Probing Fuel-Ion Species Dynamics in Shock-Driven Inertial Confinement Fusion Implosions Using Multiple Reaction Histories

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Strong shocks are ubiquitous in inertial confinement fusion (ICF) and many astrophysical plasmas,[1] and the experimental results described in this work may provide new insights into phenomena in these fields. ICF produces thermonuclear fusion in the laboratory by imploding a spherical target filled with light-ion fuel, and capsule compression begins with launching strong shock(s) into the central gas during the shock phase. During this time, sharp gradients at the shock front are expected to drive temperature and density differences between the different fuel-ion (D, T, and ^{3}He) populations. These multi-ion effects that may impact and modify plasma conditions are not modeled in average-ion-fluid codes but are simulated in kinetic-ion simulations.

In contrast with previous studies that relied on time-integrated measurements, this work[2] presents time-resolved observation of fuel-ion species dynamics in ICF implosions using DT and D^{3}He reaction histories (Fig. 1). These reaction histories were measured with a particle x-ray temporal diagnostic (PXTD),[3] which captures the relative timing between these reaction histories with unprecedented precision (~10 ps). These time-resolved measurements are contrasted with average-ion-fluid *DUED* and multi-ion *LSP* simulations. The difference between the measured fusion reaction histories during the shock phase is consistent with rapidly changing fuel-ion composition caused by a strong shock in the central gas of an ICF target.

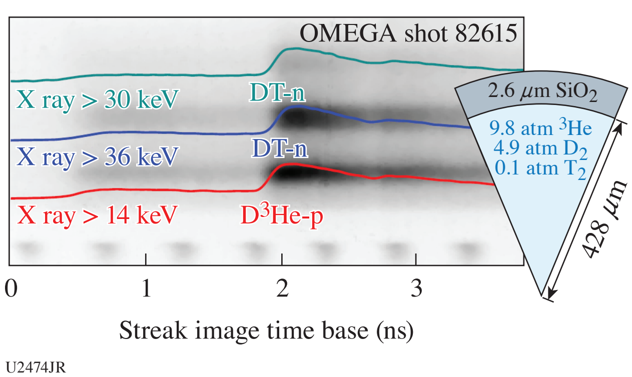

Figure 1
PXTD streak image on OMEGA shot 82615. The target is a thin-glass capsule filled with D^{3}He and a trace of T$_2$. PXTD measured both the x-ray emissions as well as the D^{3}He and DT reaction histories from the implosion.

This experiment uses an exploding-pusher platform,[4] which is simple and ideal for studying the multi-ion dynamics during the shock phase in an ICF implosion. The reason for this is that shock-phase plasma conditions (temperature, density, ion mean-free-path, shock strength) are similar in all these implosions. These exploding-pusher targets are 860 μm in diameter with a 2.7-μm-thick SiO_2 shell. The gas-fill density is 2.2 mg/cm^3, with an atomic fuel composition of 49.6% D, 49.7% ^{3}He, and 0.7% T. These targets are driven symmetrically by 60 laser beams on the OMEGA Laser System with a total energy of 14.4 kJ using a 0.6-ns-sq pulse shape. These implosions are hydrodynamic-like, with $\lambda_{\text{ii}}/R_{\text{burn}} \sim 3$, where λ_{ii} is the ion mean free path and R_{burn} is the fuel radius at peak burn.

The primary measurements in this experiment are the absolute DT and D^{3}He reaction histories, which are simultaneously measured with the PXTD (Fig. 1). This is done by measuring the time-arrival histories of the monoenergetic 14.1-MeV DT-n and 14.7-MeV D^{3}He-p as they escape the implosion. Since all measurements are made with the same diagnostic, the relative timing uncertainty between the DT and D^{3}He reaction histories is ~10 ps (versus ~40 to 50 ps, with the standard method of cross-timing between two stand-alone diagnostics). This innovation is crucial to capturing the relative timing between different nuclear burns with sufficiently high precision to enable meaningful comparison between measurements and simulations. In comparison with the average-ion-fluid *DUED*[5] simulation (Fig. 2), a significantly higher D^{3}He reaction rate is observed relative to DT at the onset of the shock burn. This is observed on all four shots, and higher-than-expected ion temperature alone early in time in the fuel cannot explain this observation.

