance Matrix





$$\chi^2 = (x - x_0)^T \Sigma^{-1} (x - x_0)$$

Summary

- It is possible to infer the configuration of an unknown radiation source from its radiation signatures
- Sandia has developed and implemented techniques to solve this inverse transport problem based on gamma spectrometry
- Solutions based on multiple complementary signatures are generally better constrained
- Sandia is working with University of Florida and University of Michigan to develop methods to solve inverse transport problems using gamma spectrometry and neutron multiplicity signatures