Time-Dependent Nuclear Measurements of Mix in Inertial Confinement Fusion

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(Received 19 January 2007; published 24 May 2007)

The first time-dependent nuclear measurements of turbulent mix in inertial confinement fusion have been obtained. Implosions of spherical deuterated-plastic shells filled with pure $^3$He gas require atom-scale mixing of the shell and gas for the D-$^3$He nuclear reaction to proceed. The time necessary for Rayleigh-Taylor (RT) growth to induce mix delays peak nuclear production time, compared to equivalent capsules filled with a D$_2$-$^3$He mixture, by $\pm 75$ ps, equal to half the nuclear burn duration. These observations indicate the likelihood of atomic mix at the tips of core-penetrating RT spikes.

DOI: 10.1103/PhysRevLett.98.215002

PACS numbers: 52.57.Fg, 47.27.wj, 52.25.Tx, 52.70.Nc

Ignition and high gain in inertial confinement fusion (ICF) [1,2] are critically dependent on mitigation of the Rayleigh-Taylor (RT) instability. ICF capsules typically consist of a spherical shell filled with a gaseous fuel, and are imploded using lasers (direct-drive) or x rays (indirect-drive) to rapidly deposit energy and ablate the capsule surface. The RT instability, which is the growth of nonuniformities at a density interface when a low-density material accelerates a high-density material, occurs during two distinct intervals in ICF implosions. During the acceleration phase, the low-density ablating plasma accelerates the solid shell inwards, and perturbations seeded by energy deposition nonuniformities or initial capsule surface roughness feeds through to the inner fuel-shell surface. During the deceleration phase, shortly before the time of maximum capsule compression, growth of the RT instability at the fuel-shell interface quickly saturates, resulting in small-scale, turbulent eddies that leads to atomic-scale mixing of the fuel and shell [3]. RT growth and the resulting mixing processes disrupt the formation of the hot-spot on the inner surface (Fig. 1). The fill pressures of the D$_2$-$^3$He and the pure $^3$He mixtures in CH and CD capsules were chosen to give equal initial fill mass densities $p_0$, at values of 0.5 or 2.5 mg/cm$^3$. Because fully ionized D and $^3$He have the same value of $(1 + Z)/A$, mixtures with the same mass density have the same total particle density when fully ionized, and can be considered hydrodynamically equivalent [16].

Implosions of CH and CD capsules were observed using simultaneous measurements of products from two distinct primary nuclear reactions to study the nature and timing of mix. The $^3$He reaction, $D + ^3$He $\rightarrow ^4$He + p, and the DD-$n$ reaction, $D + D$ $\rightarrow ^3$He + n, have dramatically different composition and temperature sensitivities [16], which is used herein to constrain possible mix scenarios. The $^3$He reaction depends much more strongly on temperature due to the doubly-charged $^3$He reactant, and when the reactant species are initially separated, such as in CD capsules, they must be mixed before nuclear production will occur [17].
sponding to the shock (at /\text{.0024})

The proton source and shell mass [18]. A larger correction factor is needed as the mean source radius approaches the

\[ 3\text{He} \]

filled with pure \[ \text{D}_2 \]

above the typical noise level of \(/\text{.0002})

addition, nuclear production in CD implosions continues even

rate in CD capsules compared to equivalent CH capsules. In

FIG. 1. Measurements of the \[ \text{D}^3\text{He} \]

D2

from implosions of spherical plastic (CH) shells filled with an

shell on the atomic scale for \[ \text{D}_3\text{He} \]

burns. CD capsule implosions require mixing of the fuel and

histories show distinct times of

spectral measurements of nascent 14.7 MeV

results in a typical

time necessary for hydroinstabilities to induce fuel-shell mix

show that no such mix has occurred at shock-bang time. The

50 ps.

mean-energy downshift of measured proton spectra [18].

\[ /\text{.0026} \]

\[ \text{CD} \]

reaction rate (s\(^{-1}\))

\[ 10^{16} \]

\[ 10^{17} \]

\[ 10^{18} \]

D3He

reaction rate history from the proton current at the

scintillator is obtained by deconvolution of the detector

response from the streak camera image. \[ \text{D}^3\text{He} \] proton

spectral measurements [18] are then used to infer the

\[ \text{D}^3\text{He} \] reaction rate history from the proton current at the

scintillator. Additional details on PTD instrumentation and
data processing are described by Frenje et al. [19].

