Multifluid interpenetration mixing in directly driven inertial confinement fusion capsule implosions[a]

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Mixing between the shell and fuel in directly driven single shell capsule implosions causes changes in yield, burn history, burn temperature, areal density, x-ray image shape, and the presence of atomic mix. Most observations are consistent with a mix model using the same values of its single free parameter as with indirectly driven single shell and double shell capsules. Greater mixing at lower gas pressure fills reduces capsule yield. Time dependent mixing growth causes truncation of the burn history. This emphasizes early yield from the center of the capsule, raising the observed burn temperature. Mixed fuel areal densities are lower because fuel moves through the shell and the observation weights earlier times when areal density is lower. Shell x-ray emission mixing into the fuel fills in the limb brightened image to produce a central peak. Implosions of ^{3}He filled capsules with a layer of deuterated plastic show substantial atomic mix. © 2004 American Institute of Physics. [DOI: 10.1063/1.1667486]

I. INTRODUCTION

From the beginning[1] mixing driven between the surrounding shell and hydrogen fuel by instability growth has been recognized to cause performance degradation in inertial confinement fusion (ICF) capsules. Instability growth in ICF capsules was reviewed by Lindl,[2] and more recently for directly driven capsules by Meyerhofer[3] and Regan.[4] A large number of papers have been dedicated to diagnosing and modeling the mixing in directly driven implosions. Li *et al.*[5] showed the presence of atomic mix simply by the existence of protons produced by the deuterium–helium (D–^{3}He) nuclear reaction from physically separated deuterated plastic and ^{3}He gas. Often models present a static configuration of mixed materials consistent with time integrated observations.[3,6] In other cases data is obtained which demonstrates mix in time dependent differences of temperatures, densities, or areal densities[4,7] from unmixed calculations. In this paper we will apply the dynamic mix model of Scannapieco and Cheng[8] to both time integrated and resolved observations from directly driven single shell capsule implosions. Observations from both previously published[5,6] and unpublished implosions on the Omega laser[9] give direct evidence of mix, including yield degradation, and changes in burn history, burn temperature, areal density, x-ray image shape, and atomic mix. The model has been previously ap-

plied to indirectly driven single shell capsules[10] and both directly and indirectly driven double shell capsules.[11] The fact that approximately the same parameter setting applies to all capsules suggests that a common mix phenomenon occurs roughly independent of small initial perturbations.

The Scannapieco and Cheng model assumes that within each computational cell all species are atomically mixed (share the same volume), and are at the same temperature, but retain their individual velocities $\vec{u}_i$. Two species i and j (for example, deuterium fuel and plastic shell) couple to each other through a phenomenological collision frequency ν_{ij} given by

$$\nu_{ij} \equiv \frac{C}{\Lambda_{ij} + L_{ij}}$$

and $L_{ij}(t) = \alpha \int_0^t \left(\frac{\rho(\tau)}{\rho(t)} \right)^{1/3} |\vec{u}_i - \vec{u}_j| d\tau,$

where Λ_{ij} is the collisional mean free path.[12] The implicit assumption is made that subgrid scale perturbation growth has become so nonlinear that the flow is independent of unmodeled initial perturbations. The extent of mixing is governed by the parameter free parameter α and by the collisional mean free path Λ.

The model is implemented in two dimensions where it represents mixing on a scale smaller than the calculational grid. Christensen *et al.*[13] used it to study mix in implosions with controlled low order 2D asymmetries. An alternative to
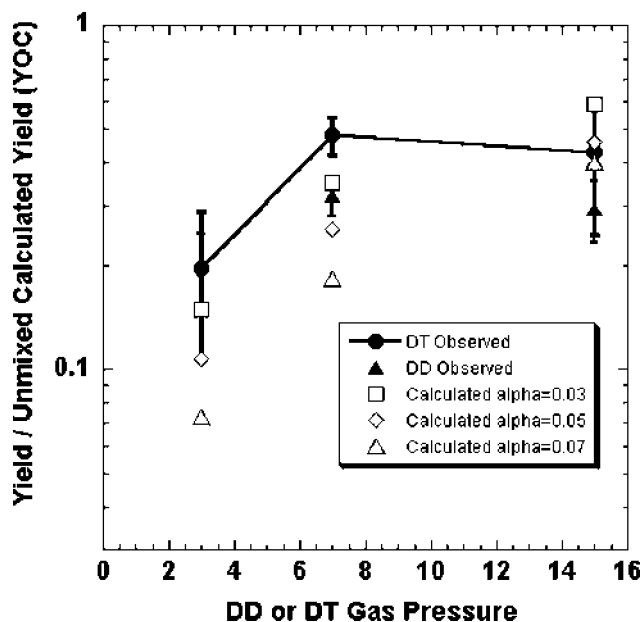

