Relationship of secondary nuclear production to implosion characteristics at OMEGA

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Two models ("hot-spot" and "uniform") are commonly used to relate secondary yields to $\rho R_{\text{fuel}}$ but give slightly different results.

- Does either model represent real implosions well?

$\rho R_{\text{fuel}}$ inferred from secondary proton and neutron yields are often very different.

- Is one of them more accurate?
- Is the theory wrong?

We use simulations to predict the effects of capsule structure on the accuracy of the diagnostic method.

We investigate some issues experimentally by comparing new results for thin (~2 $\mu$m) glass shell capsules to previous results for thick (~20 $\mu$m) plastic shell capsules.

- Do inferred $\rho R_{\text{fuel,proton, hot-spot (uniform)}}$ and $\rho R_{\text{fuel,neutron, hot-spot (uniform)}}$ agree better for thin shell targets, which have:
  - Higher $T_e$ and lower $\rho R_{\text{fuel}}$ (which decreases "saturation" effects for secondary protons)
  - less fuel-shell mix
Two species of secondary products can be measured at OMEGA

Secondary protons

\[
D + D \rightarrow n + ^3\text{He} \ [0.82 \text{ MeV}]
\]

\[
^3\text{He} \ [\leq 0.82 \text{ MeV}] + D \rightarrow \alpha + p \ [12.6-17.5 \text{ MeV}]
\]

Secondary neutrons

\[
D + D \rightarrow p + ^{\text{T}} \ [1.01 \text{ MeV}]
\]

\[
^\text{T} \ [\leq 1.01 \text{ MeV}] + D \rightarrow \alpha + n \ [11.9-17.2 \text{ MeV}]
\]
Secondary protons and neutrons are produced in different regions of the plasma.

![Graphs showing the production of protons and neutrons in 1 g/cc, 3keV plasma.](image)
Hot-spot and uniform models are commonly used to relate secondary yield to $\rho R_{\text{fuel}}$

<table>
<thead>
<tr>
<th>Hot-spot model</th>
<th>Uniform model</th>
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<tbody>
<tr>
<td>• Capsules have constant temperature and density</td>
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</tr>
<tr>
<td>• All the primary particles are generated at the center of a capsule</td>
<td>• Primary particles are generated uniformly in a capsule</td>
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</table>
Ratio of secondary proton and neutron yields to primary neutron yield ($Y_{2p}/Y_{1n}$ and $Y_{2n}/Y_{1n}$) are used to infer $\rho R_{\text{fuel}}$.

Ratio of secondary proton and neutron yields to primary neutron yield ($Y_{2p}/Y_{1n}$ and $Y_{2n}/Y_{1n}$) are used to infer $\rho R_{\text{fuel}}$.
Hot-spot and uniform models give slightly different results

\[ Y_{2p} / Y_{1n} \]

\[ Y_{2n} / Y_{1n} \]

\[ \rho R_{\text{fuel}} \ (\text{g/cm}^2) \]
$\rho R_{\text{fuel,2p}}$ and $\rho R_{\text{fuel,2n}}$ disagree for thick (~20 $\mu$m) shell capsules.
To predict effects of capsule structure, a simple peaked $T_i$ profile was assumed.

- $<T_i> = 3.0$ keV
- $<\rho_D> = 1.0$ g/cc
- Radius of each layer was adjusted to give different values of $\rho R_{fuel}$

Related modeling has been published by
Secondary protons and neutrons can sample different temperatures and densities.
Simulations for the peaked temperature profile agree well with the hot-spot model for low $\rho R_{\text{fuel}}$ but deviate at higher values.
For cryogenic targets, yields of secondary particles need to be used more carefully since they are produced in a limited region of the fuel.

