

Separation of light ion species in the transition from shock-dominated to compressive inertial confinement fusion implosions

N. V. Kabadi¹,^{*}† P. J. Adrian¹,[‡] T. Evans, M. Gatu Johnson¹, C. K. Li, F. H. Séguin, G. D. Sutcliffe¹,[§]
R. D. Petrasso¹, and J. A. Frenje¹

Massachusetts Institute of Technology, Plasma Science and Fusion Center, Cambridge, Massachusetts 02139, USA

C. Forrest, V. Yu Glebov, R. Janezic², and C. Stoeckl²||

Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA



(Received 9 February 2025; accepted 12 August 2026; published 23 September 2026)

A series of glass-shell D³He gas-filled implosions was carried out on the OMEGA Laser Facility. In these experiments, the thicknesses of the glass shells were varied from 4.2 to 9.4 μm, producing implosions that spanned from shock-to-compression-dominated emission. Data from several diagnostics were used to infer the conditions and nuclear yields for the D³He-p and DD-n reactions during shock and compression burns. From the inferred yields and ion temperatures, the deuterium fractions in the hot spot during both emission phases were estimated. It is found that there is a substantial surplus (~5%) of deuterium in the hot spot compared to the initial fill fraction during both shock and compression phases for all implosion types. This is the first measurement indicating persistent species separation throughout both phases of inertial confinement fusion (ICF) implosions. In ICF implosions, deviations from a 50:50 species ratio will decrease the fusion rate, directly impacting performance. Future ICF implosion design work would benefit from including models that capture multi-ion dynamics.

DOI: [10.1103/hzvv-p4d6](https://doi.org/10.1103/hzvv-p4d6)

I. INTRODUCTION

In laser-driven inertial confinement fusion (ICF) implosions, the goal is to implode a spherical capsule to reach the high densities and temperatures necessary to achieve a burning plasma state. In both direct and indirect-drive ICF, the compression is initiated by a series of shocks traversing the dense cryogenic fuel layer. These shocks coalesce near the shell-gas interface and propagate through the lower density (~0.3 mg/cm³) central gas as a single strong shock ($M \sim 10$). The shock strengthens as it converges. Near shock convergence and rebound, there is a period in which the central plasma is in a low-density high-temperature state and the hydrodynamic assumption of high ion collisionality breaks down. The elevated temperature during this phase can also lead to substantial nuclear reaction rates, especially for reactions whose reactivities increase sharply with temperature,

like deuterium helium-3 (D³He) fusion. This period of emission is referred to as the shock phase. Subsequently, the dense outer shell continues to converge, substantially increasing the central density and initiating the primary nuclear burn, referred to as the compression phase [1].

Strong spherical shocks are prevalent not only in ICF plasmas, but also in astrophysical plasmas. In these systems, the postshocked material has equilibration timescales and mean free paths that are comparable to or larger than the system scale [2–4]. This indicates a potentially collisionless regime where different ion species could have independent dynamics. In particular, the strong gradients present in the shock front can drive separation, causing the two species to develop distinct density profiles. Previous experiments that used shock-driven deuterium-tritium (DT) and D³He gas-filled implosions to study the shock-convergence phase indicated the presence of this spatial disequilibrium (species separation) as well as thermal disequilibrium (thermal decoupling) of the ion species, and absolute yield degradation [2,5–8]. Other experiments have implicated species separation and multi-ion physics as the cause of anomalous fusion yields in compressive implosions, and these phenomena may originate from the preceding shock phase [9–13]. These results indicate that an understanding of all phases of an ICF implosion, and in particular the transition from shock to compression, is necessary to design a robust ignition platform [14].

Present modeling and experiments rely heavily on average-ion hydrodynamic simulations, which cannot capture multi-ion dynamics. Simulations that solve the Fokker-Planck equation to capture multi-ion and kinetic dynamics exist [15,16] and have advanced the field in recent years. Other

*Contact author: neelkabadi@lle.rochester.edu

†Present address: University of Rochester Laboratory for Laser Energetics, Rochester, NY, USA.

‡Present address: Pacific Fusion, San Leandro, CA, USA.

§Present address: Livermore National Laboratory, Livermore, CA, USA.

||Present address: Marvel Fusion, Hamburg, Germany.

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

TABLE I. Measured experimental parameters and uncertainties. Δ is the shell thickness, OD is the shell outer diameter, ρ_0 is the initial fill density, f_D is D fraction in the fill, and E_L is the laser energy.

OMEGA shot no.	Δ (unc) (μm)	OD (unc) (μm)	ρ_0 (unc) (mg/cm^3)	f_D (unc)	E_L (unc) (kJ)
100786	4.2 (0.3)	886.4 (2)	3.11 (0.03)	$0.89 (8 \times 10^{-3})$	25.5
100792	6.0 (0.3)	831.4 (2)	3.11 (0.03)	$0.89 (9 \times 10^{-3})$	26.0
100796	7.8 (0.3)	839.7 (2)	3.11 (0.03)	$0.89 (8 \times 10^{-3})$	25.8
100798	9.4 (0.3)	817.0 (2)	3.11 (0.02)	$0.89 (4 \times 10^{-3})$	25.4

multi-ion hydrodynamic simulations are becoming available. These advanced multi-ion and kinetic capabilities are not the current standard for ICF modeling. A basic understanding of the important multi-ion physics will allow better implosion modeling. In this article, experimental results from a series of D^3He gas-filled implosions with varying shock and compression strength are used to understand the persistence of species separation from the shock-convergence phase through peak compression.

II. EXPERIMENTAL METHODS

A series of D^3He gas-filled implosions was carried out at the Omega Laser Facility [17]. The capsules were glass shells with an $\sim 840 \mu\text{m}$ outer diameter that were driven by a 1-ns square laser pulse delivering 26 kJ. The thickness of the glass shells was varied from 4.2 to 9.4 μm . Measured capsule and laser parameters are shown for each experiment in Table I. The uncertainties on the fill density and initial D fraction are estimated from the measured diffusion loss rate for each capsule. The thinner/lower mass shells experience strong converging shocks, which produce substantial shock yields. When the rebounding shock reaches the shell interface, the system disassembles as the residual shell mass is too low to withstand the shock pressure. Thicker shell implosions have distinct shock and compression phases, as the residual shell mass is sufficient to continue compression after the rebounding shock reaches the shell. As the shell gets thicker, the shock strength decreases and the peak convergence and compression yield increase. This interplay of shock and shell dynamics can be seen in the Lagrangian trajectory plots shown in Fig. 1. These experiments generate conditions relevant to the shock-convergence phase of hot-spot ignition experiments such as those conducted at the National Ignition Facility (NIF) [2,5]. The subsequent compression was not as strong as an ICF implosion, but strong enough to elucidate relevant trends. Glass-shell implosions of this type have previously been used extensively for the study of kinetic and multi-ion dynamics of the ICF hot spot [2,5,7].

