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The impact of fuel-ion diffusion in Inertial Confinement Fusion (ICF) implosions is assessed using nuclear reaction yield ratios and reaction histories. In T³He-gas-filled (with trace D) shock-driven implosions, the observed TT / T³He yield ratio is ~2× lower than expected from temperature scaling. In D³He-gas-filled (with trace T) shock-driven implosions, the timing of the D³He reaction history is ~ 50 ps earlier than the DT reaction histories, and average-ion hydrodynamic simulations cannot reconcile this timing difference. Both experimental observations are consistent with reduced T ions in the burn region as predicted by multi-ion diffusion theory and Particle-in-Cell (PIC) simulations.

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I. INTRODUCTIONS

In Inertial Confinement Fusion (ICF) [1], a spherical target filled with fusion fuel is compressed to reach fusion temperature and density. Conventionally, ICF implosion simulations and modeling heavily rely on average-ion hydrodynamic codes. Understanding the roles of ion kinetics and diffusion has become more important since the start of the National Ignition Campaign [2] in 2009, as highlighted by recent theoretical [3,4], simulation [5-7], and experimental [8-12] studies. However, most of the experimental results focused on time-integrated measurements, which average over the implosion burn duration and obscure these important effects.

In a hot-spot ignition design, strong shocks are launched into the gas, and the convergence and rebound of these shocks are thought to set up the initial conditions for hot spot formation. These shocks distribute energy to particles proportional to their masses, creating a temperature disequilibrium between the ions and electrons. Because the electrons are more mobile than the ions, they stream ahead and preheat the upstream material. This separation between ions and electrons also creates strong electric fields across the shock front, in addition to the sharp pressure and density gradients. These self-generated electric fields have been observed in ICF implosions [13], as well as in planar shock-tube [14] experiments.

Recent ICF implosion experiments suggest that kinetic and multi-ion-fluid effects can impact performance in ways not captured by standard hydrodynamic codes such as DUED [15]. These experimentally-observed effects include reduced yield [8], temperature difference between ion species [9], unexpected yield scaling [12], ion diffusion [10], and ion species separation [11]. To address these experimental results, hydrodynamic codes with reduced ion kinetic models [5] and kinetic-ion codes [16] have been used to better capture these multi-ion and kinetic physics in ICF implosions.

In this work, the impact of ion diffusion in T³He-gas-filled (with trace D) shock-driven implosions and D³He-gas-filled (with trace T) shock-driven implosions is discussed. Sec. II will outline the experiment and observables. Sec. III will interpret these data in the context of multi-ion diffusion theory, average-ion hydrodynamic simulations, and Particle-in-Cell (PIC) simulations. Sec. IV will discuss future directions and potential implications of these findings.

II. SHOCK-DRIVEN IMPLOSION EXPERIMENTS

The OMEGA experiments in this work use shock-driven implosions [17] as an experimental platform to probe kinetic and multi-ion effects during shock propagation and rebound in ICF implosions. A shock-driven implosion is one where the bulk of fusion reactions occurs from shock heating of the fuel. These simple implosions have been invaluable for studying ICF implosion dynamics because they are low convergence, 1-D in nature, and insensitive to drive asymmetry and hydrodynamic mix [10]. The two sets of implosions described in this work are T³He-gas-filled (with trace D) shock-driven implosions and D³He-gas-filled (with trace T) shock-driven implosions. The spherical targets have an outer diameter of 860 μm with a ~2.3-μm-thick SiO₂ shell. All sixty laser beams [18] (351 nm, ~ 14 kJ total, 0.6 ns square pulse shape) are used to illuminate the target. 2-D smoothing by spectral dispersion, polarization smoothing, and phase plates are used to improve laser uniformity.

These implosions are hydrodynamic-like, with Knudsen number (Nk) ~ 0.3, estimated here as ratio of the burn-averaged ion mean free path (λi) and the fuel radius (Rburn) at peak nuclear burn. For the D³He-gas-filled (with trace T) implosions, the primary observables are the D³He-p and the DT-n. For the T³He-gas-filled (with trace D) implosions, the primary observables are the T³He-d and the TT-n. The relevant DT, D³He, TT, and T³He nuclear reactions are given...
by:

\[ \text{D} + \text{T} \rightarrow \alpha (3.5 \text{ MeV}) + n (14.1 \text{ MeV}) \] (1)

\[ \text{D} + ^3\text{He} \rightarrow \alpha (3.6 \text{ MeV}) + p (14.7 \text{ MeV}) \] (2)

\[ \text{T} + \text{T} \rightarrow \alpha (\leq 6.6 \text{ MeV}) + 2n (\leq 10.6 \text{ MeV}) \] (3)

\[ \text{T} + ^3\text{He} \rightarrow \alpha (4.8 \text{ MeV}) + d (9.5 \text{ MeV}) \] (BR \sim 43\%) (4)