FIG. 1. Yield degradation with decreasing fill gas pressure (higher convergence). Calculations for both DT and DD differ only slightly ($\sim 2\%$) and are plotted together.

a subgrid model might be to perform an ensemble of 2D or 3D simulations of instability growth with high order perturbations and extract common behavior from the results. If the calculations were fully Lagrangian (i.e., mass cannot move between zones), then they would not be able to include the atomic mixing demonstrated to exist by Li *et al.*[5] The presence of atomic mix is one reason why hydrodynamic instability growth alone cannot explain these direct drive experiments. However high resolution Eulerian calculations (e.g., Schmitt *et al.*[14]) might produce subgrid scale atomic mixing through numerical diffusion, effectively a subgrid model. They then might be able to model the almost fully atomically mixed experiments. In this way they might model known asymmetries and perturbations, as well as incorporating numerically created atomic mix on the unresolved scales. In this paper we use only one-dimensional implosion calculations within which the Scannapieco and Cheng model represents the turbulent mixing.

II. YIELD DEGRADATION

Progressively greater degradation of observed yield as the convergence ratio increases is one of the most prominent indications of mixing. Reducing the fill gas pressure increases the convergence in an unmixed calculation. Wilson *et al.*[10] showed that for indirectly driven single shell capsules, the Scannapieco and Cheng mix model with $\alpha \sim 0.03$–0.05 matches the yield degradation for many different implosions. Similarly $\alpha \sim 0.05$–0.10 describes the yield degradation of double shell capsules.[11] In Fig. 1 we have plotted the observed yield[6] divided by our yield calculated without mixing (YOC or yield over clean) for both DD (pure deuterium) and DT (50% deuterium, 50% tritium) filled capsules versus fill gas pressure. The unmixed yield from a directly driven capsule depends upon the electron conduction

flux limiter used. The value of this limiter (0.046) was chosen to produce the observed implosion times, and hence to approximate well the implosion hydrodynamics. The observations show a difference in the YOC between DD and DT capsules with the same fill pressure that is not understood. Our mix model shows only slight, $\sim 2\%$, changes in the YOC between DD and DT, so we have plotted one calculated YOC at each gas pressure for $\alpha = 0.03$, 0.05, and 0.07. Considering uncertainties in the unmixed calculated yield, and differences between DD and DT, in addition to the random yield variations represented by the error bars, we believe an $\alpha \sim 0.03$–0.05 represents the yield degradation seen in these capsules.

III. BURN HISTORY

The time history of the yield rate of directly driven ICF capsules can be measured with the Neutron Temporal Diagnostic (NTD)[15] and often shows the presence of mix. Since mixing with our model increases in time, we would expect little degradation of the burn at early times, and much degradation later. For a capsule with a 20 μm thick plastic wall and 15 atm of DD or DT is it difficult to see this degradation. The measured burn history has approximately the same shape as that calculated without mixing.[3] The yield of a non-igniting ICF capsule can be divided into two parts, a "first shock" yield and a "compression" yield. The first shock yield is produced starting when the first shock reaches the capsule center and during the time when the reflected shock moves outward until it reaches the incoming shell. This yield should be little affected by mix. The "compression" yield is generated as the shell is decelerated, while it compresses, heats, and inertially confines the fuel. The shell–fuel interface is Rayleigh–Taylor unstable and mixing should grow with time, progressively reducing the yield rate during this compression phase. The first shock yield is a very small fraction of the total yield from a 20 μm thick plastic capsule. However with a thicker wall, the compression yield is reduced and the more prominent first shock yield can be measured. It then becomes apparent that burn is truncated at late times by mixing as shown by Li *et al.* for a 20 μm thick walled capsule.[5]

We have modeled NTD signals by postprocessing neutron energy deposition in a 1 mm thick plastic scintillator foil located 2 cm from a DD filled target. Since scintillator light is produced during the time the ~ 2.45 MeV neutron passes through the foil, the signal is broadened by ~ 40 ps. In addition there is broadening due to the time of flight spreading caused by the Doppler broadening of the neutron energy. The observed or calculated signal is normalized to the capsule yield to produce an inferred yield rate.

