X-Ray Spectroscopy of Implosions at the National Ignition Facility

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The hot-spot and compressed shell of ignition-scale implosions are diagnosed with x-ray spectroscopy

- Ablator mass mixed into the hot spot is inferred from the intensity of the He\textsubscript{$\alpha$} + satellite line emission of mid-Z ablator dopants*,**
- The origin of the hot-spot mix mass is investigated using Cu and Ge dopants placed at different radial locations in the ablator***
- The compressed-shell conditions are inferred from the absorption of x rays from the hot spot by the compressed Ge-doped CH
- Hydrodynamic mixing is predicted to increase the $T_e$ and $n_e$ of the Ge-doped CH in the compressed shell

These time-integrated measurements will be extended with streaked x-ray spectroscopy using the National ignition Facility (NIF) x-ray spectrometer (NXS).

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Outline

X-ray spectroscopy of implosions at the NIF

- NIF implosion experiment
  - Supersnout II
- X-ray emission spectroscopy of the hot spot
  - hot-spot mix
- X-ray absorption spectroscopy of the compressed shell
  - hydrodynamic mixing of shell layers
- Future direction
  - streaked x-ray spectroscopy on NIF
- Conclusion
Ignition-scale capsules with trace amounts of Ge and Cu are imploded with hohlraums on the NIF.

- $E_{UV} = 1.3$ MJ to 1.8 MJ
- CH ablator
- Si dopant is a preheat shield
- Ge/Cu dopants are used for emission/absorption x-ray spectroscopy
- adiabat ($\alpha = \frac{P_{\text{fuel}}}{P_{\text{Fermi}}}$) is set by the laser drive

Two types of implosion are studied:
1. low-adiabat ($\alpha \sim 1$)*
2. high-adiabat ($\alpha \sim 3$)**

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A time-integrated, 1-D imaging spectrometer was used to record x-ray spectra in the 6- to 16-keV range.

**Supersnout II**
- 6 to 16 keV
- 100-μm resolution
- $E/dE = 100$ to 300

Supersnout II combines 1-D spectral imaging and broadband gated and time-integrated x-ray imaging in a single snout.
The ablation-surface instability* and the inner-shell deceleration instability initiate mix at different times and locations

- Find the instability criterion

\[ \vec{v}P \cdot \vec{v}\rho < 0 \]

satisfied near the dashed lines

The ablation surface reaches the Ge-doped layer, but not the Cu-doped layer.

Two-dimensional simulations predict bubbles of material from the ablation surface are mixed into the hot spot (hot-spot mix)*

The symcap target replaces the DT cryo layer with a CH surrogate layer.

Hot-spot mix and compressed-ablator $\rho R$ are diagnosed with x-ray spectroscopy near peak compression

- Mix from the ablation surface instability$^{1-3}$ →
  - Ge hot-spot emission
- Mix from the ablator/fuel interface$^{1-3}$ →
  - Cu hot-spot emission

- X-ray continuum from the hot spot is attenuated by the K edges of dopants in the compressed ablator

$^{1}$B. A. Hammel et al., High Energy Density Phys. 6, 171(2010).
The calibrated, spatially integrated x-ray spectrum contains features from the hot spot and the shell.

Strong Ge features and weak Cu features are observed.

The mix mass is estimated from the brightness of the Ge and Cu He\(_{\alpha} + \) satellite emission, assuming uniform plasma conditions

- The total time and spectrum-integrated line emission
  \[ \iint \langle P_{21}(h\nu) \rangle_{\text{meas}} \, dh\nu \, dt \] is measured

- The total line emissivity per ion \( \langle p_2(T, \rho, R)A_{21}E_{21} \rangle \) is obtained from PrismSPECT* as a function of \( T, \rho, \) and the average photon escape path length \( R. \)

