Modeling a Carbon Diagnostic System Using MCNPX

Samantha Fay and Christine Kuhn
Gettysburg College Physics Department
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Outline

• Introduction
  – What is a carbon diagnostic?
  – What is it for?

• How the diagnostic works

• Modeling
  – Why model?
  – Process
  – Results
  – Future Work
• Inertial Confinement Fusion (ICF)
OMEGA/LLE

- 60 lasers, 40 kJ of energy
- Shot chamber 3.3m diameter
• D + T $\rightarrow$ a + n (14.1 MeV) – primary
Fusion Reaction Sequence

D + T $\rightarrow$ a + n (14.1 MeV) – primary
n + D $\rightarrow$ n’ + D’ (0-12.5 MeV) – secondary
n + T $\rightarrow$ n’ + T’ (0-10.6 MeV) – secondary
D’ + T $\rightarrow$ a + n” (12.0-30.1 MeV) – tertiary
T’ + D $\rightarrow$ a + n” (9.2 - 28.2 MeV) – tertiary

- Tertiary neutrons = self-sustaining fusion
- Self-sustaining fusion = energy source, weapons research
- Conventional detectors destroyed by flux
What is a Carbon Diagnostic?

• High energy neutrons cause (n,2n) reactions in \(^{12}\text{C}\), creating \(^{11}\text{C}\)
  
  • \(^{12}\text{C} + \text{n} \rightarrow ^{11}\text{C} + 2\text{n}\)
  • \(^{11}\text{C} \rightarrow ^{11}\text{B} + \text{e}^+ + \text{?}\)
  • \text{e}^+ + \text{e}^- \rightarrow 2\text{?} \ (0.511 \text{ MeV})

• Resulting 0.511 gamma rays can be counted
• Adaptation of a copper diagnostic
• Threshold energy of $^{12}\text{C} \ (n,2n) \ ^{11}\text{C}$ reaction is 20.2 MeV

![Graph showing cross-section vs. incident neutron energy.]

• Cross-section: probability of reaction occurring...
Using the Diagnostic
NaI(Tl) Detectors

- Detector size
  - Cylinder of 3.81cm radius, 7.62cm long
  - Cylinder of 1.5cm radius, 3cm long
Modeling the Diagnostic

• Using Monte-Carlo N-Particle Extended (MCNPX) to:
  – Model geometries
  – Simulate detection of gamma coincidences (using PTrac and PTrakker)

• Need to maximize tertiary neutron activation

• Need strong signal above background
Limitations

- Contamination protection
  - plastic
  - removable carbon covers
- Plastic protects from nitrogen in air
- Covers protect from plastic
- Size and location
  - 3.81cm radius, 40cm from reaction
  - 1.75cm radius, 10cm from reaction
Problem #1: Using $^{62}\text{Cu}$ for $^{11}\text{C}$

- MCNPX data libraries do not contain $^{11}\text{C}$ cross-sections: $^{62}\text{Cu}$ best substitute
  - Both undergo (n,2n) reactions
    - $^{63}\text{Cu}$ at primary neutron energy
    - $^{12}\text{C}$ only at tertiary neutron energy
  - Both products are positron emitters
    - $^{62}\text{Cu}$ ? 9.7 minute half-life
    - $^{11}\text{C}$ ? 20.4 minute half-life
$^{63}\text{Cu}$ vs. $^{12}\text{C}$

- $(n,2n)$ cross-section of $^{63}\text{Cu}$ is much higher than that of $^{12}\text{C}$ (by 2 orders of magnitude)
- $^{62}\text{Cu}$ produces high energy gammas that pair produce and create false detector signals
Problem #2: Time in MCNPX

- Should get one p-annihilation for each (n,2n) reaction
- We had two orders of magnitude fewer p-annihilations than (n,2n) reactions in code’s outputs
- MCNPX models only near instantaneous events: cannot wait for decays to occur
- Fewer 0.511 MeV photons produced in model than in reality as a result
Our Solution

• Calculate number of (n,2n) reactions

• Calculate how many $^{11}$C nuclei would decay while in the detectors

• Use that number as the number of source particles for a positron source in MCNPX
Activation Equation

\[ N_{\text{int}} = N_0(1 - e^{-ns t}) \]

- \( N_{\text{int}} \) = # of interacting neutrons
- \( N_0 \) = # of neutrons that hit the carbon
- \( s \) = neutron cross-section for \(^{12}\text{C}\)
- \( t \) = thickness of carbon
- \( n \) = number density = \( ?N_A/A \)
  - \( ? \) = density of carbon = 1.85 g/cm\(^3\)
  - \( N_A \) = Avogadro’s number
  - \( A \) = atomic mass of carbon = 12
• $N_{\text{int}} \left( \frac{\sigma_{(n,2n)}}{\sigma_t} \right) =$ number of (n,2n) reactions

• Number of (n,2n) reactions = Number of $^{11}\text{C}$ nuclei in system
• Transit time: 5 minutes from shot to counting system
• Carbon in detectors 80 minutes

\[ N(t) = N_0 e^{-\lambda t} \]
\[ \lambda = \frac{\ln(2)}{t_{1/2}} \]

- Half-life of $^{11}$C = 20.4 minutes = $t_{1/2}$
• 79% will decay while in detector array
  – $N(5) = 84\%$ of $^{11}\text{C}$ left
  – $N(85) = 5\%$ of $^{11}\text{C}$ left
• In MCNPX, use 79% of (n,2n) reactions as a uniform positron source in carbon geometry

• MCNPX models
  – Positron annihilation with electrons = gamma coincidence production
  – Gamma coincidence detection by NaI detectors
Geometries

Carbon disk

- Graphite foil
- Carbon Disk
- Plastic Wrap
- Cube
  - Placed 10cm from shot
  - Detectors (1.5cm radius) on all faces

Dimensions
\~ 3cm x 3cm x 3cm

Very small face,
Very small volume

Not enough (n,2n) reactions
• Cylinders
  – 10cm from shot
  – Max. radius = 1.75cm
  – Can be long or short
  – Four parallel detectors (3.81cm radius)
  – Can add detectors on ends
• Well Detector
  – Catch all gammas
  – Nonstandard design (expensive)
  – Array of four or six standard detectors may be as effective
Pulse Height Tally and Ptrack Data

We record how many...

• Total 0.511 MeV photons enter the detectors
• 0.511 MeV coincidences enter the detectors
• Total photons enter the detectors
• Photons deposit 0 energy in the detectors
• Photons deposit 0.511 MeV in the detectors
• Smallest bar (left) 40cm spot
• Other bars: Cylinders at 10cm spot, 2 to 10cm long
• Adding two 1.5 cm radius NaI detectors to an array of four 3.8 cm radius NaI detectors contributes little background.
• Replacing the two 1.5 cm detectors with two 3.8 cm NaI detectors greatly increases background counts for the same four-detector array.
Conclusions

• Optimal configuration yields high count rate with low background:
  - Carbon diagnostic: cylinder of 5 to 10 cm long, 1.75 cm radius, located 10 cm from the shot
  - Detector array: four 3.8 cm NaI detectors encircling the cylinder with one 1.5 cm detector on each end
Future Work

- Model a longer cylinder at the 10cm spot
- Test the effects of nitrogen contamination
- Determine if positron source is uniform
- Study all sources of 0.511MeV photons
- Find a way to count Compton-scattered coincidences in MCNPX
References

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