Figure 2 shows the measured and simulated NTD signals for shot 25668, without mix and with $\alpha = 0.03$, 0.04, 0.05, 0.07, and 0.10. The capsule yield is best modeled with $\alpha = 0.04$. The plastic capsule has a 943 μm diameter, a 26 μm thick wall, and contains 15 atm of DD. Comparing the observed and calculated yield rates shows there is little degradation of the first shock yield, here up to ~ 1.9 ns, substantial degradation of the compression yield, a shift of the peak
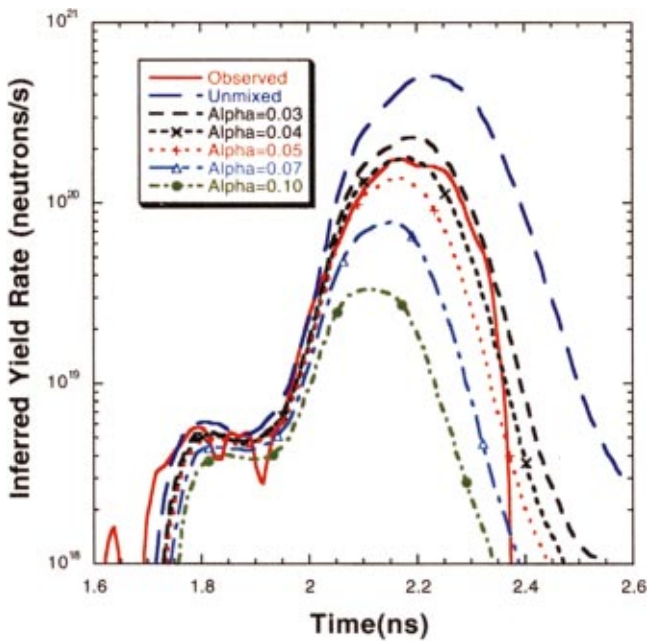
FIG. 2. (Color) Observed and simulated NTD burn history for Omega laser shot 25668, both with and without mixing.

FIG. 3. Neutron yield (left scale) and burn temperature (right scale) vs mix parameter α.

yield rate slightly earlier, and perhaps a faster falloff of the yield rate than calculated with the mix model. From the observed proton spectrum in deuterated plastic capsules with ³He gas fill Petrasso et al.[16] also concluded little or no mixing occurred during the first shock yield. This same cleaner yield during the first shock phase is also important to understanding the differences among double shell capsule yields.[11]

IV. BURN TEMPERATURE CHANGES

Mixing changes the observed burn temperature from an ICF capsule. Doppler broadening from the ion thermal velocities[17] spreads the energy of DD or DT neutrons. Because current ICF capsules scatter very few of these neutrons, a burn temperature can be inferred from the measured broadening in the neutron time-of-flight spectrum. Since this temperature is weighted by the neutrons that are actually produced, mixing can increase the measured temperature. Mixing from the shell inward will cool the outer portion of the fuel, decreasing the number of neutrons produced there and more heavily weighting the higher temperature in the clean center of the fuel. Mixing also moves the time of burn earlier to when neutron production is dominated by the hot central fuel, and especially the first shock yield. The fuel averaged burn temperature decreases as the burn progresses and our mix model captures both these effects. Figure 3 shows the degradation of yield and the increase in simulated burn measured temperatures from 1100 μm diameter, 3.9 μm thick glass capsules filled with 10 atm DT and 0.3 atm nitrogen (a residual from air). As mixing decreases the yield with increasing α, the simulated burn temperature rises from 7 keV to 8.5 keV.

