Simulation of Prompt Gamma Emission Tomography by Compton Scattering and The Implementation of a Neutron Tomography System

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Outline

In a nutshell

Top Level Summary:

Combine three techniques to understand the structural composition of a material.

Three Techniques		
Technique	Energy Resolution	Spatial Resolution
Germanium Detector (HPGe)	High	None
Compton Camera	Med	Med
Neutron Tomography	None	High

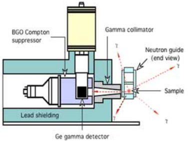


Figure: Germanium Detector with Compton suppressor. (NIST)

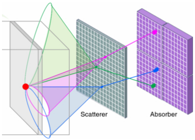


Figure: Compton Camera. (Kim et. al. 2013)

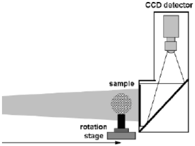


Figure: Neutron tomography schematic. (Manescu et. al. 2013)

In a nutshell

Application:

- Studying Chloride transport in concrete. Structural degradation.
- Hydrogen ion diffusion through metals. Hydrogen blistering and embrittlement of metals (Fuel Cells and Fusion Reactors).

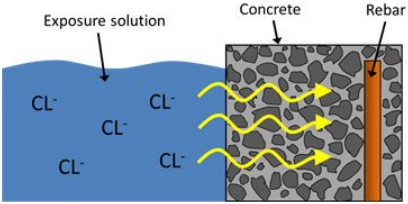


Figure: Chloride attacking concrete structure. (Nielsen 2004)

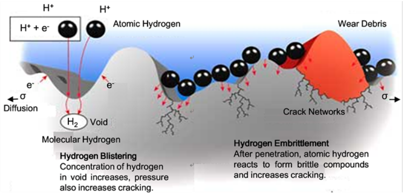


Figure: Instrument diagram of the NCNR. (Zhang 2016)

Prompt Gamma Activation Analysis (PGAA)

- Characteristic gamma-radiation emitted under neutron capture
- Gammas typically in the MeV range (eg. 2.22 MeV for ^{1}H)
- Bulk elemental composition analysis for a sample
- Non-destructive

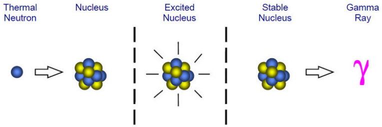


Figure: Neutron activated prompt gamma process. (Frontier Tech C.)

1g sample 24 hour measurement	
Range (μg)	Elements
0.01-0.1	B, Cd, Sm, Gd
0.1-1	H, Cl, In, Nd
1-100	Na, S, K, Ti, and more

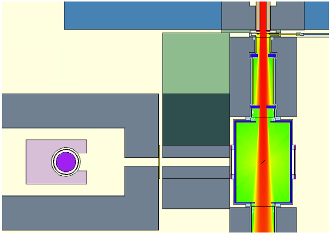


Figure: PGAA station at the NCNR. Neutron beam with HPGe detector and lead shielding.

Compton Camera

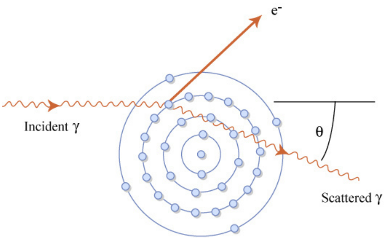


Figure: Schematic view of Compton scattering. (MIT OCW)

$$\frac{1}{E'} - \frac{1}{E} = \frac{1}{m_e c^2}(1 - \cos\theta), \quad (1)$$

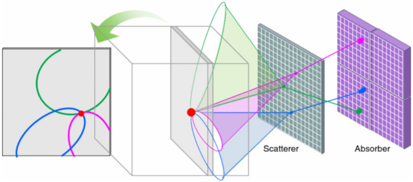


Figure: Compton Camera. (Kim et. al. 2013)

- Compton scattering applied to imaging
- Energy and spatial resolution
- Commonly used in astronomy
- Improved resolution with Cadmium Zinc Telluride (CZT) detectors and miniaturized on-board electronics

Neutron Tomography

- Images generated by transmitting neutrons through a sample.
- Inverted contrast to X-ray tomography (insensitive to high Z-materials).
- 3D reconstruction using computed tomography.