- The total number of Ge ions under steady uniform conditions
  \[ N_{\text{Ge}} = \frac{\iint \langle P_{21}(h\nu) \rangle_{\text{meas}} \, dh\nu \, dt}{\langle p_2(T, \rho, R)A_{21}E_{21} \rangle \Delta t} \]

and the initial Ge atomic concentration give the total mix mass \( M. \)

Fitting the emission model to the data produces significant estimates of the three independent parameters \( T, \rho, \) and \( R. \)

*J. J. MacFarlane et al., High Energy Density Phys. 3, 181 (2007).*
The spectrum is fit to the model to infer the hot-spot mix mass

- $n_e = 0.9 \pm 0.1, -0.5 \times 10^{25}$ cm$^{-3}$
- $T_e = 3.0 \pm 0.6, -0.4$ keV
- $\rho R_{\text{Ge}} = 0.325 \pm 0.1, -0.025$ mg/cm$^2$
- $M_{\text{CH}}(\text{Ge, Si}) = 34 (-13, +50)$ ng
- $M_{\text{CH}}(\text{Cu}) < 2 (-1, +1)$ ng, upper limit

The Ge-doped mix mass is at least 17\texttimes more than the Cu-doped mix mass.
The ablation-front instability is primarily responsible for hot-spot mix*.

The CH(Ge) mass is 7× the CH(Cu) mass, but at least 17× more CH(Ge) mix mass than CH(Cu) mix mass was observed.

Low neutron yields and hot-spot mix mass around the 75-ng limit are observed*

The NIF requirement (driven by radiative cooling) is that the mix mass <75 ng**

Hot-spot mix-mass analysis assumes 125-ps x-ray burnwidth

Initial masses
Ablator: $2.6 \times 10^6$ ng
DT ice: $1.4 \times 10^5$ ng
DT vapor: 820 ng

Mix mass from the pure CH ablator cannot be detected with x-ray spectroscopy → lower bound on hot-spot mix.

Less hot-spot mix and higher neutron yields are observed for the high-adiabat* implosion.

The NIF requirement (driven by radiative cooling) is that the mix mass <75 ng**.

A similar trend is observed using the mix diagnostic technique of enhanced x-ray production relative to neutron yield***.

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High-Z dopants are used to diagnose the compressed ablator near stagnation

Compressed target at stagnation

Ablator: CH with high-Z dopant (Cu, Ge)

Measured x-ray spectrum around stagnation

1-D spectral image

\[ I \propto e^{-h\nu/kT} e^{-\mu_{\text{Ge}}(n_e,T_e)} \rho_{\text{Ge}} e^{-\mu_{\text{Cu}} \rho_{\text{Cu}}} e^{-\mu_{\text{CH}} \rho_{\text{CH}}} \]

Hot-spot backlighter Ge shell attenuation Cu shell attenuation CH shell attenuation

Adiabat: \( \alpha \equiv P_{\text{fuel}}/P_{\text{Fermi}} \) (set by laser pulse shape)
The Ge opacity is sensitive to changes in $n_e$ and $T_e$ of the compressed ablator.

Simulated emergent spectrum using VISTA* opacity calculations

$\rho R_{Ge} = 8$ mg/cm$^2$

Physical effects:**
1. Screening (K-edge shift)
2. Ionization ($1s$–$2p$, $1s$–$3p$)
3. Continuum lowering***
4. Stark broadening

$I \propto e^{-h\nu/kT} e^{-\mu_{Ge}(n_e, T_e)} \rho R_{Ge} e^{-M/(h\nu)^3}$

Continuum lowering* reduces the 1s–3p and 1s–2p absorption features

Simulated emergent spectrum using VISTA** opacity calculations

- Cold K edge
- $T_e = 100$ eV, $n_e = 4 \times 10^{25}$ cm$^{-3}$
- $T_e = 300$ eV, $n_e = 4 \times 10^{25}$ cm$^{-3}$

$\rho R_{Ge} = 8$ mg/cm$^2$

$\rho R_{Ge}$, $n_e$, and $T_e$ of the compressed ablator are diagnosed with x-ray absorption spectroscopy.