Figure 4 shows this burn temperature measured for 20 μm thick, DD filled plastic capsules.[5] Again the observed temperatures are higher than the calculated unmixed value
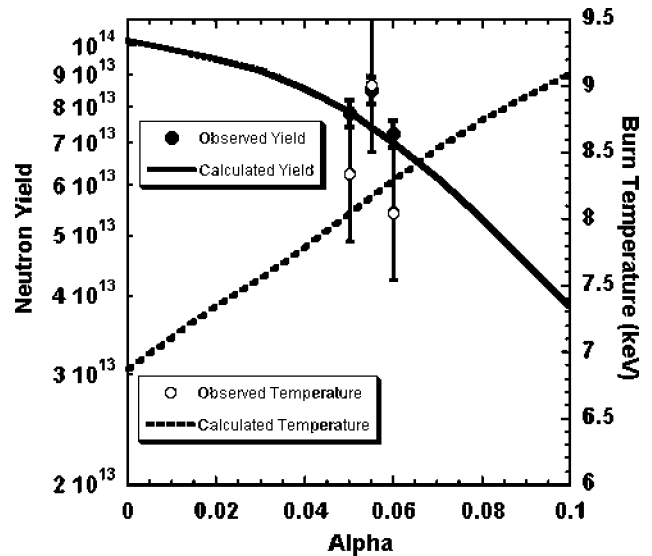
by about 1 keV. However in this case the Scannapieco and Cheng mix model does not calculate an increase, but even a decrease due to cooling. As with the glass capsule, the calculated burn temperature is higher at earlier times in the burn. If instead we make a simple mix model in which yield is generated in completely unmixed material and then abruptly terminated by mixing, we calculate the temperatures shown by a solid diamond in Fig. 4, agreeing with the measurement. The same quantitative effects occur for the burn temperature in DT filled plastic capsules, however because the DT reaction weights the measurement to higher temperatures, both the measured and calculated ion temperatures are ~1 keV higher. The discrepancy between measured and calculated temperature, and agreement with a simple abrupt
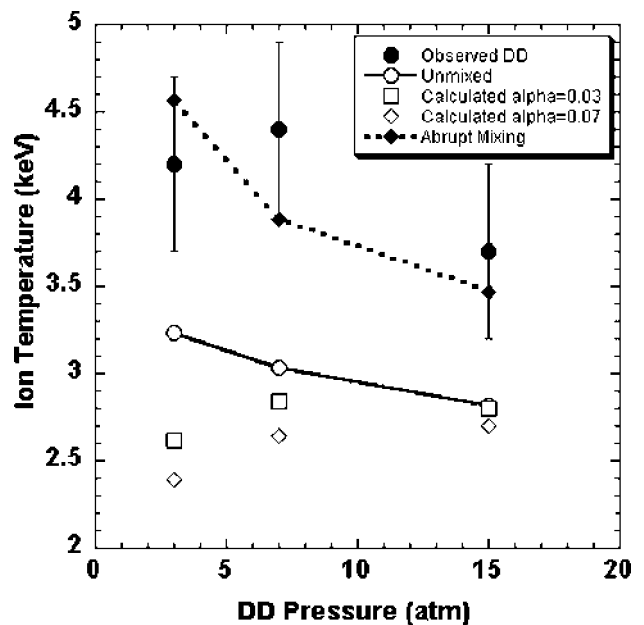

FIG. 4. Burn temperature measured, calculated with the Scannapieco and Cheng mix model, and with a simple model of abrupt mixing.

mixing model is one indication that the Scannapieco and Cheng mix model may be calculating the proper time averaged mix, but not mixing abruptly enough.

V. AREAL DENSITY CHANGES

The areal density, $\int \rho \, dr$ from the center outward, or ρR, changes because of mixing. Both fuel ρR (integral over the fuel alone), shell ρR or the sum of the two, the total ρR, can be measured. In general the ρR is growing through much of the implosion, from the time when the first shock reaches the center, during its passage through the imploding shell, to the time of peak neutron yield, and only decreasing after peak compression, near the end of the neutron yield. Using proton spectroscopy in capsules filled with D–^{3}He gas Petrasso *et al.*[16] have observed the total ρR to increase by a factor of 5 between first shock yield and compression yield in a 24 μm thick, 18 atm D–^{3}He gas filled capsule. Smalyuk *et al.*[7] observed a factor of 8 during the time of neutron production in a 4 atm capsule.

