Modeling of Multiple-Ion Heat Transport in ICF Implosions

OMEGA target
23 kJ, 1-ns square pulse

24-μm CH

D₂ (X atm) + ³He (Y atm)

435 μm

15-atm D₂ equivalent

Yₚ-norm = Yₚ \frac{6 \text{ atm} \times 12 \text{ atm}}{X \times Y}

D fraction

Yₚ-norm (×10⁸)

Experiment
Single-ion
Multi-ion with redistribution

D. Li
University of Rochester
Laboratory for Laser Energetics

50th Annual Meeting of the American Physical Society
Division of Plasma Physics
Dallas, TX
17–21 November 2008
Summary

Multiple-ion effects in thermal conduction and mix were studied using the Chapman–Enskog method

- The dependence of neutron and proton yields in $\text{D}^3\text{He}$ implosions on the $\text{D}_2$ fraction\(^1\) cannot be explained with hydrosimulation using single-ion transport models.

- The multi-ion effects modify ion thermal conduction and lead to species diffusion due to gradients in hydro profiles.

- Results of the model indicate that the modification of ion conduction due to multiple-species effects is small.

- The diffusion mechanism produces trends consistent with the experimental data for $\text{D}$ fraction larger than 50%.

Collaborators

V. N. Goncharov
A. V. Maximov
I. V. Igumenshchev
S. Skupsky

University of Rochester
Laboratory for Laser Energetics

J. R. Rygg

Lawrence Livermore National Laboratory

J. A. Frenje
R. D. Petrasso

Plasma Science and Fusion Center
Massachusetts Institute of Technology
The single-ion model deviates from the experiment measurement of neutron and proton yields.

\[ Y_p \propto X \times Y \]

\[ Y_{p\text{-norm}} = Y_p \frac{6 \text{ atm} \times 12 \text{ atm}}{X \times Y} \]

Experimental

1-D (normal)
The Chapman–Enskog method is used to derive transport coefficients

\[
\frac{\partial f_1}{\partial t} + \mathbf{v} \cdot \frac{\partial f_1}{\partial \mathbf{r}} + \frac{eE_i}{m_1} \frac{\partial f_1}{\partial \mathbf{v}} = J_{11} + J_{12} + J_{1e} \quad f_1 = f_M^1 + \delta f_1
\]

\[
(v - \mathbf{u})_i \left( x - \frac{5}{2} \right) \frac{\partial (\ln T)}{\partial r_i} + (v - \mathbf{u})_i d_i + \frac{m_1}{T} V_{ij} \frac{\partial u_i}{\partial r_j} = \frac{J_{11} + J_{12}}{f_1}
\]

- Ion heat flux
- Ion viscosity

\[
d_i = \frac{\partial (\ln P_1)}{\partial r_i} - \frac{m_1}{\rho T} \frac{\partial P_T}{\partial r_i} + \frac{1}{P_1} \frac{\partial P_e}{\partial r_i} \frac{n_1 Z_1^2}{n_1 Z_1^2 + n_2 Z_2^2} + \frac{n_2 Z_1 Z_2 (Z_1 - Z_2) eE_i}{T (n_1 Z_1^2 + n_2 Z_2^2)}
\]

TC8311
The Chapman–Enskog method is used to derive transport coefficients.

\[
\frac{\partial f_1}{\partial t} + \vec{v} \frac{\partial f_1}{\partial \vec{r}} + \frac{eE_i}{m_1} \frac{\partial f_1}{\partial \vec{v}} = J_{11} + J_{12} + J_{1e} \quad f_1 = f_M^1 + \delta f_1
\]

\[
x = \frac{m_1(\nu-u)^2}{2T}
\]

\[
(\nu-u)_i \left( x - \frac{5}{2} \right) \frac{\partial (\ln T)}{\partial r_i} + (\nu-u)_i d_i + \frac{m_1}{T} V_{ij} \frac{\partial u_i}{\partial r_j} = \frac{J_{11} + J_{12}}{f_1}
\]

Ion heat flux

Ion viscosity

\[
d_i = \frac{\partial (\ln P_1)}{\partial r_i} - \frac{m_1}{\rho T} \frac{\partial P_T}{\partial r_i} + \frac{1}{P_1} \frac{\partial P_e}{\partial r_i} \frac{n_1Z_1^2}{n_1Z_1^2 + n_2Z_2^2} + \frac{n_2Z_1Z_2(Z_1-Z_2)eE_i}{T(n_1Z_1^2 + n_2Z_2^2)}
\]
Ion heat flux and diffusion velocity depend on ion temperature and pressure gradient

\[
\delta f_1 = f_M^1 (v - u)_i \left[ \Phi_1(v) \frac{\partial \ln T}{\partial r_i} + \Phi_2(v) d_i \right]
\]

\[
\Phi(x) = \sum_n a_n L_n^{3/2}(x)
\]

\[
\bar{q}_1 = \int \tilde{v} \frac{mv^2}{2} \delta f_1 d\tilde{v} \quad \delta \bar{u}_1 = \frac{1}{n_1} \int \tilde{v} \delta f_1 d\tilde{v}
\]
The modifications due to multi-ion conduction to the hydro profile are small.

Only the modifications to the thermal conduction are included.
The difference in diffusion velocity leads to the particle redistribution.

\[
\delta u_D \neq \delta u_{He}
\]

\[
m_D n_D \delta u_D + m_{He} n_{He} \delta u_{He} = 0
\]

Redistributed density is used only to calculate the reaction rate.
The trend predicted by the diffusion mechanism is consistent with the experiment for large D fraction.

\[
Q_{ie} \text{ (single-ion)} = \frac{3m_e n_e}{\langle m_i \rangle \tau_{ei}} (T_e - T_i)
\]

\[
Q_{ie} \text{ (multi-ion)} = 3m_e n_e (T_e - T_i) \left( \frac{1}{m_1 \tau_{e1}} + \frac{1}{m_2 \tau_{e2}} \right)
\]
Multiple-ion effects in thermal conduction and mix were studied using the Chapman–Enskog method.

- The dependence of neutron and proton yields in $D^3He$ implosions on the $D_2$ fraction$^1$ cannot be explained with hydrosimulation using single-ion transport models.

- The multi-ion effects modify ion thermal conduction and lead to species diffusion due to gradients in hydro profiles.

- Results of the model indicate that the modification of ion conduction due to multiple-species effects is small.

- The diffusion mechanism produces trends consistent with the experimental data for $D$ fraction larger than 50%.

---