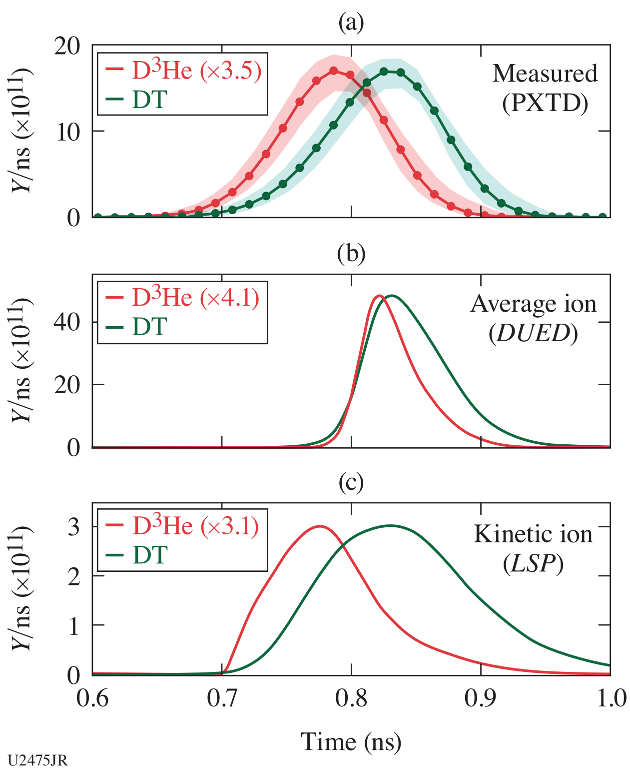

Figure 2
Absolute D^{3}He (red) and DT (blue) reaction histories measured by PXTD and simulated by *DUED* and *LSP*, for OMEGA shot 82615. The magnitudes of the D^{3}He histories are scaled to match the DT histories for clarity in each case. Uncertainties in the PXTD data are indicated by the shaded regions.

The measured timing difference is consistent, however, with ion-species separation driven by sharp pressure gradients at the shock front in the implosion. The dominant terms driving the D and ^{3}He ions forward relative to the T ions are from the ion pressure gradient (barodiffusion,[6] which accelerates the lighter D ions ahead) and the electron pressure gradient (electrodiffusion,[7] which accelerates the higher-charge ^{3}He ions ahead).

Fuel-ion–species separation is also observed in a kinetic-ion *LSP*[8] simulation, which, unlike the average-ion-fluid code *DUED*, treats the D, T, and ^{3}He ion population separately. During shock convergence, fuel-ion–species separation has already developed between the D, T, and ^{3}He ions, with the T ions lagging behind the shock front. This led to a depletion of T ions on the central fuel region when the shock rebounds, delaying the DT burn relative to the D^{3}He burn. Qualitatively, *LSP* simulations clearly demonstrate how fuel-ion–species separation that developed during shock propagation and rebound manifest as a timing differential between reaction histories (Fig. 2).

In summary, the time-resolved DT and D^{3}He reaction rates in hydrodynamic-like shock-driven implosions cannot be explained by average-ion simulations and is attributed to ion-species separation between the D, T, and ^{3}He ions during shock convergence and rebound. At the onset of the shock burn, the ^{3}He/T fuel ratio in the burn region inferred from the measured reaction histories is much higher as compared to the initial ^{3}He/T gas-fill ratio. Since T and ^{3}He have the same mass but a different charge, these results indicate that the charge-to-mass ratio plays an important role in driving fuel-ion–species separation during strong shock propagation. It is unclear how these multi-ion effects affect implosion performance during the deceleration and compression phase since existing experimental results have been mixed. A planned upgrade to the PXTD diagnostic (the cryoPXTD) will provide improved nuclear and x-ray data for these implosion experiments, as well as time-resolved electron temperature measurement for the OMEGA cryogenic program. Future work includes quantifying these effects in very hydrodynamic shock-driven implosions; in very kinetic implosions; in the ablative phase of compressive implosions; and in astrophysical settings such as SN 1987a (Ref. 1), where nonequilibrium kinetic effects and signatures (such as temperature differences between ion species) could be present.

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