Li *et al.*[5] used a different technique to measure ρR. In DT filled capsules they observed either the deuterons or protons that had been accelerated by scattering with a 14 MeV neutron. If the fuel geometry is fixed (assuming either a uniformly distributed source, or a fixed source at the center) then the number of the scattered deuterons is proportional to the fuel ρR and the number of protons to the plastic shell ρR. We have simulated these measurements by postprocessing our calculations, which include time and spatially dependent neutron production and mixing, to obtain the number of neutron scatterings off deuterium and hydrogen. We then normalized to the fuel ρR of the 15 atm filled capsule. Whether the calculation is unmixed or with $\alpha = 0.1$, the calculated ρR of the plastic shell differs in no significant way from the measured ρR (60 to 65 mg/cm^2).

However, the ρR of the fuel is sensitive to mixing. As seen in Fig. 5, the calculated fuel ρR without mixing is almost unchanged as the gas fill pressure is reduced. Additional compression compensates for the smaller amount of gas. But the measurements at 7 and 3 atm fills are much lower than the unmixed calculation. Calculated with mixing of $\alpha = 0.03$, the inferred ρR is lower by a factor of 2, but not as low as the 3 atm data, even if $\alpha = 0.10$. Two effects combine to produce a reduction. The first is that neutron scattering occurs during the burn. Earlier burn will sample a lower value of the rising ρR. Second, the fuel and shell interpenetrate, decreasing the fuel ρR and increasing the shell ρR. The fuel alone does not reach as high a ρR as the clean calculation, but the shell converges more, maintaining the high total ρR.

For DD filled capsules the ratio of the secondary DT neutron yield (from tritons produced in the D–D reaction) to the D–D neutron yield is another measure of the fuel ρR. Tritons produced in the D–D reaction collide with deuterons to produce high-energy neutrons. The secondary neutron ratios, normalized to the ρR of the unmixed 15 atm capsule, are also plotted in Fig. 5. These observations agree quite well with the simulated scattering measurement of fuel ρR and differ from the observed scattering values. This difference
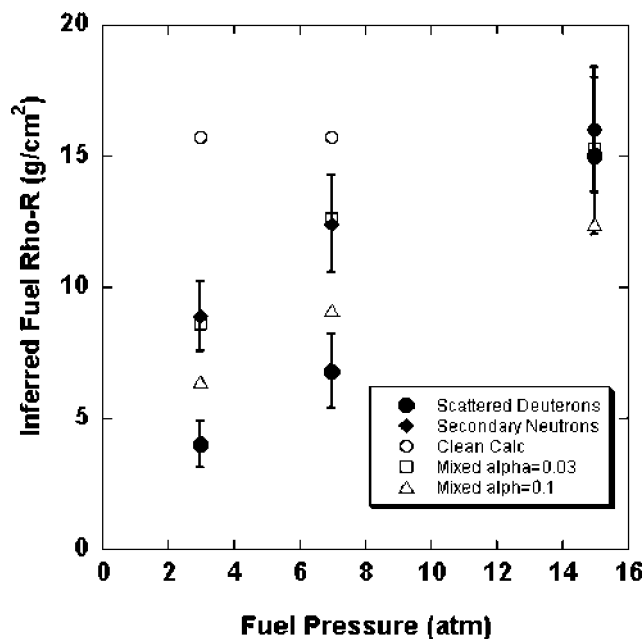

FIG. 5. Fuel areal density, ρR, inferred from observed secondary neutrons and from observed and calculated scattered deuterons.

between the scattered deuteron and secondary neutron measurements may be due to the same unknown mechanism that causes YOC values to differ for DT and DD capsules.

VI. X-RAY IMAGE SHAPE

The profile of a capsule's x-ray image can show the presence of mixing if the image is taken at energy high enough that x rays produced in the mixing region can escape the capsule. X-ray emission from a compressed capsule is dominated by emission from the shell material and calculations of that emission from unmixed implosions often show a limb brightened image. When shell material mixes into the fuel, x-ray emission fills in the center of the image, leading to first a flattened radial profile, then, if mixing is deep enough, a centrally peaked profile. Marshall *et al.*[18] have used this technique with titanium doped layers in directly driven plastic shells to verify that greater SSD bandwidth reduced mixing. Regan *et al.*[19] used this as a diagnostic of mix.