Temporal measurements of 2.45-MeV neutrons from the

DD-\text{n} nuclear reaction were obtained using the neutron
temporal diagnostic (NTD) [20], which works on the same

principle as the PTD, but is optimized for neutron detection.

Although the DD reaction rate in CD capsule implosions is below the noise floor of the NTD, integrated DD yields were readily obtained using time-of-flight neutron detectors [21].

Implosions of CH capsules with \[ \text{D}^3\text{He} \] fuel characteristically emit \[ \text{D}^3\text{He} \] protons at two distinct times (Fig. 1). The shock burn is induced by the collapse of an ingoing spherical shock, and occurs before the imploding shell starts to decelerate. About 250 ps later, during the deceleration phase, the compression burn occurs as the imploding capsule compresses and reheats the fuel. In contrast to the two stages of proton emission observed in CH capsule implosions with \[ \text{D}^3\text{He} \] fills, CD capsules emit protons only during the later phase (Fig. 1), confirming the hypothesis that there is no mix at the time of shock collapse [22] first presented by Petrasso et al. [5].

Measurements of time-integrated nuclear yields demonstrate that capsules with lower \( \rho_0 \) have an increased susceptibility to mix [6,9]. Yields increased with lower \( \rho_0 \) for CD capsule implosions, even though low \( \rho_0 \) is less favorable for nuclear production in the capsule core, as seen through the decrease in yields for CH capsules (see Fig. 1 and Table I). The increase in yields for lower \( \rho_0 \) cannot be attributed to a difference in the temperature profile because both DD-\text{n} and \[ \text{D}^3\text{He} \] yields increased by about the same factor of 1.8, despite markedly different composition and temperature dependence. Additional mix of \[ \text{He} \] with the CD shell in low \( \rho_0 \) implosions must be invoked to explain the yield trends [23].

The time necessary for RT growth to induce turbulent, atomic-scale mixing of the fuel and shell results in a delay
in the bang time (defined as the time of peak D$^3$He reaction rate) of CD capsules compared to equivalent CH capsules of 83 ± 37 ps and 69 ± 21 ps for high and low $\rho_0$ (Fig. 2 and Table I), respectively; this is equal to about half the typical 150 ps burn duration (defined as the full temporal width above half peak reaction rate). The delay is calculated as the difference between the ensemble averages of CD and CH capsule bang times, and the error is calculated as the quadrature sum of the standard errors of the mean for each ensemble average. Measurements of DD-$n$ bang time in CH capsules closely match the observed D$^3$He bang time (Fig. 2). However, the DD reaction rate in CD capsules was too low for robust timing measurements.

The observed bang-time delay is not an artifact of limitations of the diagnostics or experimental setup. The timing jitter of the PTD is the same for CH and CD implosions, and is less than 20 ps, while bang-time errors of only 10 ps are introduced in the deconvolution process by proton energy spectrum uncertainties. A small systematic difference in shell thickness between CH and CD capsules was corrected using a 13 ps adjustment to the bang-time delay.

Table I. The number of shots in different ensembles of implosions of D$^3$He-filled CH capsules and D$^3$He-filled CD capsules with two values of initial fill density $\rho_0$ is shown, along with ensemble averages and standard errors of the mean for several experimental observables: bang time and burn duration for DD-$n$ and D$^3$He nuclear reaction histories, time-integrated DD-$n$ and D$^3$He yields ($Y_y$ and $Y_p$), and areal density $\rho L$. Standard errors are quoted in the same units as the averages, except for the yields, which are expressed as a percent. Only the compression component is included for $Y_y$ and $\rho L$ in CH capsules.

