

# Nuclear measurements of fuel-shell mix in inertial confinement fusion implosions at OMEGA<sup>a)</sup>

J. R. Rygg,<sup>b)</sup> J. A. Frenje, C. K. Li, F. H. Séguin, R. D. Petrasso,<sup>c)</sup> J. A. Delettrez, V. Yu. Glebov, V. N. Goncharov, D. D. Meyerhofer,<sup>d)</sup> P. B. Radha, S. P. Regan, and T. C. Sangster

*Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139 and Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623*

(Received 3 November 2006; accepted 19 January 2007; published online 24 April 2007)

Direct drive spherical implosions on the OMEGA laser system [T. R. Boehly *et al.*, *Opt. Commun.* **133**, 495 (1997)] have shown that increased capsule convergence results in increased susceptibility to fuel-shell mix. Mix results from saturation of the Rayleigh-Taylor instability, leading to small-scale, turbulent eddies and atomic-level mixing of the high-density compressed shell with hot, low-density fuel from the core. To sensitively probe the extent of mix, nuclear yields were measured from implosions of capsules filled with pure <sup>3</sup>He. The plastic capsule shell contains a deuterated plastic (CD) layer either on the inner surface or offset from the inner surface by 1 μm. Mixing of D from the shell with hot <sup>3</sup>He in the core is necessary to produce 14.7 MeV D<sup>3</sup>He protons in such capsules. D<sup>3</sup>He-proton spectral measurements have been used to constrain the amount of mix at shock time, to demonstrate that some of the fuel mixes with the offset CD layer, and that capsules with a higher initial fill density or thicker shell are less susceptible to the effects of mix. © 2007 American Institute of Physics. [DOI: 10.1063/1.2671761]

## I. INTRODUCTION

Turbulent mix is a vital concern in inertial confinement fusion (ICF),<sup>1,2</sup> as it can quench the nuclear burn in the hot spot prematurely, or even extinguish it entirely. The saturation of Rayleigh-Taylor (RT) instability growth at a density interface leads to small-scale, turbulent eddies that in turn lead to mixing of the high- and low-density materials.<sup>3</sup> These mixing processes can disrupt the formation of the low-density hot spot, lowering its temperature and reducing its volume. The resulting lower nuclear production can fail to ignite the capsule. Understanding the extent of mix under different conditions is a crucial step toward mitigating its adverse effects.

A substantial and sustained effort to understand hydrodynamic instabilities and mix has been ongoing for many decades, due in large part to their heavy impact on ICF. Reviews of the literature on experimental, computational, and theoretical work on hydrodynamic instabilities and mix can be found on, for example, the first page of Refs. 4 and 5. Related work on mix in ICF implosions includes papers by Li,<sup>6</sup> Radha,<sup>7</sup> Regan,<sup>8</sup> Wilson,<sup>9</sup> as well as many others.

This paper reviews and extends aspects of the work published by Li *et al.*<sup>6</sup> over a wider range of capsule parameters. In addition, we calculate a quantitative upper limit on the null result published by Petrasso *et al.*<sup>10</sup> of the amount of mix at the time of shock collapse, which occurs before the onset of the deceleration phase. Results from time-dependent

nuclear production history measurements of the mix region will be published elsewhere.<sup>11</sup> A brief review of the causes and effects of mix can be found in Sec. II. The experimental setup is described in Sec. III. Experimental observations are shown in Sec. IV. Section V describes the constraint on the amount of fuel-shell mix between shock collapse and deceleration phase onset. Section VI summarizes the results.

## II. CAUSES AND EFFECTS OF MIX

When a fluid of density  $\rho_1$  accelerates a heavier fluid of density  $\rho_2$ , the fluid interface is RT unstable. The rapid growth of initial perturbations sends spikes of the heavy fluid into the light fluid, while bubbles of the light fluid penetrate into the heavy fluid. The exponential growth eventually saturates into a nonlinear regime where the spike and bubble amplitudes grow quadratically in time. As the spikes and bubbles continue to interpenetrate, velocity shear between the two fluids results in further instability (the drag-driven Kelvin-Helmholtz instability), causing the spike tips to “mushroom” and roll up on increasingly finer scales, increasing the vorticity of the flow and eventually leading to mixing of the two fluids on the atomic scale.

