Indications of the Rygg Yield Anomaly in Indirect Drive D-\(^3\)He Implosions

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Abstract

The Rygg effect, an anomalous yield reduction in imploding inertial confinement capsules with D-\(^3\)He fill, has been demonstrated repeatedly in direct drive experiments. Yield is found to diminish as a function of \(^3\)He fraction relative to the yield expected from hydrodynamic scaling\(^1,2\). OMEGA implosions of DD and D\(^3\)He-filled capsules in cylindrical and rugby hohlraums\(^3\) provide evidence for the Rygg effect in the indirect drive geometry. In the future, as part of our NLUF research program, we plan to look for the presence of the effect in hohlraum implosions directly.

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Anomalous reduction in scaled direct drive yields has been linked to $^3$He content.

$^3$He fuel (▲, ▼): Hydroequivalent, scaled DD-n yields were compared shot-to-shot. THD+$^3$He fuel (●): DT-n yields were scaled to 1-D simulated yields.

Atwood Number and EOS can be kept constant for a variety of ‘hydroequivalent’ \{D,^{3}\text{He}\} pressures

Atwood number: \[
\frac{\rho_{\text{shell}} - \rho}{\rho_{\text{shell}} + \rho}
\]

Equation of State: \[
p = \left[ \frac{\rho \left( + Z \right)}{A} \right] \frac{k_B T}{m_p}
\]

For both D and \(^{3}\text{He}\), \(\frac{(1+Z)}{A} = 1\):

Fixed \(\rho \Rightarrow\) equivalent Atwood # and EOS in D\(^3\)He mixtures, preserving hydrodynamic behavior.

For any fraction of deuterium, a fill pressure may be chosen to set the mass density:

\[
P_{D_2} + \frac{3}{4} P_{^{3}\text{He}} = X_0
\]

where \(X_0\) is the hydroequivalent fill pressure for pure \(D_2\).
Hydrodynamic scaling for equivalent fuels fails to explain the observed behavior.

Hydrodynamics wrongly predicts the scaled yields $\tilde{Y}$ to be equal for equivalent fuel mixtures.

\[
Y_n = \frac{f_D^2}{\rho^2} \int_{\mathbb{R}^3} \frac{\mathcal{E}, t}{2m_p} \langle \sigma v \rangle_{DD-n} d^3\vec{r} dt \rightarrow \tilde{Y}_n = \frac{\rho^2 - f_D^2}{f_D^2} Y_n
\]

Enhanced barodiffusion due to large electric fields provides a potential mechanism

- “Strong” electric fields across shock fronts increase the diffusion coefficient for the lower-Z ion species
- During the implosion, deuterium diffuses out of the core faster than \( ^3\text{He} \)
- Estimates ~ \textbf{30% reduction} in n yield for \( \text{D}^3\text{He} \) mixtures with \( f_D = 0.5 \)

\[\rho = \text{total density}\]
\[\alpha = \text{light ion species concentration}\]

\[\Delta\alpha < 0, \alpha, \rho, \Delta x, 2\Delta x, 3\Delta x,\text{Radius A.U.}\]

\(^1\) Peter Amendt, O.L. Landen, H.F. Robey, C.K. Li, R.D. Petrasso, unpublished
Barodiffusive effect accurately describes yield reductions for capsules with trace high-Z impurities.

Effect of trace Argon on DD neutron yield (model)

- Model (Mach# = 1.25)
- 50 atm DD + 0.026 atm Ar
- 10 atm DD + 0.026 atm Ar
- Experimental Yield-over-Clean

Does the anomaly affect ignition performance?

• The barodiffusion theory predicts that the “strong” effect (due to shocks) is only present when $Z_1 \neq Z_2$
  - DT yield is directly affected only weakly ($\lesssim 1\%$)
  - T decay to $^3$He will dampen yields

• This mechanism can decrease performance substantially if trace impurities are present
On June 16th, 2009 several rugby and cylindrical hohlraums were shot on OMEGA

From H.F. Robey, APS 2009, Invited Talk
Comparison of hohlraum data to simulations shows evidence of reduced yield

DD scaled neutron yields for indirect drive \{D,^{3}He\} capsules

Yield-Over-Clean (YOC) from simulations by H. Robey, LLNL
Analytical comparison is complicated by trace gasses and non-hydroequivalent fuels

- Implosion dynamics make yield scaling more difficult for capsules with non-uniform values of $X_0$
- All capsules contained trace Ar (0.026 atm) and residual air (0.05 atm)
  - This is known to reduce the DD-n yield by a factor of 2-3, see pg 5.

**Hydroequivalent DD Fill Pressure $X_0$ at shot time**

![Graph showing $X_0$ (atm) vs. shot time]

- DD
- D-3He
Shot-to-shot comparison of yields is unfeasible for this data due to lack of information

### Mathematical Expression

\[ Y_n = \frac{1}{2} n_D^2 \left\langle \rho, t \right\rangle_{DD-n} d^3 \vec{r} dt \propto \rho^2 R_b T_i^m t_b \propto \left(\frac{R_b}{\rho}\right)^3 CR^3 T_i^m t_b \]

Where (CR) is the compression ratio; \( m \approx 3.5 \) at these temperatures

**• D³He shot yields were too low for NTD to record the burn duration (\( t_b \))**

**• Experimental (CR) behavior is unknown above 15 atm**
  - has been shown to be \( \sim \) constant between 3 and 15 atm, due to fuel-shell mix
  - At 15 atm, \( CR_{exp} \approx CR_{1D-sim} \)

A series of shots is being designed to investigate the Rygg effect in indirect drive implosions.

- Sample fill Pressures:
  
<table>
<thead>
<tr>
<th>$f_D$</th>
<th>$P_{D2}$</th>
<th>$P^3_{He}$</th>
<th>$P_{tot}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>12.5 atm</td>
<td>38.9 atm</td>
<td>51.4 atm</td>
</tr>
<tr>
<td>0.5</td>
<td>20.8</td>
<td>27.8</td>
<td>48.6</td>
</tr>
<tr>
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<td>29.2</td>
<td>16.7</td>
<td>45.8</td>
</tr>
<tr>
<td>1</td>
<td>41.67</td>
<td>0</td>
<td>41.67</td>
</tr>
</tbody>
</table>

- Fielded Diagnostics:
  - 3nTOF ($Y_{DDn}$)
  - CPS ($Y_{D3He}$)
  - WRF-n ($Y_{D3He}, Y_{DDn}$)
  - PRM (self-emission radiography)
Summary & Future Work

• An anomalous reduction in the yield of capsules filled with mixtures of D and $^3$He has been demonstrated in direct drive ICF

• Indirect drive experiments are indicative of the D-$^3$He anomaly as well

• A series of shots will be planned to look for the Rygg Effect in indirectly driven capsules as part of our NLUF research program.

• We will also investigate the presence of the effect in direct drive exploding pusher capsules
The Rygg Effect
& Hydrodynamic Equivalence
Theory & Possible Explanations
Indirect Drive Experiments