Thermal Decoupling of Deuterium and Tritium During the Inertial Confinement Fusion Shock-Convergence Phase

N. V. Kabadi,[1] R. Simpson,[1] S. Atzeni,[2] J. Eriksson, P. J. Adrian,[1] A. Bose,[1] J. A. Frenje,[1] M. Gatu Johnson,[1] B. Lahmann,[1] C. K. Li,[1] C. E. Parker,[1] F. H. Séguin,[1] G. D. Sutcliffe,[1] C. J. Forrest,[3] S. Fess,[3] V. Yu. Glebov,[3] R. T. Janezic,[3] O. M. Mannion,[3] H. G. Rinderknecht,[3] M. J. Rosenberg,[3] C. Stoeckl,[3] G. Kagan,[4] M. Hoppe,[5] R. Luo,[5] M. Schoff,[5] C. Shuldberg,[5] H. W. Sio,[6] J. Sanchez,[6] L. Berzak Hopkins,[6] D. Schlossberg,[6] K. Hahn,[6] C. Yeamans,[6] and R. D. Petrasso[1]

[1]Plasma Science and Fusion Center, Massachusetts Institute of Technology
[2]Dipartimento SBAI, Universit'a degli Studi di Roma "La Sapienza," Italy
[3]Laboratory for Laser Energetics, University of Rochester
[4]Centre for Inertial Fusion Studies, The Blackett Laboratory, Imperial College, UK
[5]General Atomics
[6]Lawrence Livermore National Laboratory

A series of experiments using DT gas-filled, shock-driven implosions was carried out at the Omega Laser facility. The capsules were nominally 2.3-μm-thick glass shells with an 860-μm outer diameter that were driven by a 0.6-ns square laser pulse delivering 15 kJ. Both the initial fill densities (0.2 to 4 mg/cm^3) and fill ratios (40% to 97% D) were varied. These experiments generated conditions relevant to the shock-convergence phase of hot-spot ignition experiments such as those conducted at the National Ignition Facility (NIF), without being complicated by a subsequent compression phase. With a high ablation rate and minimal residual shell mass, implosions of this type are insensitive to hydrodynamic instabilities. Data from shock-driven, indirect-drive exploding pushers (IDEP's) conducted on the NIF are also used. In these experiments, the spectral DTn and DDn ion temperatures (T_{sDTn} and T_{sDDn}) are inferred from the width of the produced neutron spectra as measured by neutron time-of-light diagnostics. To infer the level of thermal decoupling, the apparent species temperatures (T_{T} and T_{D}) can be inferred directly from the measured spectral temperatures based on the species masses (m_{D} and m_{T}) without accounting for emission weighting due to temperature profiles:

$$T_{\text{D}} = T_{\text{sDDn}}, \tag{1}$$

$$T_{\text{T}} = T_{\text{sDTn}} + \frac{m_{\text{D}}}{m_{\text{T}}}\left(T_{\text{sDTn}} - T_{\text{sDDn}}\right). \tag{2}$$

The differential equation governing the evolution of the ratio of two-ion temperatures due to ion–ion equilibration is given by

$$\frac{d}{\mathrm{d}t}\frac{T_2}{T_1} = -\frac{1}{\tau_{12}}\left(\frac{T_2}{T_1}\right)^2 + \left(\frac{1}{\tau_{12}} - \frac{1}{\tau_{21}}\right)\frac{T_2}{T_1} + \frac{1}{\tau_{21}}, \tag{3}$$

where τ_{21} is the characteristic time at which species 2 equilibrates with species 1, which can be calculated from observables. The solution to this equation, when ignoring the weak dependence on species fraction, can be written as

$$\frac{T_2}{T_1} = \tanh\left[\frac{t}{\tau_{\text{ii}}} + \operatorname{atanh}\left(R_0\right)\right], \tag{4}$$

where the integration constant R_0 is the temperature ratio as t goes to 0 and the total equilibration time is given by the harmonic mean of the τ_{12} and τ_{21}:

$$\tau_{ii} = 2\left[\frac{1}{\tau_{12}} + \frac{1}{\tau_{21}}\right]^{-1}. \tag{5}$$

This dynamic model can be applied to the average observables from an implosion. For the average time scale, τ_N is calculated from the measured DT neutron emission time τ_{DTn}:

$$\tau_N = \frac{\tau_{DTn}}{\tau_{ii}}. \tag{6}$$

Figure 1 shows the apparent ratio of T_T to T_D plotted versus τ_N for three different D:T fill ratios. The observed trend is consistent for all fill fractions and well described by the equation

$$\frac{T_T}{T_D} = \tanh\left[\tau_N + \text{atanh}\left(1.52 \pm 0.04\right)\right], \tag{7}$$

indicating a trend that begins at ≈1.5 and decays to 1 (or thermal equilibrium) at a rate determined by τ_N. Since the initial temperature ratio will be dominated by shock coupling based on ion-species properties, we conclude that the shock coupling scales linearly with mass (D and T have identical charge), $T_i \propto m_i$. Coupling directly proportional to mass is consistent with the rebounding shock stagnating the incoming flow and converting the flow energy of a species into thermal energy. It is also consistent with predictions for the mass dependence of shock coupling[1,2] and recent astrophysical observations of collisionless shock heating.[3]

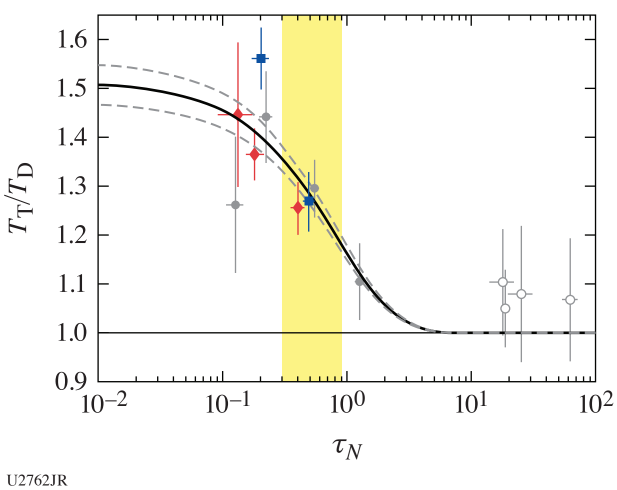

Figure 1
Apparent temperature ratio versus the normalized equilibration time scale for DT gas-filled implosions. Red diamonds are 97:3, gray circles 50:50, and blue squares 40:60 D:T atomic fill ratio. The open gray circles are from NIF IDEP's. All points are consistent with the equation T_T/T_D $[\tau_N + \text{atanh}(1.52 \pm 0.04)]$, shown by the solid black curve with dashed 95% confidence interval. The reduced χ^2 statistic for this fit is 0.96. The yellow-shaded region represents the conditions most relevant to the shock-convergence phase in NIF ICF implosions.

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