In ICF, both the acceleration and deceleration phases have RT unstable surfaces.<sup>2</sup> The low-density ablating mass pushes against the high-density “payload” during the acceleration phase, and after further convergence and compression, the high-density shell is stopped by the low-density hot spot during the deceleration phase. Initial perturbations are seeded by laser and target surface nonuniformities, and growth of these perturbations during the acceleration phase can feed through to the inner surface and contribute to seeding perturbations for the deceleration phase.<sup>2</sup>

<sup>a)</sup>Paper R11 2, *Bull. Am. Phys. Soc.* **51**, 254 (2006).

<sup>b)</sup>Invited speaker.

<sup>c)</sup>Also Visiting Senior Scientist at LLE.

<sup>d)</sup>Also at Departments of Mechanical Engineering and Physics and Astronomy.

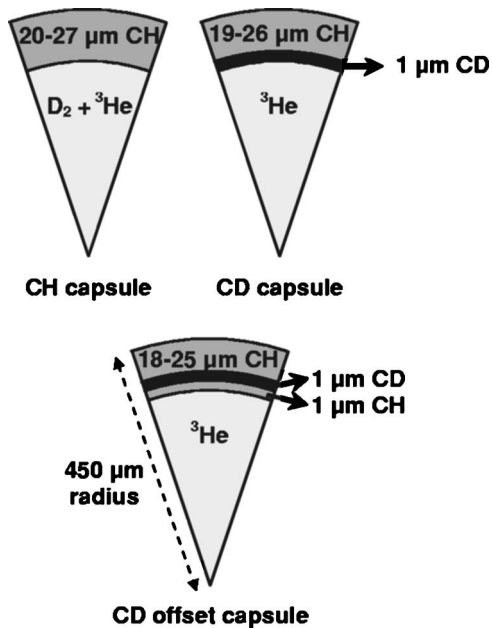


FIG. 1. 0.5 or 2.5 mg/cm<sup>3</sup> of pure <sup>3</sup>He gas fills a 20–27 μm thick plastic shell with a 1 μm deuterated layer either adjacent to the inner surface (CD capsule) or offset from the inner surface by 1 μm (CD offset capsule). The reference (CH capsule) contains D<sup>2</sup>He gas and has no deuterated layer. Whereas the reference capsule will produce D<sup>3</sup>He protons whenever the fuel gets sufficiently hot, the CD capsules will only produce D<sup>3</sup>He protons if the fuel and shell become atomically mixed.

Unmitigated RT growth during the acceleration phase can eventually break through the shell, compromising its compressibility, and reducing the attainable areal density of the assembled target at stagnation. RT growth during the deceleration phase can send spikes of cold, dense fuel into the central hot spot, potentially disrupting its formation. Even if the spikes do not reach the center, their penetration and the resultant mixing of the cold, dense shell with the hot, low-density hot spot will cool the outer regions of the hot spot, reducing the volume participating in nuclear production.

### III. EXPERIMENTAL SETUP

Direct-drive implosions were conducted at OMEGA,<sup>12</sup> with 60 beams of frequency-tripled (351 nm) UV light in a 1-ns square pulse and a total energy of 23 kJ. 1 THz bandwidth smoothing by spectral dispersion and polarization smoothing of the laser beam were used.<sup>13</sup> The beam-to-beam energy imbalance was typically between 2 and 4% rms. The spherical capsules had diameters between 860 and 940 μm, plastic shell thicknesses of 20, 24, or 27 μm, and a surface coating of 0.1 μm of aluminum.

Three target configurations were used (Fig. 1). The reference “CH” capsules had shells made of plastic (CH), and a gaseous fill of D<sub>2</sub> and <sup>3</sup>He. “CD” capsules had gaseous fills of pure <sup>3</sup>He, and a shell made mostly of CH, except for a 1 μm layer of deuterated plastic (CD) on the inner surface. “CD offset” capsules are like the CD capsules, except that the 1 μm CD layer is offset from the inner surface by 1 μm of CH. The composition of the ordinary plastic consists of an H to C ratio of 1.38, and the deuterated plastic has a D to C ratio of 1.56.<sup>6</sup>

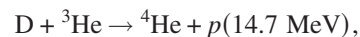
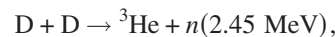
TABLE I. Predicted convergence ratio  $C_r$  calculated by LILAC for different capsule parameters. Capsules with higher convergence ratios are expected to be more susceptible to mix. The convergence ratio does not differ significantly between CH and CD capsules.