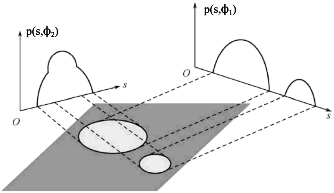


Figure: Basic idea for computed tomography. (ZvolskÃœ 2014)

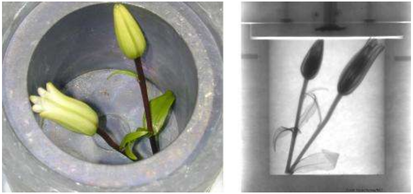


Figure: Flower in lead shielding showing the sensitivity of neutron imaging to hydrogen. (NIST)

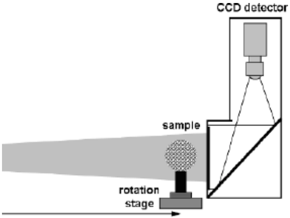


Figure: Neutron tomography schematic. (Manescu et. al. 2013)

Research Objective

My Role:

- Continued development of detector simulation to aid the design of a Compton Camera
  - Detector parameters (plane separation, position, orientation)
  - Spatial resolution
  - Energy resolution
- Assemble and evaluate a basic neutron tomography setup

Geant4 Simulation

- Geant4 is a C++ toolkit for simulating particle transport through matter.
- Developed for High Energy Physics at CERN, expanded application to medical and nuclear engineering.
- Expanding work by Ben Riley (SURF 2017)
- Outputs basic detector response for reconstruction

Figure: geant4 logo. (CERN)

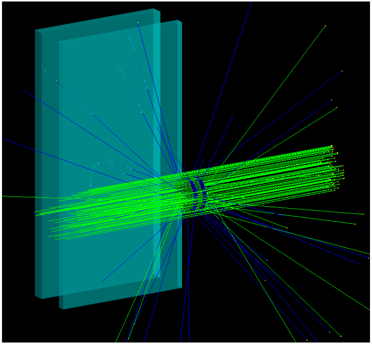


Figure: Particle tracks for Geant4 simulation of n-capture and CZT Detector.

Conic Back-projection

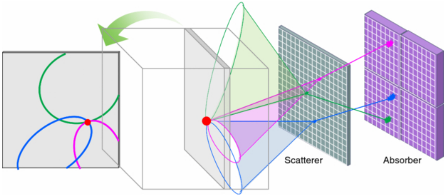


Figure: Compton Camera. (Kim et. al. 2013)

- Basic method for reconstructing sample geometries.
- Takes the basic detector output from experiment or simulation.
- Back-projection looks at the conic sections at a plane of interest.
- Different methods available for energy and spatial resolution.

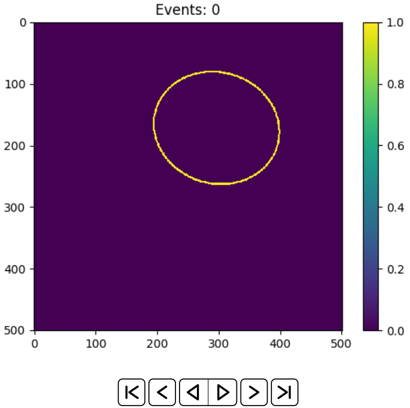


Figure: Animation of conic back-projection with the number of ideal events.

Assessment of Reconstruction Methods

Other methods we can use:

- Filtered Back-projection - Apply a frequency filter.
- Maximum Likelihood Estimation Method (MLEM) - Iterative process using guess and check like method.
- Stochastic Origin Ensemble (SOE) - Iterative process applying Metropolis-Hastings Algorithm.

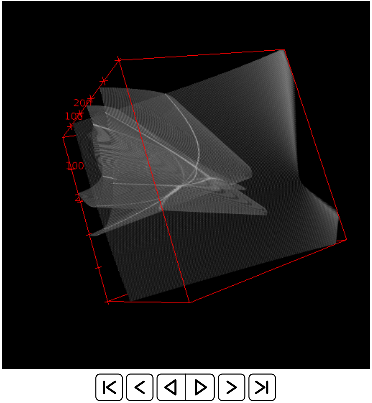


Figure: Animation of 4 cones projected into a 3D cube.

Neutron Tomography Apparatus

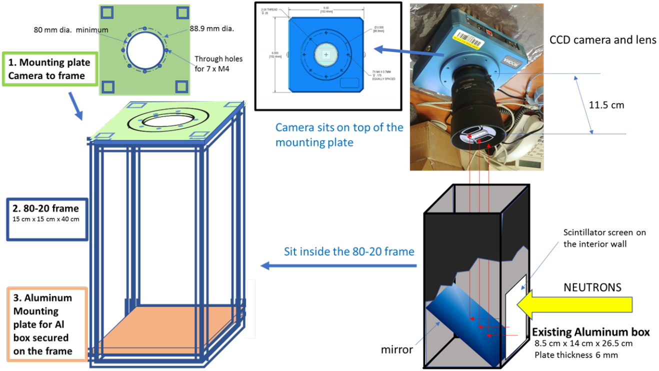


Figure: Sketch of the Neutron Tomography Apparatus for basic testing.