In a 4 μm wall glass capsule filled with 10 atm DT x rays emitted at 5 keV from the compressed core have an $\sim$50% chance of escape at maximum compression; for a 20 μm wall plastic capsule the probability is 99%. For a low convergence plastic capsule where mixing is minimal and high energy x rays readily escape, we would expect a limb brightened image as observed by Marshall *et al.*[18] For a more opaque glass capsule we would expect to see a flattened or slightly limb brightened image from an unmixed capsule, and progressively more central emission as shell material is mixed into the hot fuel center. Figure 6 shows just that for a 4.9 μm thick, 1070 μm diameter glass capsule with 5 atm DT (and 0.3 atm nitrogen) directly driven with 29 kJ. The flat profile of the unmixed capsule evolves into a centrally peaked profile as mixing (α) is increased. The x-ray profiles have been normalized to the central brightness of the
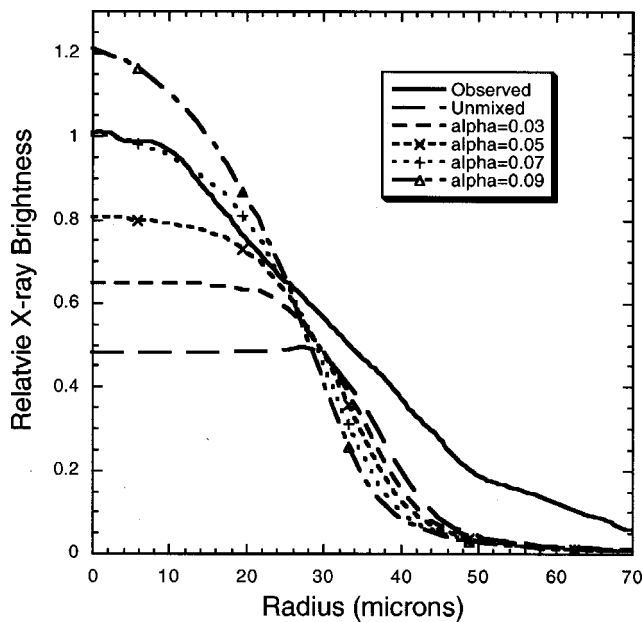
FIG. 6. The radial profiles of observed GMXI x-ray images and calculated without mixing and with different mix parameters α. The observations are normalized to the center of the $\alpha=0.07$ which matches the observed yield of the 4.9 μm wall, 5 atm DT filled glass capsule.

FIG. 7. Observed and calculated D–D neutron yield from a plastic capsule with a 1 μm thick deuterated layer on the inner surface of a 20 μm thick shell filled with ^{3}He gas.

$\alpha=0.07$ calculation which also matches the observed yield. The absolute brightness of the image is calculated to increase with mixing as shown in the figure. For a less highly mixed capsule, 3.9 μm thick, 10 atm DT, the observed profile is flat as expected from the $\alpha=0.05$ calculation which matches its yield. The flat radial profile of this 10 atm capsule and the centrally peaked profile of the 5 atm capsule are indicative of the changes caused by mixing.

VII. ATOMIC MIX

One of the assumptions of the Scannpieco and Cheng model is that all material is fully atomically mixed. Within each zone of a calculation the materials are assumed to share a single volume. Nuclear reactions occur among all the mixed materials with densities characteristic of that volume. An alternative assumption would be that materials within a zone occupy separate volumes and do not react with one another. This is commonly referred to as "chunk" mix, although it may also represent a continuous unresolved interface between materials, as would occur in an interface rippled beyond the spatial resolution of a calculation. Intermediate states would certainly exist with species being partially atomic and partially "chunk" mixed.