$\rho_0$ (mg/cm <sup>3</sup> )	Thick. (μm)	$C_r$ (1D)
0.5	20	38.0
”	24	35.2
”	27	31.5
2.5	20	14.9
”	24	14.5
”	27	13.8

The pure <sup>3</sup>He gases were filled to initial pressures of 4 and 20 atm at a temperature of 293 K, corresponding to initial mass densities ( $\rho_0$ ) of 0.5 and 2.5 mg/cm<sup>3</sup>. The D<sub>2</sub>-<sup>3</sup>He gas is an equimolar mixture of D to <sup>3</sup>He by atom, and is filled to a hydrodynamically equivalent initial pressure as the pure <sup>3</sup>He fill, as described in Ref. 14. Because fully ionized D and <sup>3</sup>He have the same value of  $(1+Z)/A$ , mixtures with the same mass density will also have the same total particle density and equation of state, and can be considered hydrodynamically equivalent. For the 4 and 20 atm <sup>3</sup>He fills, the hydrodynamically equivalent D<sub>2</sub>-<sup>3</sup>He pressures are 3.6 and 18 atm, respectively.

Hydrodynamic simulations of capsule implosions using the 1D code LILAC<sup>15</sup> showed only minor differences in the timing and profiles between the equivalent CH and CD implosions. The convergence ratio  $C_r$ , defined as the initial inner capsule radius over the fuel-shell interface radius at the time of stagnation, for capsules with different shell thickness and initial fill density, is shown in Table I.

The following primary nuclear reactions can occur in targets containing both D<sub>2</sub> and <sup>3</sup>He:



where the number in parentheses is the mean birth energy of the second product.

The set of capsules shown in Fig. 1 is ideal for studying the nature and extent of turbulent mix in ICF implosions. Whereas implosions of CH capsules will produce D<sup>3</sup>He protons whenever the fuel gas gets sufficiently hot, heating alone is not sufficient for D<sup>3</sup>He production in CD and CD offset capsules. To produce measurable D<sup>3</sup>He yields, these capsules require in addition the mixing of the fuel and shell on an atomic scale. Measurement or absence of the D<sup>3</sup>He yield in implosions of CD offset capsules can be used to ascertain the extent into the shell that turbulent mixing processes reach.

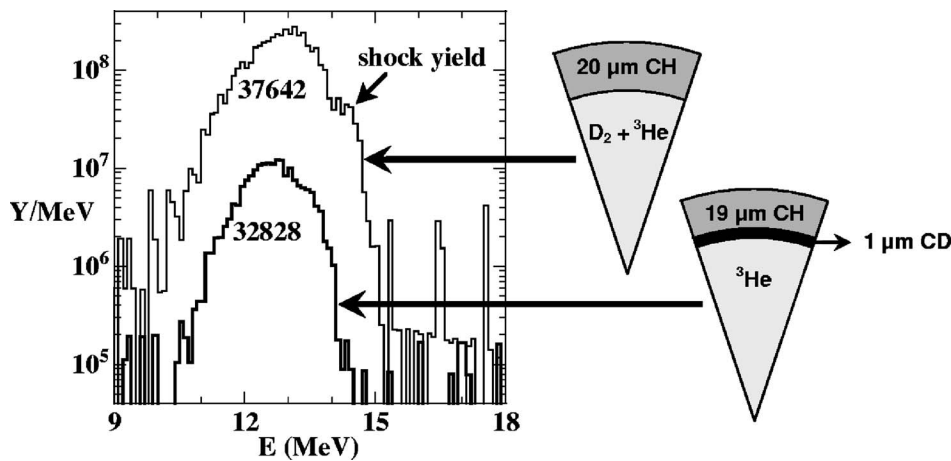


FIG. 2.  $D^3He$  proton spectra from a CH capsule (shot 37642) and from a CD capsule (shot 32828) with  $2.5 \text{ mg/cm}^3$  initial fill density. The high  $D^3He$  yield from CD implosions demonstrates the existence of fuel-shell mix. The CD implosion yield, although substantially less than the yield from the CH implosion, is much higher than what would be expected in the absence of turbulent fuel-shell mix.