By conducting experiments with high-density D^3He gas fill, the ion-ion thermal equilibration rate is sufficiently high to neglect thermal decoupling effects. For the lowest-density highest-temperature implosions, the ion-ion equilibration rate is estimated to be $< 2 \text{ ps}$, which is short compared to the dynamic timescale of $\sim 10 \text{ ps}$ [18]. In D^3He -filled implosions, the primary nuclear products are the fusion deuterium-deuterium and D^3He protons (DD-n and D^3He -p). From neutron-time-of-flight (NTOF) measurements, the DD-n yield and apparent temperature of the D ions are inferred [19]

as shown in Table II. The yield and energy spectrum of the D^3He -p are measured using wedge range filter (WRF) proton spectrometers [20]. The measured proton spectrum is impacted by the D and ^3He ion temperatures, as well as the evolving areal density of the remaining shell mass. Simultaneous measurements of the DD-n and D^3He -p histories were recorded on the particle x-ray temporal diagnostic (PXTD) [21] with $\sim 100 \text{ ps}$ temporal blurring. PXTD's temporal resolution is sufficient to discriminate the shock and compression phases, but is insufficient to track the full history of either phase. The PXTD histories and the measured yield and spectral information are used to constrain the effective temperatures and yields of the DD-n and D^3He -p reactions during both the shock flash and compression burn.

III. ANALYSIS

The thinnest shells were shock dominated, with no detectable compression component, so the measured DD-n temperature, DD-n yield, and D^3He -p yield were taken as the shock values. For thicker shells, a model was implemented to distinguish the burn-averaged ion temperatures and yields

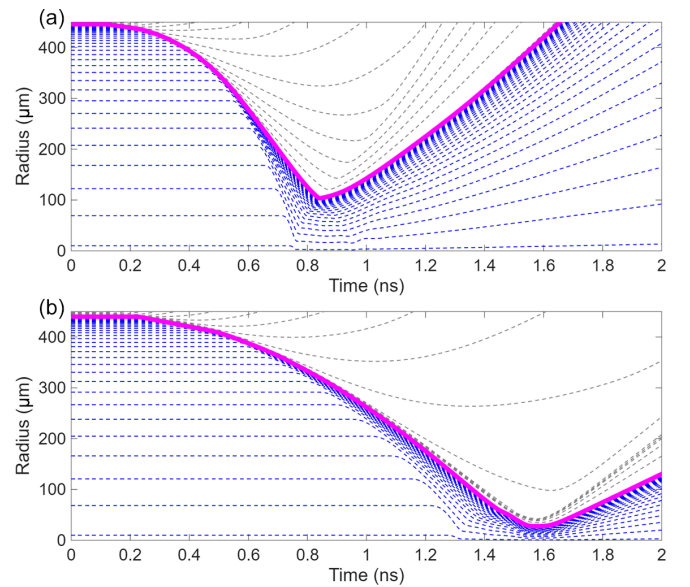


FIG. 1. HYADES simulated r - t plot for $3.11 \text{ mg}/\text{cm}^3$, 89:11 D^3He OMEGA implosions: (a) for shell thickness of $4.2 \mu\text{m}$ and (b) for a $9.4 \mu\text{m}$ thick shell. Blue dashed curves indicate the 89:11 D^3He central plasma control mass trajectories, the thick solid magenta curves are the shell-hot-spot interface, and the gray dashed curves represent the SiO_2 shell.

TABLE II. Experimental neutronics data for different shell thicknesses including DD-n yield, ion temperature, and bang time. The uncertainties on the ion temperatures and bang times are 0.51 keV and 0.05 ns, respectively.

Shell thickness (μm)	NTOF DD-n yield (+/-)	DD-n Ti (keV)	DD-n BT (ns)
4.2	2.09×10^{11} (4.17×10^9)	6.38	1.153
6	8.16×10^{10} (2.56×10^9)	5.24	1.347
7.8	4.24×10^{10} (1.97×10^9)	4.07	1.537
9.4	2.11×10^{10} (1.95×10^9)	3.50	1.627

during shock and compression. The areal density is dominated by the residual shell mass, which was modeled as a thin shell with areal density given by a Lorentzian distribution, as has been used previously for modeling of similar implosions [22,23]:

$$\rho R(t) = \frac{A}{(t - t_0)^2 + \gamma^2}, \quad (1)$$

where A , t_0 , and γ are all free parameters and t is the experiment time relative to the laser 2% rise. The emission history of the $\text{D}^3\text{He-p}$ was modeled as the sum of two Gaussians with independent timing and width:

$$Y_{\text{D}^3\text{He-p}}(t) = \frac{Y_{\text{D}^3\text{He-p,shock}}}{\sqrt{2} \times \pi \sigma_s} \exp\left[-\frac{1}{2}\left(\frac{t - t_s}{\sigma_s}\right)^2\right] + \frac{Y_{\text{D}^3\text{He-p,comp}}}{\sqrt{2} \times \pi \sigma_c} \exp\left[-\frac{1}{2}\left(\frac{t - t_c}{\sigma_c}\right)^2\right], \quad (2)$$

where Y 's are the proton yields during the shock and compression phases, σ 's are the Gaussian widths of the shock and compression components, and t 's are the shock and compression bang times. The DD-n emission history was modeled as a skew Gaussian:

$$Y_{\text{DD-n}}(t) = \frac{Y_{\text{DD-n}}}{\sqrt{2} \times \pi \sigma_{\text{DD-n}}} \exp\left[-\frac{1}{2}\left(\frac{t - t_{\text{DD-n}}}{\sigma_{\text{DD-n}}}\right)^2\right] \times \left(1 + \text{erf}\left(\frac{\alpha t}{\sqrt{2}}\right)\right), \quad (3)$$

where $Y_{\text{DD-n}}$ is the total DD-n yield, $\sigma_{\text{DD-n}}$ is the temporal width of the DD-n history, $t_{\text{DD-n}}$ is the DD-n bang time, erf is the error function, and α is the skew parameter.

The ion temperature evolution was modeled as linear with time and uniform in space:

$$T(t) = T_0 + T'_0 \times (t - t_s), \quad (4)$$

where T_0 is the hot-spot ion temperature at shock-bang time and T'_0 is the rate of temperature increase.

For each implosion, the 14 free parameters of this model were adjusted to find the best fit to the NTOF measured DD-n yield and burn-averaged ion temperature, the WRF measured $\text{D}^3\text{He-p}$ proton spectrum, and the PXTD measured DD-n and $\text{D}^3\text{He-p}$ histories. The Zimmerman stopping power model was used to account for the $\text{D}^3\text{He-p}$ energy loss when calculating the emission spectrum and history [24]. A summary of the final fit parameters for each implosion is listed in Table III. Example plots of the inferred histories for one of the experiments are included in Fig. 2. A more complete description of the fitting procedure as well as examples of the data fit quality is included in the Appendix.