Strong shock heating can potentially cause differences between the ion density profiles (ion diffusion) and/or between the ion temperature profiles (ion thermal decoupling). For example, the T and \(^3\text{He}\) ion temperatures are expected to be higher than the DT ion temperature immediately post shock because of their higher masses. To as far as reasonably possible isolate the mechanism and impact of ion diffusion, these experiments focus on relatively high gas fill density implosions (\> 2 mg/cc), corresponding to a short ion-impact ionization time (\sim 30 ps) during the shock burn as compared to the burn duration (\sim 100 ps). The second key step taken to reduce the impact of different ion temperatures is to consider reaction pairs where the reactants have the same masses, as collisional shock heating is expected to partition energy to ions according to their masses. For \(^3\text{He}\)-gas-filled (with trace T) implosions, the reaction pairs DT and \(^3\text{He}\) are considered. For \(^3\text{He}\)-gas-filled (with trace D) implosions, the reaction pairs TT and \(^3\text{He}\) are considered. As an example, for two Maxwellian ion populations with two different ion temperatures, the effective fusion temperatures \(T_{\text{fusion}}\) (for DT and \(^3\text{He}\)) are given by:

\[ T_{\text{fusion,DD}} = \frac{m_p T_{\text{DD}} + m_{^3\text{He}} T_{\text{DD}}}{m_p + m_{^3\text{He}}} \] (5)

\[ T_{\text{fusion,DT}} = \frac{m_p T_{\text{DD}} + m_{^3\text{He}} T_{\text{DT}}}{m_p + m_{^3\text{He}}} \] (6)

As Eq (5) and Eq (6) show, higher \(^3\text{He}\) and T temperatures (because of their higher masses) affect the \(^3\text{He}\) and DT fusion temperatures in the same way. In general, the fusion reaction yield integrated over the implosion duration for reactants 1 and 2 is given by:

\[ Y_{12} = \int_{1+\delta_{12}} \sigma_i n_i^2 \langle \sigma v \rangle_{12} dV dt \] (7)

Where \(f\) is the ion species fraction of reactants 1 and 2, \(n_i\) is the ion number density, and \(\langle \sigma v \rangle\) is the Maxwellian-averaged fusion reactivity. \(\delta_{12}\) is the Kronecker delta function. The fusion yield ratio can be approximated as:

\[ \frac{Y_{11}}{Y_{12}} \approx \frac{f_1 (\langle \sigma v \rangle_{11})}{2 f_2 (\langle \sigma v \rangle_{12})} \] (8)

A summary of main experiment observables is provided in Table I. A suite of optical, nuclear, and X-ray diagnostics are used to diagnose these implosions. For the main experiment observables, the \(^4\text{He}-p\) and \(^3\text{He}-d\) yields are measured by the Wedge-Range-Filter spectrometers (19) and the Charged Particle Spectrometers (20). The DT-n yield, the DT temperature, and the TT-n yield are measured by neutron time-of-flight detectors (21). The nuclear peak emission time (bang time) is measured by the Neutron Temporal Diagnostic (22).

In Table I, the observed TT/\(^3\text{He}\) and DT/\(^3\text{He}\) yield ratios have been corrected for the branching ratio in the \(^3\text{He}\) reaction, and for the fact that two neutrons are produced per TT reaction. The expected TT/\(^3\text{He}\) and DT/\(^3\text{He}\) yield ratios are calculated using the fuel fraction and fusion reactivity (Eq. 8). The reactivity ratio is a strong function of the ion temperature, and the corresponding expected yield ratio is different for each shot because different ion temperatures are measured on each shot.