Fuel-shell mix is not a requirement to produce DD-n yields in CD and CD offset implosions, but measurement of the DD-n yield provides a useful way to determine if the CD layer was heated to temperatures near 1 keV.

The primary diagnostics for this study were wedge-range-filter (WRF) spectrometers,<sup>16</sup> to measure the  $D^3He$  proton yield and spectrum, and neutron time-of-flight (nTOF) scintillator detectors,<sup>17</sup> to measure the DD-n yield. On a given shot, up to six WRF spectrometers were used simultaneously to improve the estimate of the  $D^3He$  yield.<sup>16</sup> The  $D^3He$  proton spectrum measured from implosions of  $D^3He$ -filled CH capsules often shows two distinct components, corresponding to  $D^3He$  proton emission shortly after the collapse of the converging shock, and to emission during the deceleration phase, about 300 ps later.<sup>10,18</sup>

#### IV. EXPERIMENTAL RESULTS

##### A. Yield measurements

Turbulent mixing of the fuel and shell is demonstrated by measurements of finite  $D^3He$  yields ( $Y_p$ ) in  $^3He$ -filled, CD capsules (see Fig. 2 and Ref. 6). The shock component, apparent in the spectrum of the CH capsule implosion above 14 MeV, is absent in the CD capsule. All  $D^3He$  yields re-

ported in this section for CH capsules will include only the compression component; the shock component will be considered in Sec. V.

The  $D^3He$  yields from CD capsules are at least two orders of magnitude higher than would be expected by the interaction of thermal  $^3He$  ions penetrating through the CD layer surface,<sup>6</sup> even with enhanced surface area resulting from a RT-perturbed surface; the  $D^3He$  yields are at least three orders of magnitude higher than the maximum that would be expected if there were some  $^3He$  that had diffused into the CD layer between the times of fabrication and implosion.<sup>6</sup> For yields as high as has been observed, there must be a region that has been heated to at least 1 keV, and where the fuel and shell have experienced atomic mix.

Significant  $D^3He$  yield from CD-offset implosions demonstrates that there is substantial mixing of the fuel with the “second” 1- $\mu\text{m}$  layer of the shell (Fig. 3). Thermal  $^3He$  ions cannot penetrate through the first micrometer of the shell to produce these yields, so the second micrometer must be exposed to the fuel by bubble growth, and then mixed through turbulent processes.

The decreasing yields for increasing  $\rho_0$  in CD capsules contrasts strongly with the increasing yields for increasing initial  $\rho_0$  in the reference CH capsules (Fig. 4). This is evi-

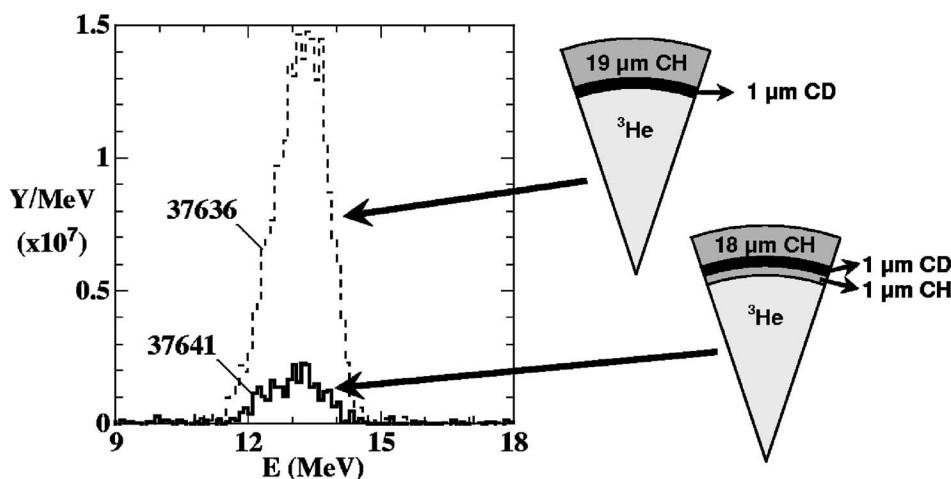


FIG. 3.  $D^3He$  proton spectra from a CD capsule (shot 37636) and from a CD offset capsule (shot 37641) with  $0.5 \text{ mg/cm}^3$  initial fill density. The  $D^3He$  yield drops by only a factor of 5 to 10 when the CD layer is offset from the inner surface by  $1 \mu\text{m}$ , demonstrating that a substantial amount of the second micrometer of the shell is mixed with the fuel.