This profile was obtained by matching $Y_{1n}$, $Y_{2p}$, $Y_{2n}$, $<T_i>$ and $\rho R_{total}$ to experimental values from shot 28900.
Comparison of experiment and simulation for cryogenic shot 28900

<table>
<thead>
<tr>
<th>Experimentally Determined Values</th>
<th>Values From the Simulation</th>
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<tbody>
<tr>
<td>• $Y_{1n}: 1.24E+11$</td>
<td>• $Y_{1n}: 1.41E+11$</td>
</tr>
<tr>
<td>• $Y_{2p}: 2.21E+8$</td>
<td>• $Y_{2p}: 2.25E+8$</td>
</tr>
<tr>
<td>• $Y_{2n}: 1.17E+9$</td>
<td>• $Y_{2n}: 1.28E+9$</td>
</tr>
<tr>
<td>• $\langle T_i \rangle: 3.6$ keV</td>
<td>• $\langle T_i \rangle: 3.56$ keV</td>
</tr>
<tr>
<td>• $\rho R_{total}: 61$ mg/cm$^2$ *</td>
<td>• $\rho R_{total}: 55.4$ mg/cm$^2$</td>
</tr>
</tbody>
</table>

Inferred Values

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<tbody>
<tr>
<td>• $\rho R_{fuel_p, hotspot}: 14.3$ mg/cm$^2$</td>
<td>• $\rho R_{fuel_p, hotspot}: 8.12$ mg/cm$^2$</td>
</tr>
<tr>
<td>• $\rho R_{fuel_n, hotspot}: 47.9$ mg/cm$^2$</td>
<td>• $\rho R_{fuel_n, hotspot}: 46.7$ mg/cm$^2$</td>
</tr>
</tbody>
</table>

* $\rho R_{total}$ is calculated using the energy downshift of secondary proton spectrum

** $\rho R_{hot}$ is the areal density of the hot neutron-producing core ($T_i \geq 0.5$ keV)
Several diagnostics are used to detect fusion products

**protons**
- Magnet-based Charged-particle spectrometers (CPS)
- Wedge-range-filter spectrometers (WRF)

**neutrons**
- Indium activation (primary neutron)
- Copper activation (secondary neutron)
- neutron Time-of-Flight (secondary neutron)
Up to 11 ports can be used for proton spectrometry on the OMEGA target chamber

= WRF spectrometers
= Magnet-based CPS’s
Two kinds of spectrometers* are used to get proton spectra

**Magnet-based Spectrometers (CPSs)**

- TARGET
- 7.6 kG MAGNET
- 50 keV
- 200 keV
- 600 keV
- 1.0 MeV
- 3.0 MeV
- 10 MeV
- 30 MeV

Particle energies identified from trajectories.

**“Wedge-Range-Filter” Spectrometers (WRFs)**

- Incident protons
- Al “wedge” filter
- CR-39

Particle energies identified from local thickness $t$ and diameter of etched proton tracks in CR-39.

Secondary proton spectra from a single thick-shell shot

Shot 20689

- 19 µm CH
- 15 atm D³He

Yield = 2.21E+8

Yield = 2.39E+8

Yield = 2.45E+8
Secondary proton spectra from a single thin shell shot

Shot 27817
- 2.1 µm glass
- 15 atm D$_3$He

Yield and Energy plots:
- Yield $= 4.20 \times 10^7$
- Yield $= 2.69 \times 10^7$
- Yield $= 4.19 \times 10^7$
- Yield $= 3.78 \times 10^7$
- Yield $= 3.00 \times 10^7$
- Yield $= 3.19 \times 10^7$
Experimental data from thin-shell capsules show better agreement between $\rho R_{\text{fuel,2p}}$ and $\rho R_{\text{fuel,2n}}$ than thick-shell and cryogenic capsules.
Summary

- Simulations with peaked temperature profile agree with the hot-spot model at low $\rho R_{\text{fuel}}$ but deviate at high values for both protons and neutrons.

- Simulations suggest that when $\rho R_{\text{fuel}} \cong 10 \text{ mg/cm}^2$ secondary neutron $\rho R_{\text{fuel}}$ can only be used as upper limit.

- For cryogenic targets, secondary yields need to be used more carefully because
  - Protons are produced mostly in the region of deuterium gas and D$_2$ ice mix
  - Neutrons are produced mostly in the inner part of D$_2$ ice region

- Secondary neutrons and protons give nearly the same results for thin-shell capsules, which have:
  - Less fuel-shell mix
  - Higher $T_e$ and lower $\rho R_{\text{fuel}}$ (which decreases “saturation” effects for secondary protons)
Future work

- Simulation using more realistic temperature and density profiles
- Collect more data from thin-shell capsules (2~3 shots are scheduled in the week of December 2, 2002).