- Construct a test neutron tomography apparatus
- Uses a ^{6}LiF:ZnS scintillator sheet to convert neutrons to light.
- Coordinate rotating stage with CCD
- Evaluate apparatus at
  - PGAA station (uncollimated neutrons)
  - BT-2 Neutron Imaging Facility (collimated neutrons).

Neutron Tomography Apparatus

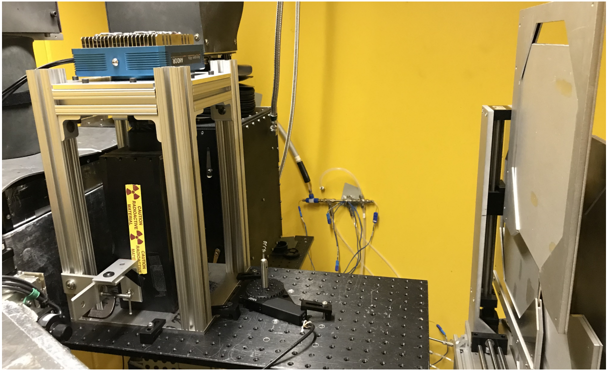


Figure: Completed Neutron Tomography Apparatus for basic testing.

- Construct a test neutron tomography apparatus
- Uses a ^{6}LiF:ZnS scintillator sheet to convert neutrons to light.
- Coordinate rotating stage with CCD
- Evaluate apparatus at
  - PGAA station (uncollimated neutrons)
  - BT-2 Neutron Imaging Facility (collimated neutrons).

Prompt Gamma Compton Camera (PGCC) Simulation

- 480x speedup
  - Skips n-capture process for performance speedup
  - Implemented gamma emmissions from random locations in samples
  - 1.8e6 Compton events per 20 min
  - Compared to 3500 Compton events per 20 min for 25 meV neutrons and 0.126 g of water
- Speedup achieved for back-projection reconstruction with multithreading

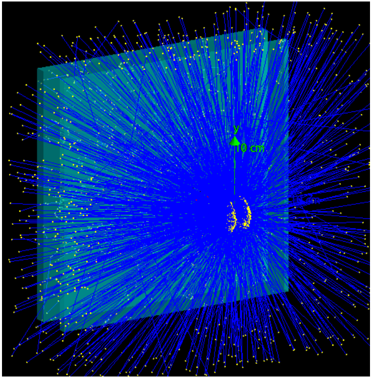


Figure: Figure showing the direct to gamma geant4 method for disk geometries.

PGCC Energy Output Comparison

- Experimental data obtained from wax disk in neutron beam.
- Geant4 data is a simulation using the direct to gamma process.
- 2.22 MeV ^{1}H peak clearly visible, Compton edge

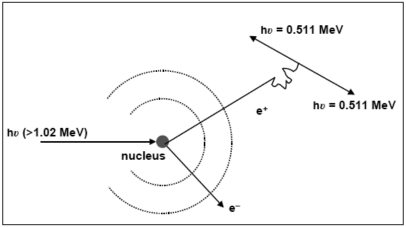
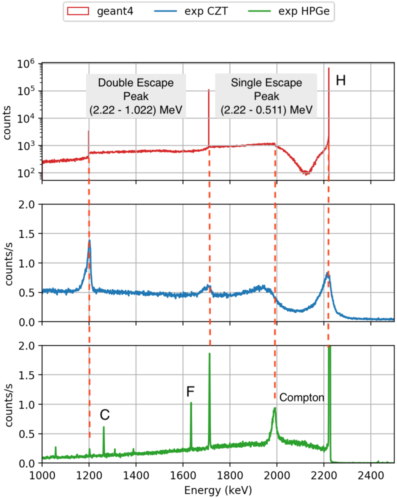


Figure: Comparison of energy spectrum's for geant4 PGCC simulation, Compton Camera, and HPGe.