From the modeled DD-n and $\text{D}^3\text{He-p}$ emission histories and temperature evolution, the yields and average ion temperatures for both reactions during the shock and compression phases were inferred. The temporal cutoff between the two phases was taken to be the local minimum in the $\text{D}^3\text{He-p}$ emission history occurring between the shock and compression $\text{D}^3\text{He-p}$ bang times, as labeled in the Fig. 2 example. The average D fractions in the hot spot (f_D) during shock and compression emission were then inferred using the second order yield-temperature relation outlined in Ref. [25]. In this model, the ratio of the $\text{D}^3\text{He-p}$ and DD-n yields is expanded to develop the following analytic expression relating the yield ratio and ion temperatures:

$$\frac{Y_{\text{D}^3\text{He-p}}}{Y_{\text{DD-n}}} = 2 \frac{1 - f_D}{f_D} \left[R_0 + \frac{1}{2} R'_0 \frac{R_0}{R'_0} (\langle T_{\text{D}^3\text{He-p}} \rangle - \langle T_{\text{DD-n}} \rangle) \right], \quad (5)$$

where R_0 , R'_0 , and R''_0 are the ratio of the $\text{D}^3\text{He-p}$ and DD-n reactivities, and its first and second derivatives with temperature, respectively. These are all evaluated at the DD-n emission-averaged ion temperature. In this equation, the yield ratio $\frac{Y_{\text{D}^3\text{He-p}}}{Y_{\text{DD-n}}}$ and emission-averaged ion temperatures $\langle T_{\text{DD-n}} \rangle$ and $\langle T_{\text{D}^3\text{He-p}} \rangle$ are inferred from the previously discussed model. R_0 and its derivatives are calculated using the Bosch-Hale reactivities [26]. The value of f_D can then be directly calculated from Eq. (5).

The resulting D fractions for the different implosions are shown in Fig. 3. For the thinnest shell, there is only a single point corresponding to the shock-bang time. For the thicker shells, there are both shock and compression data points, separated in time according to the inferred time between shock and compression bang times. Data points from the same implosion are connected with dashed lines to guide the eye. It is clear that all data points are consistent with an increase in the D fraction in the core relative to the initial value (dotted black line). The data are consistent with a single increased D fraction

TABLE III. Inferred fit parameters when applying the presented model to implosions with different shell thicknesses.

Shell thickness (μm)	$t_{\text{DD-n}}$ (ns)	$\sigma_{\text{DD-n}}$ (ns)	$\alpha_{\text{DD-n}}$ (ns^{-1})	$Y_{\text{D}^3\text{He-p,shock}}$	t_s (ns)	σ_s (ns)	$Y_{\text{D}^3\text{He-p,comp}}$	t_c (ns)	σ_c (ns)	A ($\text{ns}^2 \text{mg}/\text{cm}^2$)	γ (ns)	t_0 (ns)	T_0 (keV)	T'_0 (keV/ns)
6	1.35	0.12	-1.13	6.11×10^5	1.09	0.06	1.22×10^6	1.30	0.04	0.081	4.70×10^{-3}	1.37	16.20	-52.9
7.8	1.49	0.17	-1.13	7.67×10^4	1.23	0.06	3.47×10^5	1.44	0.04	0.46	2.00×10^{-3}	1.52	15.98	-53.0
9.4	1.61	0.09	-1	2.76×10^4	1.35	0.05	1.18×10^5	1.56	0.05	0.89	3.50×10^{-4}	1.63	15.00	-44.4

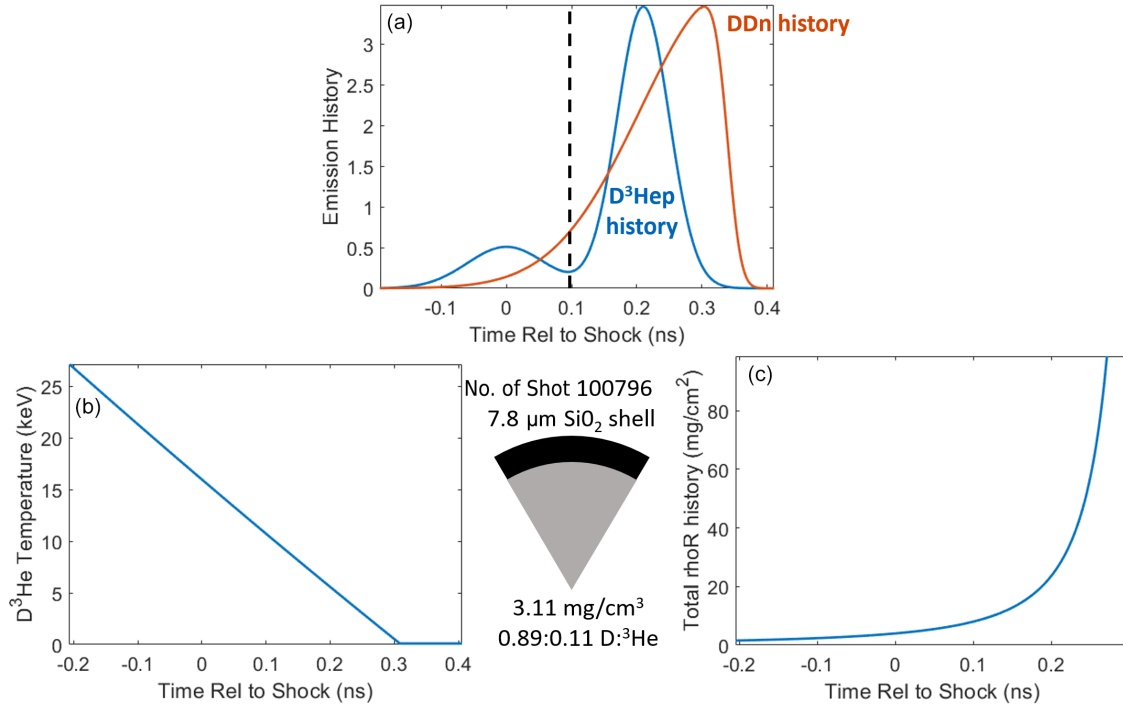


FIG. 2. The resulting histories inferred from modeling of data collected on a $7.8\ \mu\text{m}$ thick shell implosion. (a) The inferred D^3He -p and DD-n emission histories, the dashed black line indicates the imposed shock-compression transition, (b) the inferred ion temperature history, and (c) the inferred shell areal density history. All histories are plotted with the time axis shifted, so shock flash occurs at $t = 0$.

of 0.933 ± 0.002 at all times. From these results, it is clear that species separation is present in both the shock and compression phases. This is the first experimental result indicating

that light-ion species separation driven during the shock phase persists into the compression phase of ICF implosions. The experimental result of persistent species separation between phases indicates that classical ion diffusion, which serves to restore spatial equilibrium, is weak in the implosion hot spots.