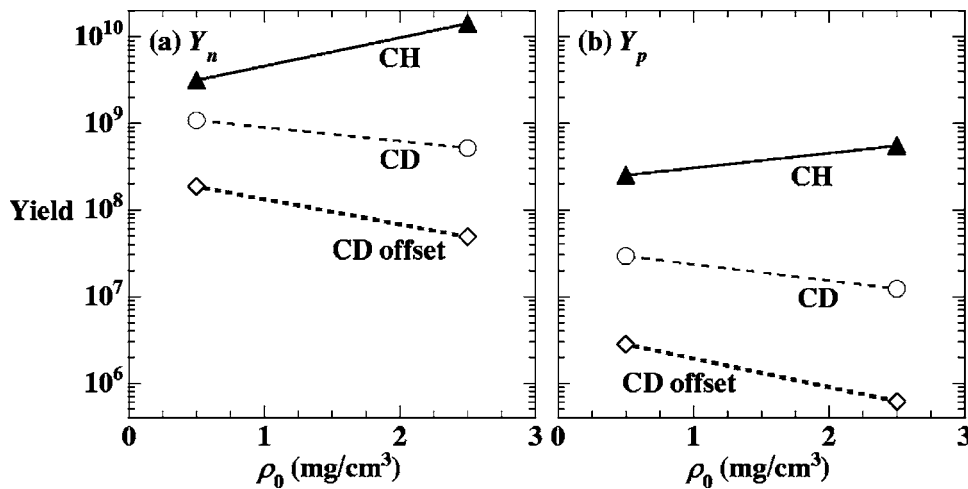


FIG. 4. (a) DD-n and (b)  $D^3\text{He}$  yields from CH (solid triangles), CD (open circles), and CD-offset (open diamonds) implosions as a function of initial fill density for  $20\ \mu\text{m}$  thick shells. Yields from CD and CD-offset implosions decrease with increasing fill density, in contrast to the increasing yields from CH implosions. Points show the mean of each shot ensemble, where the standard error in the mean is smaller than the size of the markers.

dence that the extent of mix is reduced for increasing initial fill density, since  $Y_p$  in CD implosions is lower, even though the core conditions are more favorable for nuclear production, as seen by the higher value of  $Y_p$  for CH implosions.  $Y_p$  in CD-offset implosions decreases by an additional factor of 5 and 10 compared to inner CD capsule implosions for  $0.5$  and  $2.5\ \text{mg}/\text{cm}^3$  fills, respectively.

The lower DD-n yield ( $Y_n$ ) for CD implosions with higher  $\rho_0$  indicates that less heating of the CD layer occurred in these implosions. Additional heating of the inner surface of the shell can occur through thermal conduction from and turbulent mix with the hot fuel. The lower  $Y_n$  supports the picture of reduced mix for higher-density fills.

Yields in both CH and CD implosions decrease with increasing shell thickness (Fig. 5). Thicker shells decrease  $Y_p$  by a larger factor in CD capsules compared to CH capsules, which suggests that the effects of mix are diminished. However,  $Y_n$  decreases by a smaller factor in CD capsules, which may be due to temperature effects dominating mix effects for the neutron yield in such implosions.

## B. Areal density measurements

Evidence for a delay in nuclear production can be found through measurement of the compression of the target at bang time by means of the areal density  $\rho R$ . Areal density is inferred from the mean downshift of the  $D^3\text{He}$  proton spectrum from the birth energy of  $14.7\ \text{MeV}$ , so the inferred  $\rho R$  is an average measurement of  $\rho R$  over the time of nuclear production. Because the capsule continues to compress, and  $\rho R$  to increase, throughout the deceleration phase, one would expect that if bang-time occurs during a later stage of the deceleration phase for an otherwise equivalent implosion, then the average  $\rho R$  would be higher.<sup>11,18</sup> As seen in Fig. 6, the inferred burn-averaged  $\rho R$  is higher for implosions of CD capsules than for CH capsules. This is qualitatively consistent with the later bang-times measured for CD capsules.