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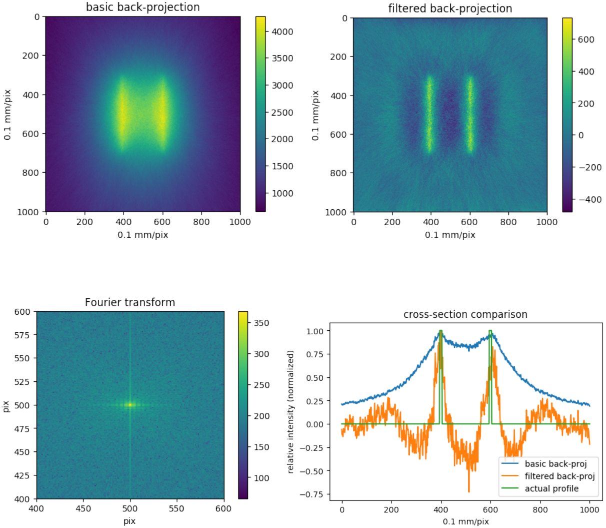
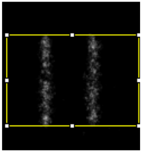
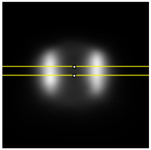
Back-Projection Methods

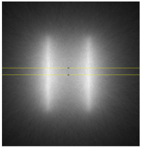


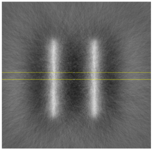
Iterative Reconstruction Methods

Statistical reconstruction | **Back projection of cones**





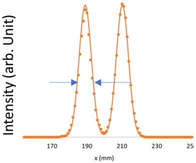




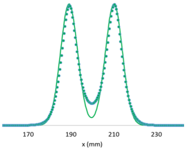
Dots: intensity profile
Lines: Gaussian approx.

-2.2 MeV gamma rays -single scattered events -2-disks -1 mm thick 2 cm apart

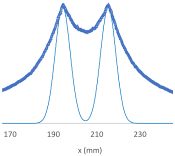
SOE



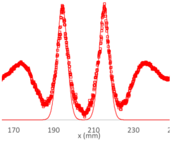
MLEM



unfiltered

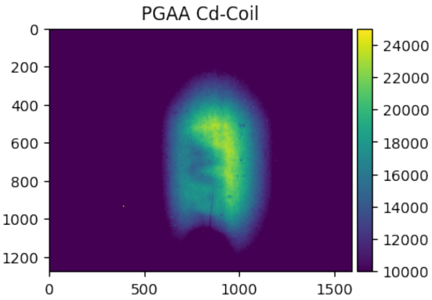


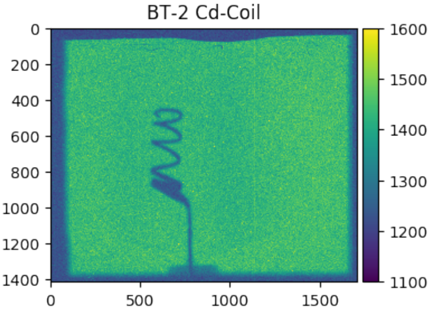
filtered



FWHM (mm)	3.5	9.4	>> 8	6

Neutron Tomography Results





PGAA vs. BT2 Comparison

- PGAA station uses uncollimated neutrons.
- BT2 uses highly collimated neutrons.

Conclusion

Key Results:

- 480x speedup using direct to gamma simulation
- Parallelization of back-projection reconstruction software
- Corresponding simulation and experimental data
- Tested n-tomography apparatus

Future Work:

- Prompt Gamma Compton Camera Simulation
  - Generalize for more complete detector response
  - Further study detector parameters
- Neutron Tomography
  - Characterize PGAA station beam
  - Investigate PGAA beam collimation
  - Assess CCD damage

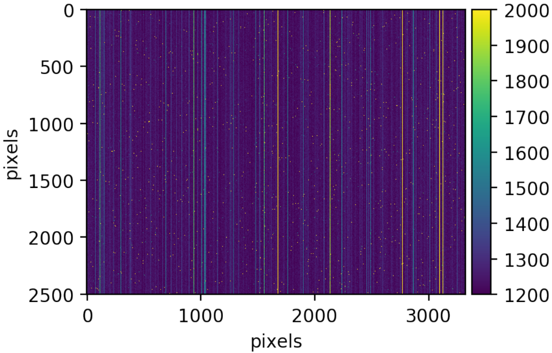
Acknowledgements

A special thanks to:

- Heather Chen-Mayer, Jake LaManna, Ryan Fitzgerald (MML/NCNR/PML)
- Joe Dura, Julie Borchers, Brandi Toliver (NIST SURF)
- Jeremy Polf, Haijen Chen (UMD)
- Ben Riley (SURF 2017)
- Fellow NCNR SURFers!