Figure 3 also includes a comparison to the D fraction inferred from HYADES radiation-hydrodynamic calculations. For the comparison to simulation, synthetic data were generated from the simulated profiles and fusion rates. These data were then analyzed using the same methods described above to infer the D fraction. HYADES calculations assume a single average-ion species, and therefore cannot capture multi-ion dynamics. As expected, when postprocessing the simulations the inferred D fraction is in good agreement with the original value. This indicates that the models used here are able to accurately infer the expected D fraction.

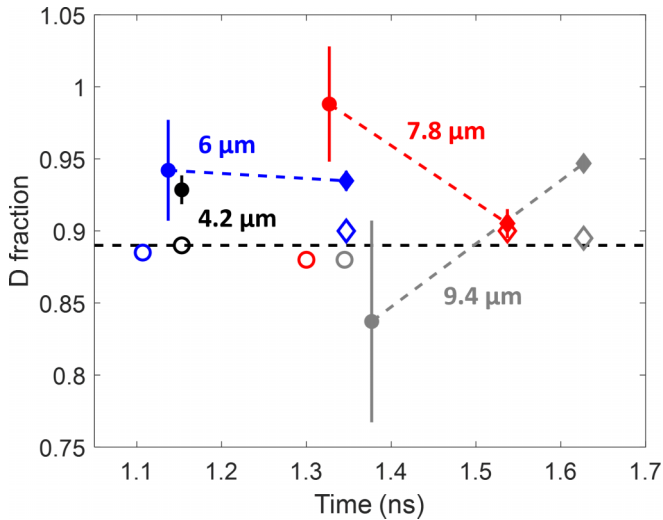


FIG. 3. The inferred deuterium fraction in the core during shock (circles) and compression (diamonds) phases for implosions of different shell thicknesses. Solid markers with error bars are experimental data; open markers are analysis of postprocessed HYADES simulations. For each implosion, the experimental shock and compression components have been separated and plotted vs time. Lines are drawn connecting the points from the same implosion to guide the eye. The dashed black line denotes the initial D fraction. Experimental data are consistent with an increase in D fraction during both phases. Processed simulations are consistent with the original D fill fraction as expected for an average-ion simulation.

IV. DISCUSSION AND CONCLUSIONS

The classical diffusion rate coefficients (Γ) of deuterium in the hot-spot plasmas are estimated using the calculations of Kagan and Tang [27,28]. The relevant timescale for diffusion to restore a hot spot with nonuniform concentration to spatial equilibrium (τ) is then estimated as

$$\tau = R^2/\Gamma, \quad (6)$$

where R is the minimum shell radius at peak emission estimated from the inferred areal density. There are two factors of R in this expression, one to set the experimental scale and another to set the concentration gradient scale. The estimated diffusion rate coefficients and timescales for these implosions are presented in Table IV. For the experiments presented in

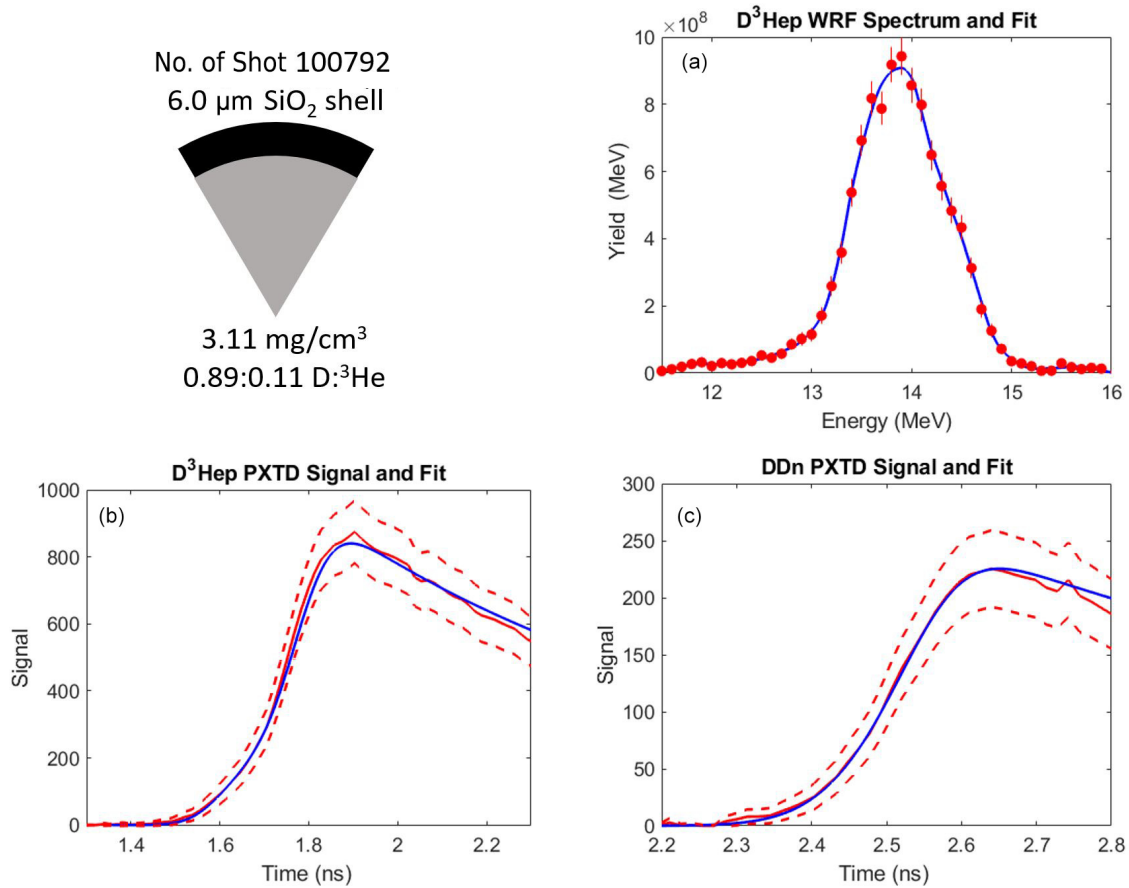


FIG. 4. Fits to the measured proton spectrum and nuclear emission histories from a 6 μm glass-shell implosion. (a) Red points with error bars are the WRF measured D³He-p spectrum and the blue curve is the fit using the described model. (b) Red curves are the measured PXTD D³He-p history with uncertainty interval and blue is the model fit. (c) Red curves are the measured PXTD DD-n history with uncertainty interval and blue is the model fit.