Experimentally, observed yield difference between shots is most likely to have been caused by differences in target shell thickness. For example, shot 86208 has the thickest shell, latest bang time, highest \(^3\text{He}-d\) yield, and lowest observed TT/\(^3\text{He}\) yield ratio. Laser parameters (total energy, pulse shape) are repeatable to within 3% and are not expected to cause this level of difference. Hydrodynamic simulations also confirm that shell thickness rather than shell diameter has the most direct impact on implosion observables. For both the TT/\(^3\text{He}\) and DT/\(^3\text{He}\) reaction

| Shot | Outer diameter (um) | \(\text{SiO}_2\) thickness (um) | \(\rho\) (mg/cc) | Fraction D | Fraction \(^3\text{He}\) | Fraction T | Bang time (ps) | TT-n yield | \(^3\text{He}-d\) yield | DT-T (keV) | TT/\(^3\text{He}\) yield, (observed) | TT/\(^3\text{He}\) yield, (expected) |
|------|-------------------|------------------|--------------|-----------|----------------|-----------|--------------|-------------|----------------|-------------|----------------|----------------------|
| 86193 | 853.7 | 2.3 | 2.80 | 0.004 | 0.50 | 0.49 | 780 | 5.26E+10 | 1.35E+09 | 11.7 | 8.0 | 20.0 |
| 86194 | 852.5 | 2.4 | 2.79 | 0.004 | 0.50 | 0.50 | 781 | 8.13E+10 | 1.41E+09 | 11.4 | 11.8 | 15.5 |
| 86195 | 855.6 | 2.2 | 2.85 | 0.004 | 0.51 | 0.49 | 766 | 7.08E+10 | 1.36E+09 | 11.3 | 10.7 | 22.0 |
| 86208 | 863.1 | 2.5 | 2.99 | 0.004 | 0.53 | 0.46 | 837 | 6.54E+10 | 2.07E+09 | 10.5 | 6.5 | 20.0 |

| Shot | Outer diameter (um) | \(\text{SiO}_2\) thickness (um) | \(\rho\) (mg/cc) | Fraction D | Fraction \(^3\text{He}\) | Fraction T | Bang time (ps) | DT-n yield | \(^3\text{He}-p\) yield | DT-T (keV) | DT/\(^3\text{He}\) yield, (observed) | DT/\(^3\text{He}\) yield, (expected) |
|------|-------------------|------------------|--------------|-----------|----------------|-----------|--------------|-------------|----------------|-------------|----------------|----------------------|
| 82614 | 889 | 2.7 | 2.02 | 0.50 | 0.50 | 0.007 | 841 | 1.98E+11 | 4.99E+10 | 11.6 | 4.0 | 5.0 |
| 82615 | 855 | 2.7 | 2.03 | 0.50 | 0.50 | 0.007 | 831 | 1.89E+11 | 5.04E+10 | 10.5 | 3.8 | 6.2 |
pairs, the observed yield ratios are lower than the expected yield ratios based on temperature scaling, and interpretations for this observation will be discussed in Sec. III.

In the D³He-gas-filled (with trace T) implosions, DT and D³He reaction histories are also simultaneously measured with high relative precision (±10 ps) using the Particle X-ray Temporal Diagnostic (PXTD) [23], as shown in Fig. 1. The timing of the D³He reaction history is ~ 50 ps earlier than the DT reaction history, and this timing differential is much larger than that predicted by average-ion DUED hydrodynamic simulations (~ 10 ps). As will be discussed in Sec. III, both the observed yield ratios and reaction histories are consistent with the D and ³He ion histories matched to the shock front relative to the T ions during shock propagation.

The second mechanism is baro-diffusion, relating to the ion pressure gradient [3]. Baro-diffusion accelerates lighter ions ahead of heavier ions, and will accelerate D ions ahead of the T ions. The second mechanism is electro-diffusion, relating to the electric potential gradient (the electric field) [4]. Electro-diffusion accelerates ions with a higher charge-to-mass ratio ahead of ions with a lower charge-to-mass ratio, and will accelerate ³He ions ahead of the T ions. In both scenarios, the T ions are behind the D ions and ³He ions as the shock propagates inward.

This qualitative picture provided by multi-ion diffusion theory is supported by kinetic-ion PIC LSP [16] simulations, which, in contrast to average-ion hydrodynamic codes, do treat the different ion species separately. In the LSP simulation, the fuel ion species are treated kinetically, while the electrons are treated as a fluid with a flux limiter of 0.06. The choice of flux limiter has been shown to minimally impact LSP results. The simulation uses 1-D spherical geometry with reflecting boundary conditions, with 2,000 cells covering a radial distance of 1,000 µm (excluding the origin to avoid numerical stability). The simulation is initialized with 5,000 particles per ion species per cell. More information on the PIC simulation setup and collision operators is discussed in [7].