CCD Damage

- Radiation damage to CCD
- Characterized by individual pixels and columns of offset by some value pixels
- Maybe correctable in post-processing



Sample Geant4 Process

```
Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0     16.6    -7.87     -100   2.5e-09        0        0         0       World initStep
    1     16.6    -7.87      -20   2.5e-09        0       80        80      Sample Transportation
    2     16.6    -7.87    -19.8  4.89e-10 2.01e-09    0.222      80.2      Sample hadElastic
    3     16.1    -8.22    -19.5         0        0    0.706      80.9      Sample nCapture
    :----- List of 2ndaries - #SpawnInStep=  2(Rest= 0,Along= 0,Post= 2), #SpawnTotal=  2 ---------------
    :       16.1     -8.22     -19.5      2.22              gamma
    :       16.1     -8.22     -19.5   0.00132           deuteron
    :----------------------------------------------------------------- EndOf2ndaries Info ---------------

*********************************************************************************************************
* G4Track Information:   Particle = deuteron,   Track ID = 3,   Parent ID = 1
*********************************************************************************************************

Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0     16.1    -8.22    -19.5   0.00132        0        0         0      Sample initStep
    1     16.1    -8.22    -19.5         0  0.00132 0.000243  0.000243      Sample hIoni

*********************************************************************************************************
* G4Track Information:   Particle = gamma,   Track ID = 2,   Parent ID = 1
*********************************************************************************************************

Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0     16.1    -8.22    -19.5      2.22        0        0         0      Sample initStep
    1     17.2    -7.52      -18      2.22        0     1.98      1.98       World Transportation
    2     62.5     20.8     40.9      2.22        0     79.5      81.5   Detector1 Transportation
    3     71.8     26.6       53      1.87        0     16.3      97.8   Detector1 compt
    :----- List of 2ndaries - #SpawnInStep=  1(Rest= 0,Along= 0,Post= 1), #SpawnTotal=  1 ---------------
    :       71.8      26.6        53     0.353                  e-
    :----------------------------------------------------------------- EndOf2ndaries Info ---------------
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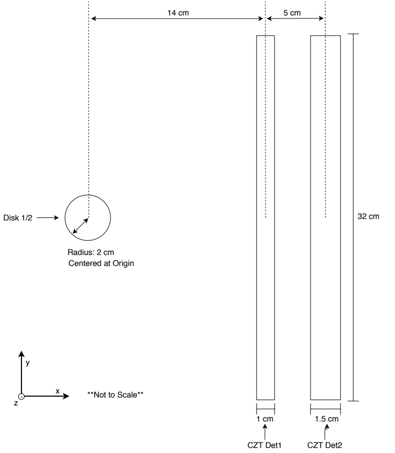
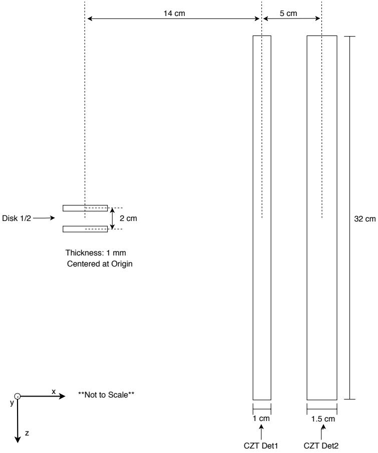
Simulation Geometry





Compton Emphasis

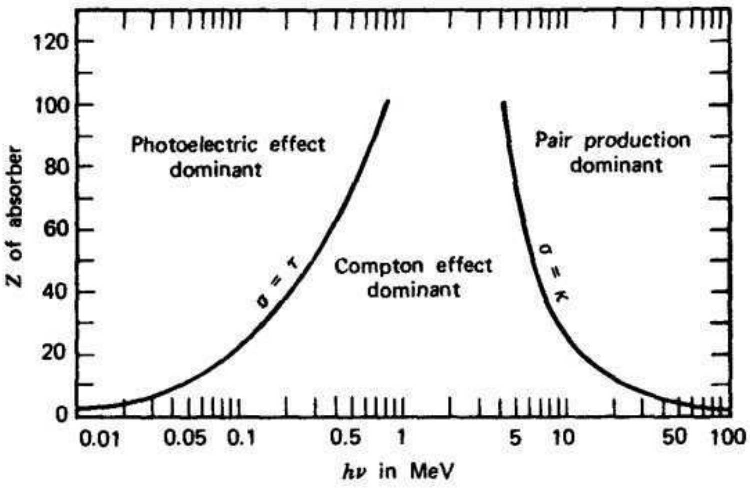


Figure: Gamma interactions. (Smet 2011)

Complication