this paper, the diffusion timescales are $\sim\text{ns}$ and substantially longer than the time between the shock and compression phases, which is $\sim 100\text{ ps}$. These disparate timescales are in agreement with the experimental results as the species separation driven by the strong gradients present during the shock phase persists through the compression phase because there is insufficient time for the hot spot to equilibrate. For an NIF-scale ignition implosion, the hot-spot diffusion timescale is estimated to also be $\sim\text{ns}$ indicating that the species separation trend present in these experiments is likely impacting ignition-relevant ICF implosions. The exact values for the diffusion rate coefficients and timescales are sensitive to how R is estimated, but the overall conclusion is robust. The strength of species separation in 50:50 DT-filled implosions is likely de-

creased relative to these experiments as the multi-ion diffusion coefficients for the D³He ratio used here have been calculated to be $\sim 2\times$ those for 50:50 D:T [28]. The measured effects are likely most prominent for the surrogate D³He gas-filled implosions regularly conducted to prepare for and tune ignition experiments on the NIF. Experiments using ICF implosions to measure nuclear-reaction cross sections will also be impacted by persistent species separation.

In conclusion, species separation is observed to persist from the shock-convergence phase into the compression phase of ICF implosions. An increase in the D fraction relative to the initial fill is observed for nearly all implosions during both the shock and compression phases. The exact mechanism giving rise to separation is unknown, but it is likely driven by the strong gradients present in the shock phase. This then persists into compression due to the low ion diffusion rate. The analysis presented here utilized several implosions in conjunction with burn-averaged, spectrally resolved, and temporally resolved diagnostics to make the first inference of species separation persisting into the convergence phase of ICF implosions. This represents the most complete experimentally resolved picture of the dynamics between these two critical phases.

An upgraded PXTD diagnostic has been implemented with decreased temporal blurring ($\sim 40\text{ ps}$). Given the time between

TABLE IV. Estimated diffusion rate coefficients Γ and diffusion timescales τ for these experiments and a NIF ignition hot spot.

Experiment	Γ ($\mu\text{m}^2/\text{ns}$)	τ (ns)
4.2 μm shell	5500	2.9
6 μm shell	1700	5.0
7.8 μm shell	540	11
9.4 μm shell	240	17
NIF ignition	1600	0.72

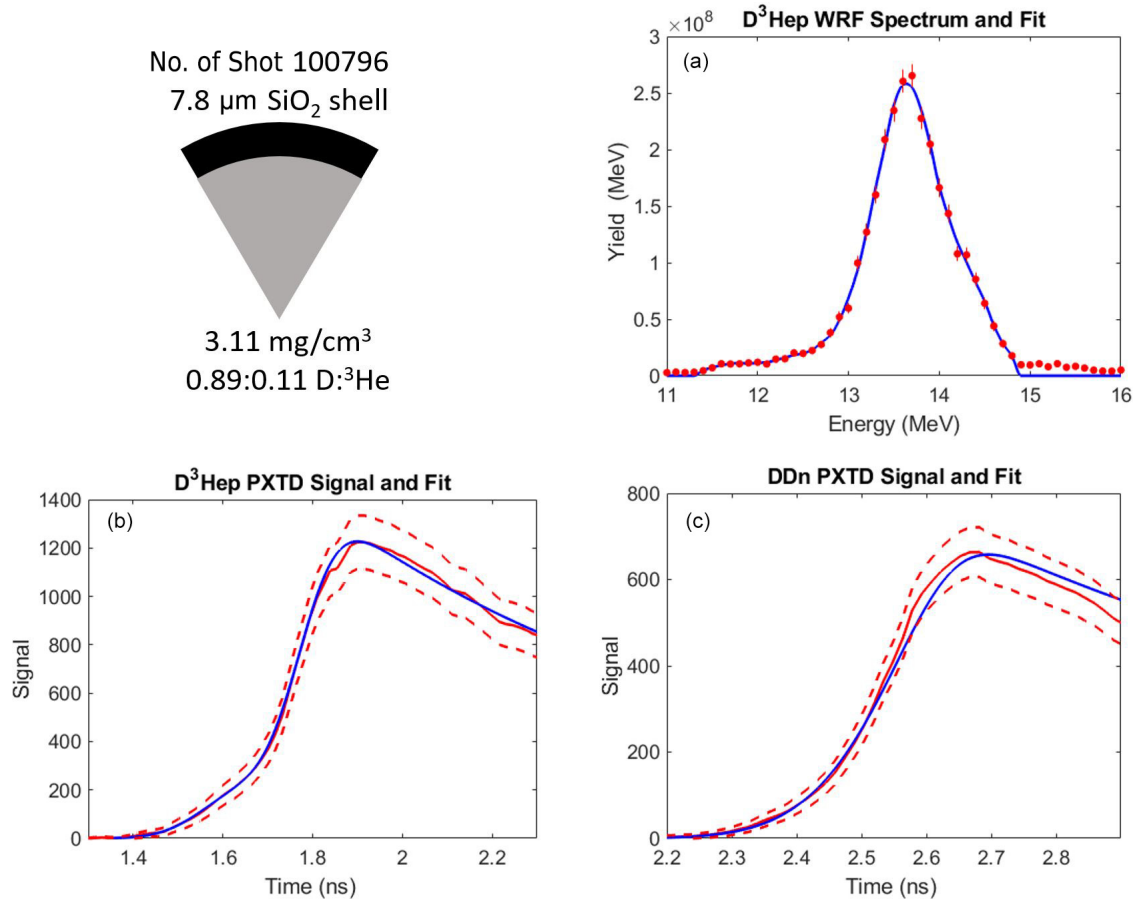


FIG. 5. Fits to the measured proton spectrum and nuclear emission histories from a 7.8 μm glass-shell implosion. (a) Red points with error bars are the WRF measured D³He-p spectrum and the blue curve is the fit using the described model. (b) Red curves are the measured PXTD D³He-p history with uncertainty interval and blue is the model fit. (c) Red curves are the measured PXTD DD-n history with uncertainty interval and blue is the model fit.

shock and compression is ~ 200 ps, future experiments using the upgraded PXTD will be able to track the continuous evolution of species separation from shock to compression in a single experiment [29,30].

ACKNOWLEDGMENTS

This material was based upon work supported by the Department of Energy, National Nuclear Security Administration under Awards No. DE-NA0003868, No. DE-NA0003938, and No. DE-NA0004144.

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein

do not necessarily state or reflect those of the United States Government or any agency thereof.

DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

APPENDIX: FITTING PROCEDURE AND QUALITY OF FITS

The 14-parameter model used to simultaneously fit the NTOF measured DD-n yield and burn-averaged ion temperature, the WRF measured D³He-p proton spectrum, and the PXTD measured DD-n and D³He-p histories consists of four equations as previously defined in the main text:

$$\rho R(t) = \frac{A}{(t - t_0)^2 + \gamma^2}, \quad (\text{A1})$$

$$Y_{\text{D}^3\text{He-p}}(t) = \frac{Y_{\text{D}^3\text{He-p, shock}}}{\sqrt{2} \times \pi \sigma_s} \exp \left[-\frac{1}{2} \left(\frac{t - t_s}{\sigma_s} \right)^2 \right] + \frac{Y_{\text{D}^3\text{He-p, comp}}}{\sqrt{2} \times \pi \sigma_c} \exp \left[-\frac{1}{2} \left(\frac{t - t_c}{\sigma_c} \right)^2 \right], \quad (\text{A2})$$

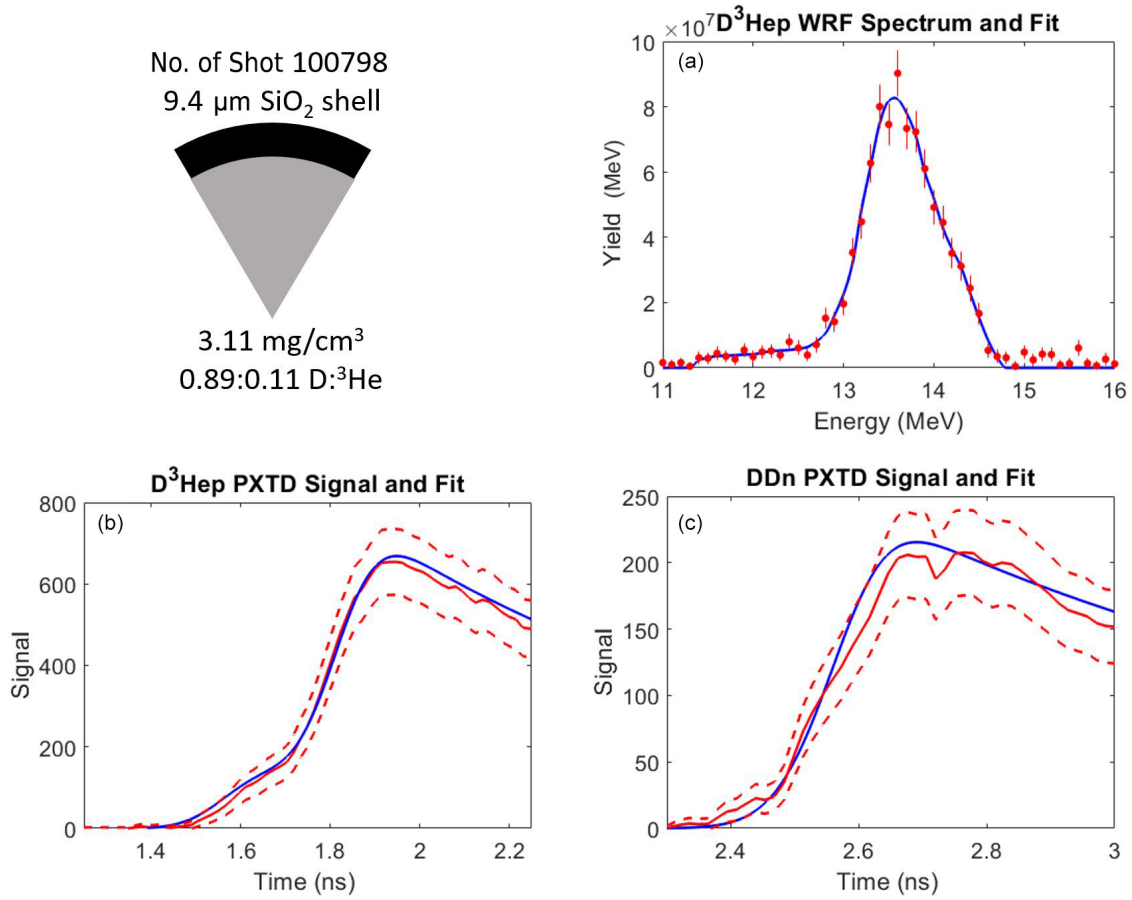


FIG. 6. Fits to the measured proton spectrum and nuclear emission histories from a 9.4 μm glass-shell implosion. (a) Red points with error bars are the WRF measured D³He-p spectrum and the blue curve is the fit using the described model. (b) Red curves are the measured PXTD D³He-p history with uncertainty interval and blue is the model fit. (c) Red curves are the measured PXTD DD-n history with uncertainty interval and blue is the model fit.

$$Y_{\text{DD-n}}(t) = \frac{Y_{\text{DD-n}}}{\sqrt{2} \times \pi \sigma_{\text{DD-n}}} \exp \left[-\frac{1}{2} \left(\frac{t - t_{\text{DD-n}}}{\sigma_{\text{DD-n}}} \right)^2 \right] \times \left(1 + \operatorname{erf} \left(\frac{\alpha t}{\sqrt{2}} \right) \right), \quad (\text{A3})$$

$$T(t) = T_0 + T'_0 \times (t - t_s). \quad (\text{A4})$$

For each implosion, the 14 free parameters of this model were adjusted using a nonlinear least-squares fitting approach. In particular, the iterative trust-region-reflective algorithm available in matlab was used [31]. For each iteration, the fit observables were calculated and compared to the measured quantities. The total DD-n yield is explicit in the model and directly constrained by the measured value. The total emission-averaged $\langle T_{\text{DD-n}} \rangle$ is calculated by averaging $T(t)$ in time weighted by $Y_{\text{DD-n}}(t)$. The D³He-p spectrum is calculated by numerical integration, where the spectrum is calculated at many time steps and summed. At each time, the birth spectrum is calculated based on $T(t)$ and $Y_{\text{D}^3\text{He-p}}(t)$ [32]. The proton energy spectrum exiting the implosion is computed using a thin-shell spherical model [23] with areal density $\rho R(t)$ and the Zimmerman stopping power model

[24]. For both the DD-n and D³He-p PXTD data, the arrival histories at the detector are calculated based on the time-resolved spectrum exiting the implosion and the time needed for these particles to propagate 3.1 cm to the detector. For the D³He-p, this information is already computed when calculating the emission average energy spectrum. For DD-n, the energy spectrum is taken to be the birth spectrum at $T(t)$ [32]. For the PXTD DD-n history, the arrival history is convolved with the detector's temporal response which consists of 126 ps FWHM Gaussian convolved with a long exponentially decaying tail. For the D³He-p history, the energy deposited in the 1 mm thick EJ-232 [33] PXTD scintillator is calculated using the Stopping and Range in Materials (SRIM) stopping power curves taking into account the the diagnostic filtering (200 μm Ti + 100 μm Ta) [34]. The proton energy deposited versus time is then convolved with the detector response. The goodness of fit is calculated based on the sum of square differences between the measured and modeled values, inversely weighted by the measurement uncertainties. The trust-region-reflective algorithm is used to update the model parameters iteratively until a best fit is found. Convergence was reached when subsequent iterations produced changes in the modeled observables less than one tenth of their uncertainties.