The experimental results of these experiments are summarized in Table II. The mean and standard error are shown of the DD-n and  $D^3\text{He}$  yields ( $Y_n$  and  $Y_p$ ) and the areal density  $\rho R$  inferred from the mean downshift of  $14.7\ \text{MeV}$   $D^3\text{He}$  protons for CH, CD, and CD-offset capsules. Also

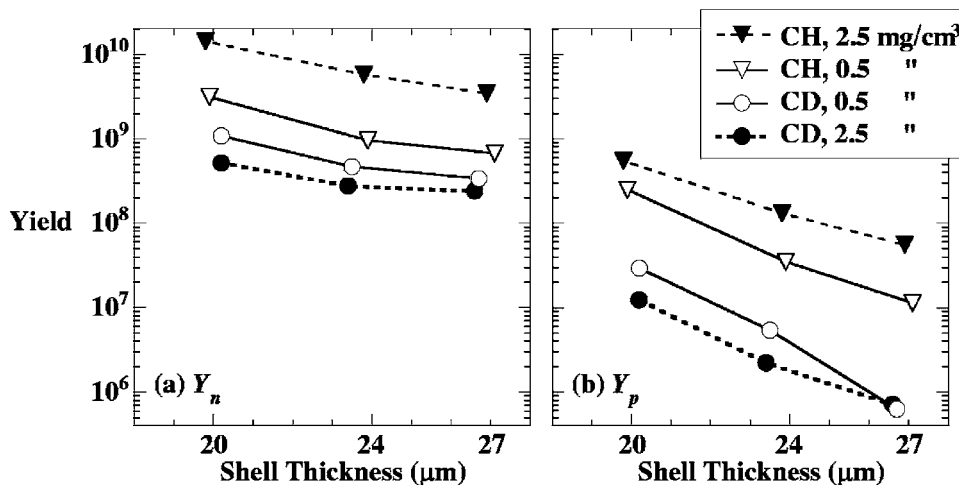


FIG. 5. (a) DD-n and (b)  $D^3\text{He}$  yield in CH (triangles) and CD (circles) capsules with low (open markers) and high (solid markers)  $\rho_0$  as a function of shell thickness. Capsules with lower  $\rho_0$  are more susceptible to mix for all shell thicknesses.

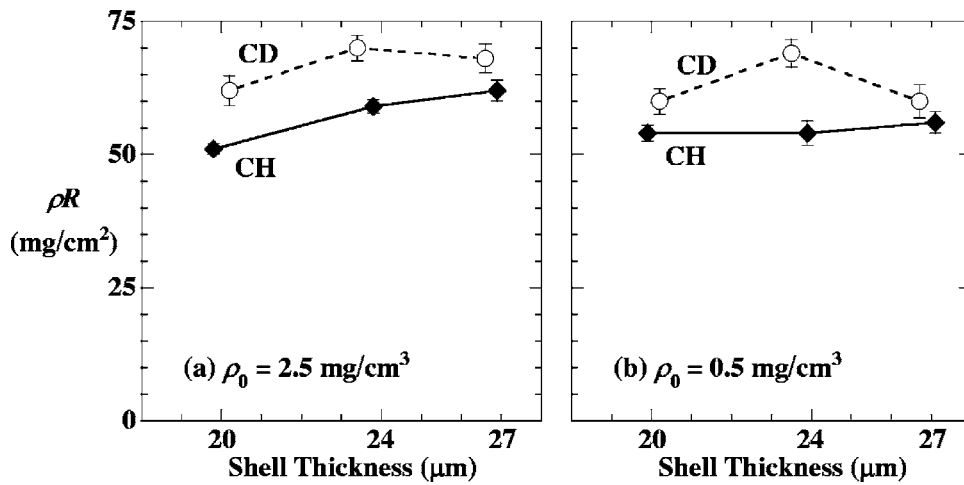


FIG. 6. Mean and standard error of  $\rho R$ 's for CH (solid markers) and CD (open markers) implosions as a function of shell thickness with (a) high- and (b) low-density fills. The  $D^3He$  burn averaged  $\rho R$  is consistently higher for CD capsules.

shown is the number of shots of each kind. The mean is the average of measured values within a given shot ensemble, and the standard error is the standard deviation of the measurements divided by the square root of the number of shots.