The presence and extent of atomic mix can be diagnosed if two reacting species are placed in physically separate capsule components. Li et al.[5] report on experiments using a 1 μm thick deuterated plastic layer on the inner surface of a plastic shell containing ^{3}He gas. The presence of nuclear collisions between the deuterium and ^{3}He creates 14.7 MeV protons that escape the capsule and are measured in charged particle spectrometers. Without atomic mixing between the deuterated plastic and the ^{3}He there is almost no yield. (A yield $\sim 10^{-3}$ times as large as was measured could arise
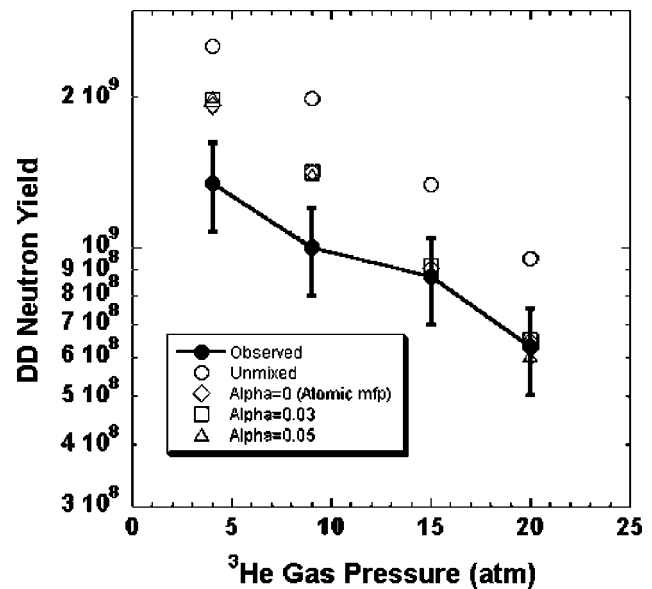
from ^{3}He gas permeating the plastic before the laser strikes the target.) The neutrons produced by deuterium fusion (D–D) in these targets are slightly sensitive to mixing, since mixing deuterium into higher central temperatures could increase yield, but it would also decrease the deuterium density. The primary factor in D–D neutron production is the implosion temperature and density achieved. For this reason it is important to match the D–D neutron yield as well as the D–^{3}He proton yield.

Figure 7 shows both the calculated and observed D–D neutron yields. The observed yield is about a factor of 2 below the unmixed yield and is consistent with any α from 0 to 0.05. The calculated degradation is dominated by the atomic mean free path, Λ. Figure 8 compares the D–^{3}He proton yields. In this case there is no proton yield from an unmixed capsule. The proton yield is sensitive to α. A value of 0.03 is nearly consistent with the observations, and $\alpha=0.05$ produces a yield as much as a factor of 2 too high. In a simple model the proton yield is proportional to the atomic mix fraction, and we conclude that the experiment is consistent with the Scannapieco and Cheng model with an atomic mix fraction of 50–100 %.

Li et al.[5] also reported results from implosions with a deuterated plastic layer offset from the inner surface by 1 μm. The yields for all the gas fill pressures are about a factor of 10 lower, consistent with mixing penetrating only a fraction of 1 μm of the CH inner surface. For these results our mix model is not so successful. The observed D–D neutron yield is consistent with the unmixed yield. Using $\alpha=0.03-0.05$ gives a factor of 2 too little neutron yield. On the other hand, the calculated proton yields for 20 and 15 atm fills are correct using $\alpha=0.05$, but factors of 6 and 50 too low for the 9 and 4 atm filled capsules. As expected more mixing occurs as the fill pressure decreases, but mix induced cooling reduces the temperature, decreasing the proton yield
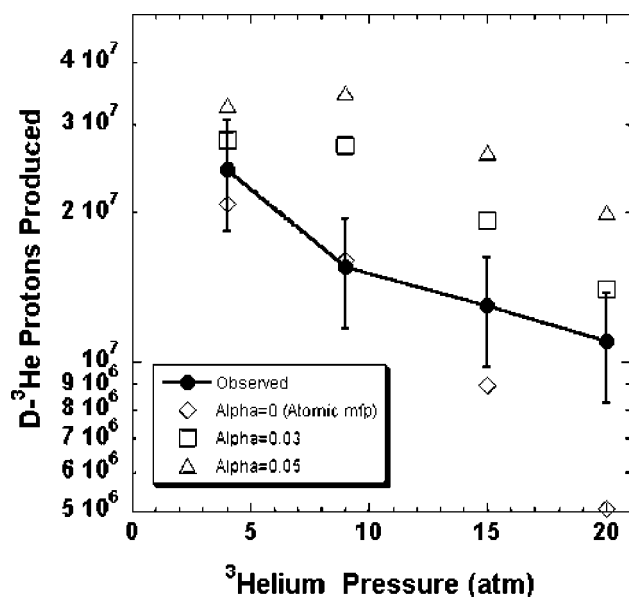
FIG. 8. Observed and calculated D–³He proton yield from a plastic capsule with a 1 μm thick deuterated layer on the inner surface of a 20 μm thick shell filled with ³He gas.

too much. The measured temperature of the deuterated layer is 1.8–2.3 keV, while our calculation gives only 1–1.2 keV. It is apparent that our mix model, or our unmixed calculation or both are incorrect for these offset layers.