Minimal bounds were put on the model parameters to enforce basic physical constraints. All values must be positive (other than α , which is negative) and $t_c > t_s$. To check for solution uniqueness, the fit procedure was repeated with randomized starting points $\sim 10\times$. The solutions were found to be independent of starting point to within the convergence condition. This model was applied to the three thicker shell implosions and not the thinnest shell, which has no discernible compression phase. The resulting fits to the $D^3\text{He}$ -p spectra and nuclear emission histories for the 6, 7.8, and $9.4\mu\text{m}$ shell experiments are shown in Figs. 4, 5, and 6,

respectively. It can be seen that this model and fit procedure are able to match the data to within the diagnostic uncertainties.

Uncertainty in fit parameters is calculated based on the diagnostic uncertainty and numerically calculated Jacobian at the converged solution. This uncertainty is then propagated to the final inferred D fraction by a Monte Carlo approach, where the fit parameters are randomly sampled within their uncertainties and the distribution of inferred D fractions is tracked. The width of this distribution is taken to be the final uncertainty on the inferred D fraction.

-
- [1] J. D. Lindl, P. Amendt, R. L. Berger, S. G. Glendinning, S. H. Glenzer, S. W. Haan, R. L. Kauffman, O. L. Landen, and L. J. Suter, The physics basis for ignition using indirect-drive targets on the National Ignition Facility, *Phys. Plasmas* **11**, 339 (2004).
 - [2] M. Rosenberg, H. Rinderknecht, N. Hoffman, P. Amendt, S. Atzeni, A. Zylstra, C. Li, F. Séguin, H. Sio, M. G. Johnson, *et al.*, Exploration of the transition from the hydrodynamiclike to the strongly kinetic regime in shock-driven implosions, *Phys. Rev. Lett.* **112**, 185001 (2014).
 - [3] S. Park, S. A. Zhekov, D. N. Burrows, G. P. Garmire, and R. McCray, A Chandra view of the morphological and spectral evolution of supernova remnant 1987A, *Astrophys. J.* **610**, 275 (2004).
 - [4] M. Miceli, S. Orlando, D. N. Burrows, K. A. Frank, C. Argiroffi, F. Reale, G. Peres, O. Petruk, and F. Bocchino, Collisionless shock heating of heavy ions in SN 1987A, *Nat. Astron.* **3**, 236 (2019).
 - [5] H. G. Rinderknecht, M. Rosenberg, C. Li, N. Hoffman, G. Kagan, A. Zylstra, H. Sio, J. Frenje, M. Gatu Johnson, F. Seguin, R. Petrasso, P. Amendt, C. Bellei, S. Wilks, J. Delettrez, V. Glebov, C. Stoeckl, T. Sangster, D. Meyerhofer, and A. Nikroo, Ion thermal decoupling and species separation in shock-driven implosions, *Phys. Rev. Lett.* **114**, 025001 (2015).
 - [6] H. Sio, O. Larroche, S. Atzeni, N. V. Kabadi, J. A. Frenje, M. Gatu Johnson, C. Stoeckl, C. K. Li, C. J. Forrest, V. Glebov, P. J. Adrian, A. Bose, A. Birkel, S. P. Regan, F. H. Seguin, and R. D. Petrasso, Probing ion species separation and ion thermal decoupling in shock-driven implosions using multiple nuclear reaction histories, *Phys. Plasmas* **26**, 072703 (2019).
 - [7] H. Sio, J. Frenje, A. Le, S. Atzeni, T. Kwan, M. Gatu Johnson, G. Kagan, C. Stoeckl, C. Li, C. Parker, *et al.*, Observations of multiple nuclear reaction histories and fuel-ion species dynamics in shock-driven inertial confinement fusion implosions, *Phys. Rev. Lett.* **122**, 035001 (2019).
 - [8] H. Rinderknecht, P. Amendt, M. Rosenberg, C. Li, J. Frenje, M. Gatu Johnson, H. Sio, F. Séguin, R. Petrasso, A. Zylstra, G. Kagan, N. Hoffman, D. Svyatsky, S. Wilks, V. Y. Glebov, C. Stoeckl, and T. Sangster, Ion kinetic dynamics in strongly-shocked plasmas relevant to ICF, *Nucl. Fusion* **57**, 066014 (2017).
 - [9] D. T. Casey, J. A. Frenje, M. Gatu Johnson, M. J.-E. Manuel, H. G. Rinderknecht, N. Sinenian, F. H. Séguin, C. K. Li, R. D. Petrasso, P. B. Radha, *et al.*, Evidence for stratification of deuterium-tritium fuel in inertial confinement fusion implosions, *Phys. Rev. Lett.* **108**, 075002 (2012).
 - [10] J. R. Rygg, J. A. Frenje, C. K. Li, F. H. Séguin, R. D. Petrasso, J. A. Delettrez, V. Y. Glebov, V. N. Goncharov, D. D. Meyerhofer, S. P. Regan, T. C. Sangster, and C. Stoeckl, Tests of the hydrodynamic equivalence of direct-drive implosions with different D_2 and ^3He mixtures, *Phys. Plasmas* **13**, 052702 (2006).
 - [11] H. W. Herrmann, J. R. Langenbrunner, J. M. Mack, J. H. Cooley, D. C. Wilson, S. C. Evans, T. J. Sedillo, G. A. Kyrala, S. E. Caldwell, C. S. Young, *et al.*, Anomalous yield reduction in direct-drive deuterium/tritium implosions due to ^3He addition, *Phys. Plasmas* **16**, 056312 (2009).
 - [12] S. C. Hsu, T. R. Joshi, P. Hakel, E. L. Vold, M. J. Schmitt, N. M. Hoffman, R. M. Rauenzahn, G. Kagan, X.-Z. Tang, R. C. Mancini, Y. Kim, and H. W. Herrmann, Observation of interspecies ion separation in inertial-confinement-fusion implosions, *Europhys. Lett.* **115**, 65001 (2016).
 - [13] T. R. Joshi, S. C. Hsu, P. Hakel, N. M. Hoffman, H. Sio, and R. C. Mancini, Progress on observations of interspecies ion separation in inertial-confinement-fusion implosions via imaging x-ray spectroscopy, *Phys. Plasmas* **26**, 062702 (2019).
 - [14] H. G. Rinderknecht, P. A. Amendt, S. C. Wilks, and G. Collins, Kinetic physics in ICF: Present understanding and future directions, *Plasma Phys. Control. Fusion* **60**, 064001 (2018).
 - [15] O. Larroche, H. G. Rinderknecht, M. J. Rosenberg, N. M. Hoffman, S. Atzeni, R. D. Petrasso, P. A. Amendt, and F. H. Séguin, Ion-kinetic simulations of D- ^3He gas-filled inertial confinement fusion target implosions with moderate to large Knudsen number, *Phys. Plasmas* **23**, 012701 (2016).
 - [16] W. T. Taitano, A. N. Simakov, L. Chacón, and B. Keenan, Yield degradation in inertial-confinement-fusion implosions due to shock-driven kinetic fuel-species stratification and viscous heating, *Phys. Plasmas* **25**, 056310 (2018).
 - [17] T. R. Boehly, D. L. Brown, R. S. Craxton, R. L. Keck, J. P. Knauer, J. H. Kelly, T. J. Kessler, S. A. Kumpan, S. J. Loucks, S. A. Letzring, F. J. Marshall, R. L. McCrory, S. F. B. Morse, W. Seka, J. M. Soures, and C. P. Verdon, Initial performance results of the OMEGA laser system, *Opt. Commun.* **133**, 495 (1997).
 - [18] N. V. Kabadi, R. Simpson, P. J. Adrian, A. Bose, J. A. Frenje, M. Gatu Johnson, B. Lahmann, C. K. Li, C. E. Parker, F. H. Séguin, *et al.*, Thermal decoupling of deuterium and tritium during the inertial confinement fusion shock-convergence phase, *Phys. Rev. E* **104**, L013201 (2021).
 - [19] V. Y. Glebov, C. Stoeckl, T. C. Sangster, S. Roberts, G. J. Schmid, R. A. Lerche, and M. J. Moran, Prototypes of