### V. CONSTRAINT ON THE POSSIBILITY OF MIX DURING THE COASTING PHASE

Comparative analysis of  $D^3He$ - $p$  spectra from CH and CD implosions can be used to place an upper bound on the possible amount of mix at shock time. For the representative spectrum of a CH capsule shown in Fig. 7, the total yield in the region from 14.2 to 14.7 MeV, corresponding to the shock component, is  $1.7 \pm 0.2 \times 10^7$ , or  $3.7 \pm 0.3\%$  of the total yield. The yield in the same region of the representative spectrum from a CD capsule comes to  $2.6 \pm 2.5 \times 10^4$ , equal to  $0.14 \pm 0.13\%$  of the total yield, and is consistent with zero.

The “shock yield” of the CD implosion ( $\leq 2.6 \times 10^4$ ) comes to at most 0.15% of the shock yield of the correspond-

ing CH implosion ( $1.7 \times 10^7$ ). This yield ratio can be used to constrain the deuterium fraction by atom  $f_D \leq 0.05\%$  in the fuel of the CD implosion during shock burn, by application of Eq. (5) in Ref. 14. Equation (5) assumes that  $f_D$  is uniform through the fuel region, so it does not preclude the more likely physical situation of deuterium concentrations higher than the above constraint in the outer, cooler region of the fuel.

### VI. SUMMARY

The extent of fuel-shell mix has been shown to include a substantial amount of the shell from the inner first and second  $\mu m$  of the original material using  $^3He$ -filled, CD-shelled target implosions. The observed yields are higher than is consistent with diffusive mixing, and so must be the result of turbulent mixing down to the atomic scale.

The improved stability of capsules with higher initial

TABLE II. Experimental yield and areal density results of CH, CD, and CD-offset capsule implosions. The values shown are the mean and standard error of all shots in a particular ensemble, with the yield errors expressed as a percent of the mean. The quoted  $D^3He$  yield and areal density for CH capsules is that due to the compression component only.

Type	$\rho_0$ ( $mg/cm^3$ )	Thick. ( $\mu m$ )	Num. shots	$Y_n$ ( $\times 10^8$ )	Error (%)	$Y_p$ ( $\times 10^7$ )	Error (%)	$\rho R$ ( $mg/cm^2$ )	Error
CH	0.5	19.9	17	31.3	6	24.3	11	54	1.5
''	''	23.9	9	9.6	6	3.5	12	54	2.3
''	''	27.1	8	6.7	7	1.13	30	56	2.0
''	2.5	19.8	61	142	4	54.4	5	51	1.0
''	''	23.8	26	58	5	13.2	8	59	1.3
''	''	26.9	16	35	5	5.6	8	62	2.0
CD	0.5	20.2	7	10.8	10	2.9	10	60	2.4
''	''	23.5	5	4.7	7	0.54	9	69	2.6
''	''	26.7	2	3.4	7	0.06	7	60	3.1
''	2.5	20.2	11	5.2	8	1.25	13	62	2.8
''	''	23.4	7	2.7	15	0.22	19	70	2.4
''	''	26.6	4	2.4	5	0.07	4	68	2.7
CD-off	0.5	19.2	3	1.9	17	0.28	28	52	1.7
''	''	23.7	2	1.2	14	-	-	-	-
''	2.5	18.4	5	0.5	24	0.06	14	55	3.0
''	''	22.8	3	1.2	49	-	-	-	-