Fig. 2a illustrates shock propagation in a kinetic-ion LSP simulation that treats the ion populations separately. This simulation is for a D³He-gas-filled (with trace T) implosion. In Fig. 2, as the shock is propagating inward at t = 0.63 ns, the D and ³He ions are racing ahead. The T ions are notably lagging behind the shock front. This ion species separation at t = 0.63 ns during shock convergence developed in a triton depletion in the burn region during shock rebound at t = 0.73 ns (when the shock yields are being produced). As expected from the low convergence, mixing of the SiO₂ ions into the fuel plasma is negligible in the LSP simulation.

![Figure 1: D³He (red) and DT black reaction histories measured on the PXTD in D³He-gas-filled (with trace T) implosions.](image)

![Figure 2: Density profiles from an LSP simulation of a D³He-gas-filled (with trace T) implosion at t = 0.63 ns and t = 0.73 ns, during shock convergence and shock rebound, respectively. The ion density profiles for D, T, and ³He are in blue, gold, and red, respectively.](image)

These differences in the ion density profiles in the kinetic simulation from average-ion-fluid simulation in turn translate to differences in the timing of the simulated reaction histories, which is shown in Fig. 3. In the DUED simulations, the D³He and DT bang times (times of peak thermonuclear production) are nearly simultaneous (within 10 ps), which is very different from the measured timing difference and well outside the measurement uncertainty. In contrast, the simulated peak timing difference between the D³He and DT reaction histories in the kinetic-ion LSP simulation (~ 50 ps) is in much closer agreement with measurements.

III. DATA INTERPRETATION

Ion species separation in a multi-component plasma is driven by sharp pressure and temperature gradients at the shock front, and depends on both local plasma conditions (pressure, temperature) and differences in charge and mass between the different ion species [4]. This is a hydrodynamic treatment of multi-ion-species diffusion, which is strictly valid only when the ion-ion mean free path is small compared to the gradient scale lengths. However, this treatment does produce qualitatively correct behaviors as long as the plasma is not very kinetic.

In particular, two diffusion mechanisms play important roles in the interactions between D, ³He, and T ions at the shock front, and these mechanisms are driven by the differences in the ions’ charges and masses. The first mechanism is baro-diffusion, relating to the ion pressure gradient [3]. Baro-diffusion accelerates lighter ions ahead of heavier ions, and will accelerate D ions ahead of the T ions. The second mechanism is electro-diffusion, relating to the electric potential gradient (the electric field) [4]. Electro-diffusion accelerates ions with a higher charge-to-mass ratio ahead of ions with a lower charge-to-mass ratio, and will accelerate ³He ions ahead of the T ions. In both scenarios, the T ions are behind the D ions and ³He ions as the shock propagates inward.
Figure 3: a) DUED-simulated and b) LSP-simulated $^3$He (red) and DT (black) reaction histories for a $^3$He (with trace T) shock-driven implosion.

In simulations, the absolute timing and amplitude of the reaction histories (relative to the start of the laser pulse) are strongly affected by many factors (laser energy, absorption, equations of state, flux limiter, etc). However, the relative timing between the reaction histories is a much more robust and insensitive quantity in the simulation. In the kinetic-ion simulation, the absolute nuclear yield is quite a bit lower than measured because the laser drive is truncated when the kinetic-ion calculations began. This has been shown to not affect the relative timing of the simulated reaction histories.

IV. DISCUSSION AND CONCLUSION

The impact of ion diffusion during the shock phase of ICF implosions has been investigated using both time-integrated and time-resolved nuclear observables. The lower-than-expected $T/T^3$He yield ratios (in $T^3$He-gas-filled implosions with trace D) and lower-than-expected DT/$^3$He yield ratios (in $D^3$He-gas-filled implosions with trace T) are consistent with tritium depletion in the burn region during shock rebound. At the same time, the observed earlier $^3$He reaction history timing relative to DT measured using the PXTD and comparison with kinetic-ion simulations provide additional indications that this tritium depletion is related to fuel-ion-species separation that developed during shock propagation into the fuel.

These experimental observations provide new insights into kinetic and multi-ion physics not modeled in average-ion hydrodynamic codes. The experiments here focused on the shock phase of ICF implosions. Using both time-integrated and time-resolved nuclear observables, future experiments will explore these kinetic and multi-ion physics as implosion plasma conditions become increasingly more collisional. Future work will also begin probing how these kinetic and multi-ion effects that developed during the shock phase propagate into and affect hot spot formation during the later compression phase.

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