- National Ignition Facility neutron time-of-flight detectors tested on OMEGA, *Rev. Sci. Instrum.* **75**, 3559 (2004).
- [20] F. H. Seguin, J. A. Frenje, C. K. Li, D. G. Hicks, S. Kurebayashi, J. R. Rygg, B.-E. Schwartz, R. D. Petrasso, S. Roberts, J. M. Soures, D. D. Meyerhofer, T. C. Sangster, J. P. Knauer, C. Sorce, V. Y. Glebov, C. Stoeckl, T. W. Phillips, R. J. Leeper, K. Fletcher, and S. Padalino, Spectrometry of charged particles from inertial-confinement-fusion plasmas, *Rev. Sci. Instrum.* **74**, 975 (2003).
- [21] H. Sio, J. A. Frenje, J. Katz, C. Stoeckl, D. Weiner, M. Bedzyk, V. Glebov, C. Sorce, M. Gatu Johnson, H. G. Rinderknecht, *et al.*, A particle x-ray temporal diagnostic (PXTD) for studies of kinetic, multi-ion effects, and ion-electron equilibration rates in inertial confinement fusion plasmas at OMEGA (invited), *Rev. Sci. Instrum.* **87**, 11D701 (2016).
- [22] V. A. Smalyuk, P. B. Radha, J. A. Delettrez, V. Y. Glebov, V. N. Goncharov, D. D. Meyerhofer, S. P. Regan, S. Roberts, T. C. Sangster, J. M. Soures, C. Stoeckl, J. A. Frenje, C. K. Li, R. D. Petrasso, and F. H. Séguin, Time-resolved areal-density measurements with proton spectroscopy in spherical implosions, *Phys. Rev. Lett.* **90**, 135002 (2003).
- [23] J. A. Frenje, C. K. Li, F. H. Seguin, J. Deciantis, S. Kurebayashi, J. R. Rygg, R. D. Petrasso, J. Delettrez, V. Y. Glebov, C. Stoeckl, F. J. Marshall, D. D. Meyerhofer, T. C. Sangster, V. A. Smalyuk, and J. M. Soures, Measuring shock-bang timing and ρR evolution of D³He implosions at OMEGA, *Phys. Plasmas* **11**, 2798 (2004).
- [24] G. Zimmerman, Recent developments in Monte Carlo techniques, LLNL Report No. UCRL-JC-105616, 1990.
- [25] N. V. Kabadi, P. J. Adrian, A. Bose, D. T. Casey, J. A. Frenje, M. G. Johnson, B. Lahmann, O. M. Mannion, R. D. Petrasso, H. G. Rinderknecht, F. H. Séguin, H. W. Sio, G. D. Sutcliffe, and A. B. Zylstra, A second order yield-temperature relation for accurate inference of burn-averaged quantities in multi-species plasmas, *Phys. Plasmas* **28**, 022701 (2021).
- [26] H.-S. Bosch and G. M. Hale, Improved formulas for fusion cross-sections and thermal reactivities, *Nucl. Fusion* **32**, 611 (1992).
- [27] G. Kagan and X.-Z. Tang, Electro-diffusion in a plasma with two ion species, *Phys. Plasmas* **19**, 082709 (2012).
- [28] G. Kagan and X.-Z. Tang, Thermo-diffusion in inertially confined plasmas, *Phys. Lett. A* **378**, 1531 (2014).
- [29] N. Kabadi, P. Adrian, C. Stoeckl, A. Sorce, H. W. Sio, M. Bedzyk, T. Evans, S. Ivancic, J. Katz, J. Knauer, J. Pearcy, D. Weiner, R. Betti, A. Birkel, D. Cao, M. G. Johnson, S. P. Regan, R. D. Petrasso, and J. Frenje, The phase-2 particle x-ray temporal diagnostic for simultaneous measurement of multiple x-ray and nuclear emission histories from OMEGA implosions (invited), *Rev. Sci. Instrum.* **93**, 103538 (2022).
- [30] N. Kabadi, A. Sorce, C. Stoeckl, H. W. Sio, P. Adrian, M. Bedzyk, J. Frenje, J. Katz, J. Knauer, J. Pearcy, D. Weiner, B. A. Aguirre, R. Betti, A. Birkel, D. Cao, M. Gatu Johnson, D. Patel, R. D. Petrasso, and S. P. Regan, A multi-channel x-ray temporal diagnostic for measurement of time-resolved electron temperature in cryogenic deuterium–tritium implosions at OMEGA, *Rev. Sci. Instrum.* **92**, 023507 (2021).
- [31] The MathWorks, Inc., Matlab version: 23.2.0 (r2023b), 2023, <https://www.mathworks.com>.
- [32] L. Ballabio, J. Kallne, and G. Gorini, Relativistic calculation of fusion product spectra for thermonuclear plasmas, *Nucl. Fusion* **38**, 1723 (1998).
- [33] Eljen Technology, EJ-232 scintillator, 2021, <https://eljentechnology.com/products/plastic-scintillators/ej-232-ej-232q>.
- [34] J. F. Ziegler, M. Ziegler, and J. Biersack, SRIM—The stopping and range of ions in matter (2010), *Nucl. Instrum. Methods Phys. Res., Sect. B* **268**, 1818 (2010).