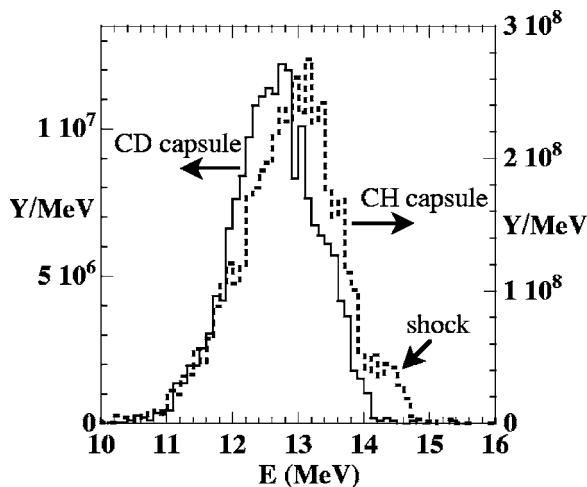


FIG. 7.  $D^3He$  proton spectra from implosions of  $20\ \mu\text{m}$  thick shells filled with  $2.5\ \text{mg}/\text{cm}^3$  of fuel with CH (shot 37642, dotted) and CD (shot 32828, solid) shell configurations. The shock component of the CH implosions comes to 3.7% of the total yield, whereas the shock component contribution to the CD implosion spectrum is consistent with zero.

fuel density and thicker initial shells has been confirmed by comparing the yield trends of CH, CD, and CD-offset capsules. Increasing the capsule fill density decreased the  $D^3He$  and DD-n yields for CD capsules, and increased the yields for CH capsules, demonstrating that the extent of mix is reduced for increasing initial fill density.

The  $D^3He$  shock yield in CD capsules with high initial fill density was constrained to be less than 0.14% of the total  $D^3He$  yield, and the average atomic fraction of deuterium in the fuel during the shock-burn has been constrained to be less than 0.05%, and is consistent with zero.

## ACKNOWLEDGMENTS

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.

<sup>1</sup>J. Nuckolls, L. Wood, A. Thiessen *et al.*, *Nature (London)* **239**, 139 (1972).

<sup>2</sup>S. Atzeni and J. Meyer-Ter-Vehn, *The Physics of Inertial Fusion* (Oxford University Press, Oxford, 2004).

<sup>3</sup>P. E. Dimotakis, *Annu. Rev. Fluid Mech.* **37**, 329 (2005).

<sup>4</sup>G. Dimonte, *Phys. Plasmas* **6**, 2009 (1999).

<sup>5</sup>A. J. Scannapieco and B. Cheng, *Phys. Lett. A* **299**, 49 (2002).

<sup>6</sup>C. K. Li, F. H. Séguin, J. A. Frenje *et al.*, *Phys. Rev. Lett.* **89**, 165002 (2002).

<sup>7</sup>P. B. Radha, J. Delettrez, R. Epstein *et al.*, *Phys. Plasmas* **9**, 2208 (2002).

<sup>8</sup>S. P. Regan, J. A. Delettrez, F. J. Marshall *et al.*, *Phys. Rev. Lett.* **89**, 085003 (2002).

<sup>9</sup>D. C. Wilson, C. W. Cranfill, C. Christensen *et al.*, *Phys. Plasmas* **11**, 2723 (2004).

<sup>10</sup>R. D. Petrasso, J. A. Frenje, C. K. Li *et al.*, *Phys. Rev. Lett.* **90**, 095002 (2003).

<sup>11</sup>J. R. Rygg, J. A. Frenje, C. K. Li *et al.*, "Time-dependent nuclear-measurements of fuel-shell mix in inertial confinement fusion," *Phys. Rev. Lett.* (submitted).

<sup>12</sup>T. R. Boehly, D. L. Brown, R. S. Craxton *et al.*, *Opt. Commun.* **133**, 495 (1997).

<sup>13</sup>S. Skupsky and S. Craxton, *Phys. Plasmas* **6**, 2157 (1999).

<sup>14</sup>J. R. Rygg, J. A. Frenje, C. K. Li *et al.*, *Phys. Plasmas* **13**, 052702 (2006).

<sup>15</sup>J. Delettrez, R. Epstein, M. C. Richardson *et al.*, *Phys. Rev. A* **36**, 3926 (1987).

<sup>16</sup>F. H. Séguin, J. A. Frenje, C. K. Li *et al.*, *Rev. Sci. Instrum.* **74**, 975 (2003).

<sup>17</sup>R. A. Lerche and T. J. Murphy, *Rev. Sci. Instrum.* **63**, 4880 (1992).

<sup>18</sup>J. A. Frenje, C. K. Li, F. H. Séguin *et al.*, *Phys. Plasmas* **11**, 2798 (2004).