VIII. CONCLUSIONS

Directly driven ICF capsules offer a wealth of information and techniques to test models of mixing. The Scannapieco and Cheng model when applied to these capsules with the same values of its adjustable parameter as for indirectly driven single shell and for double shell capsules, gives good but not perfect agreement with yield, burn temperature, burn history, areal density, and profile shape. Experiments confirm that atomic mixing is present, although perhaps not the 100% atomic mix assumed in the model. The experiments also show areas where the model may be improved, such as more rapid mixing. A current direct drive ignition capsule design[20] contains a DT ice shell surrounded by a very thin layer of plastic that is rapidly ablated away. This design avoids mixing between plastic and fuel, and so avoids the mixing that our model is designed to calculate and that is prevalent in current directly driven ICF capsules. Designs[21] using DT loaded foam ablators and pure DT may however lead to some yield degradation by mixing of that foam into pure DT. Calculations of these capsules with our mix model remain to be done.

[1] J. H. Nuckolls, L. Wood, A. Thiessen, and G. B. Zimmerman, Nature (London) **239**, 139 (1972).
[2] J. D. Lindl, *Inertial Confinement Fusion* (Springer-Verlag, New York, 1998), p. 26.
[3] D. D. Meyerhofer, J. A. Delettrez, R. Epstein *et al.*, Phys. Plasmas **8**, 2251 (2001).
[4] S. P. Regan, J. A. Delettrez, F. J. Marshall *et al.*, Phys. Rev. Lett. **89**, 085003 (2002).
[5] C. K. Li, F. H. Séguin, J. A. Frenje *et al.*, Phys. Rev. Lett. **89**, 16502 (2002).
[6] P. B. Radha, J. Delettrez, R. Epstein *et al.*, Phys. Plasmas **9**, 2208 (2002); P. B. Radha (private communication).
[7] V. A. Smalyuk, J. A. Delettrez, S. B. Dumanis *et al.*, Phys. Rev. Lett. **90**, 135002 (2003).
[8] A. J. Scannapieco and B. Cheng, Phys. Lett. A **299**, 49 (2002).
[9] J. M. Soures, R. L. McCrory, C. P. Verdon *et al.*, Phys. Plasmas **3**, 2108 (1996).
[10] D. C. Wilson, A. J. Scannapieco, C. W. Cranfill *et al.*, Phys. Plasmas **10**, 4427 (2003).
[11] D. C. Wilson, N. D. Delamater, G. D. Pollak *et al.*, "Mixing in double shell capsules," in *Proceedings of Third International Conference on Inertial Fusion Sciences and Applications* (American Nuclear Society, La Grange Park, IL, 2004).
[12] S. I. Braginskii, in *Reviews of Plasma Physics*, edited by M. A. Leontovich (Consultants Bureau, New York, 1965), Vol. 1, p. 205.
[13] C. R. Christensen, D. C. Wilson, C. W. Barnes *et al.*, Phys. Plasmas **11**, 2771 (2004).
[14] A. J. Schmitt, D. Colombant, D. Fyfe *et al.*, Phys. Plasmas **11**, 2716 (2004).
[15] R. A. Lerche, D. W. Phillion, and G. L. Tietbohl *et al.*, Rev. Sci. Instrum. **66**, 933 (1995).
[16] R. D. Petrasso, J. A. Frenje, C. K. Li *et al.*, Phys. Rev. Lett. **90**, 095002 (2003).
[17] H. Brysk, Plasma Phys. **15**, 611 (1973).
[18] F. J. Marshall, J. A. Delettrez, R. Epstein *et al.*, Phys. Plasmas **7**, 2108 (2000).
[19] S. P. Regan, J. A. Delettrez, R. Epstein *et al.*, Phys. Plasmas **9**, 1357 (2002).
[20] P. W. McKenty, V. N. Goncharov, R. P. J. Town *et al.*, Phys. Plasmas **8**, 2315 (2001).
[21] S. E. Bodner, D. G. Colombant, J. H. Gardner *et al.*, Phys. Plasmas **5**, 1901 (1998).