![FIG. 2. Mean and standard error of D$^3$He (diamonds) and DD-$n$ (circles) compression-bang times from CH (open markers) and CD (solid markers) capsule implosions as a function of initial fill density. In CD capsules, D$^3$He bang time consistently occurs ~75 ps later than in CH capsules.](image)

![FIG. 3. Mean and standard error of proton-emission-path-averaged areal densities ($\rho L$) for CH (open markers) and CD (solid markers) implosions as a function of initial fill density. D$^3$He proton spectral measurements are used to infer this compression-burn averaged $\rho L$, where the shock component of CH implosion spectra has been excluded. For CH capsules, the radial areal density ($\rho R$) can be obtained from $\rho L$ using a small correction ($\rho R \sim 0.93 \rho L$) which depends on the shell aspect ratio. The relation between $\rho R$ and $\rho L$ for CD capsules sensitively depends on the source profile as the mean source radius approaches the mean shell radius—that $\rho L$ is not much higher than in CH capsules suggests that the source profile is still centrally peaked.](image)
stages of compression, combined with the larger total mass of fuel in such capsules, is enough to prolong nuclear production even after production would have been quenched in a CH implosion (Fig. 1).

Furthermore, systematically later nuclear production in CD capsule implosions leads to higher expected $pL$. The mean radial areal density $\rho R$ increases throughout the deceleration phase as the shell continues to compress, so protons will selectively sample higher $\rho R$ (and $pL$) if they are emitted later in time. This effect is in addition to the potentially higher $\rho L$ for CD capsules from geometric effects due to a noncentralized proton source profile, described above.

As seen in Fig. 3 and Table I, $pL$ is 9% and 18% higher for implosions of CD capsules than for equivalent CH capsules with low and high $\rho_0$, respectively [25]. These values are not much higher, suggesting that one or both of the effects described above might not be as significant as expected. On this basis we conjecture that the source of protons in CD capsules may be dominated by atomic mixing at the tips of RT spikes from the shell that drive into the hot core, which would result in a more central proton emission profile, and a smaller increase in $\rho L$.

In summary, temporal measurements of $^3$He protons emitted from ICF implosions of CD-shelled, $^3$He-filled capsules offer new and valuable insights into the dynamics of turbulent mixing induced by saturation of the Rayleigh-Taylor instability. The first such measurements have demonstrated that bang time is substantially delayed as RT spikes driven into the core.

The authors express their gratitude to the OMEGA engineers and operations crew who supported these experiments. This work was supported in part by the U.S. Department of Energy Office of Inertial Confinement Fusion (Grant No. DE-FG03-03NA00058), by the Lawrence Livermore National Laboratory (Subcontract No. B543881), by the Fusion Science Center for Extreme States of Matter and Fast Ignition (Contract No. 412761-G), and by the Laboratory for Laser Energetics (Subcontract No. 412160-001G) under Cooperative Agreement No. DE-FC52-92SF19460, University of Rochester, and New York State Energy Research and Development Authority.

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[4] See, for example, Section 8.9 of Ref. [2] for a review of the literature.
[17] Nonatonic mix scenarios fail to produce significant yield, since thermal $^3$He ions cannot penetrate far enough into the CD layer. For example, to give $^3$He yields comparable to those observed, it can be shown that all $^3$He ions in the fuel ($\sim 2 \times 10^{17}$) would have to be launched into the CD layer at energies of 50 keV, grossly higher than the typical fuel ion temperature of 4 keV.
[22] Or that such mix, if present, has been insufficiently heated to give nuclear production.
[23] For example, if it is assumed that the DD-$n$ yield increase is due only to an increase in the temperature of the mix region, then the fraction of $^3$He fuel contained in the mix region must be 3 times greater for low $\rho_0$ to produce the observed $^3$He yield increase.
[24] The 13 ps reduction in the delay corrects for a $1/3 \mu$m systematic difference in the total thickness of the CH and CD shells, where the timing of each burn history was adjusted by $(40 \text{ ps}) \times (20 - \Delta)$, with $\Delta$ as the capsule thickness in $\mu$m. The 40 ps/$\mu$m correction factor was obtained by a linear fit of CH capsule bang times over a range of thicknesses from 15 to 27 $\mu$m.
[25] The slightly higher ($<2\%$) initial shell mass in CD capsules due to the high density of the 1 $\mu$m thick CD layer and the systematic thickness difference has a minimal impact on $\rho L$ ($<1\%$).