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A range of compressed plasma conditions is inferred for the low-adiabat implosion

Inferred plasma conditions:

- $n_e = 4 (-1, +6) \times 10^{25} \text{ cm}^{-3}$
- $T_e = 250 (-100, +75) \text{ eV}$
- $\rho R_{Ge} = 7 (-3, +3) \text{ mg/cm}^2$

Similar analysis was performed for the high-adiabat implosion.
Two-dimensional simulations show density and temperature in the DT-fuel layer is higher than in the compressed ablator.

- 2-D HYDRA simulation of low-adiabat implosion near stagnation

Simulated spatially and temporally averaged $T_e$ and $n_e$ of the compressed ablator are compared with the experimental results.
Simulated $T_e$ and $n_e$ of the compressed ablator without mix are much lower than the experiment

- 2-D HYDRA simulation of the low-adiabat implosion
The effects of hydrodynamic mixing of the target layers was explored with an $\ell = 100$ perturbation.

- 2-D HYDRA simulation of the low-adiabat implosion

The $\ell = 100$ mode perturbation slightly increases the simulated values.
Low-adiabat

Spatial average of simulated values over the entire compressed ablator is closer to experiment

- 2-D HYDRA simulation of the low-adiabat implosion

![Graphical representation of 2-D HYDRA simulation showing spatial distribution of electron density and temperature.]

Significant mixing of CH(Ge) and CH(Cu) layers must occur.
Low-adiabat

Spatial average of simulated values over the inner compressed ablator is comparable to experiment

• 2-D HYDRA simulation of the low-adiabat implosion

With \( \ell = 100 \) perturbation

\[
\begin{align*}
\text{Time} & \quad \text{Spatial average} \\
0.3 & \quad 0.8 \\
0.8 & \quad 2.5 \\
2.5 & \quad 7.7 \\
7.7 & \quad 23.7
\end{align*}
\]

\( n_e (\times 10^{25}) \quad \text{cm}^{-3} \)


- Measurement may be weighted to the highest \( T_e \) and \( n_e \).
High-adiabat

The 2-D simulation without mixing for the high-adiabat implosion is close to the experimental result

- 2-D HYDRA simulation of the high-adiabat implosion

Experiment versus simulation

Less hydrodynamic mixing of target layers is inferred for the high-\( \alpha \) implosion compared to the low-\( \alpha \) one.
Hydrodynamic mixing is predicted to increase the $T_e$ and $n_e$ of the Ge-doped CH in the compressed shell.

The low-adiabat implosion has more hydrodynamic mixing of the target layers than the high-adiabat one.
Future direction

Time-resolved x-ray spectroscopy will be recorded on the NIF with the NXS

NXS/DISC
- Partially overlapping spectral windows in 2- to 18-keV range
- \( E/dE \approx 100 \)
- \( dt \geq 8 \) ps
- mm-scale x-ray sources
- absolute calibration

\textit{DISC} = Diagnostic insertion manipulator imaging streak camera

A time-integrated photometric calibration of NXS was performed on OMEGA

Performance qualification shot on the NIF was successfully completed on 3 June.

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The cold Ge K edge was measured using a laser-driven, planar Ge target.

\[ \rho R_{\text{Ge}} = 8.3 \pm (2.8, +0.1) \text{ mg/cm}^2 \] is inferred from this calibration shot using the cold opacity.*

The “He$\alpha$” feature is composed of $2p$–$1s$ transitions from L-shell ionization species.

Core conditions:
- $kT \approx 2$ keV
- $Z \approx 26$ (C-like) through 30 (He-like)

He$\alpha$ resonance and intercombination lines:
- $n = 1, s$ or $\ell = 0$
- $n = 2, \ell = 1$
- $2p$–$1s$
- $h\nu = 10.22, 10.28$ keV
- $p$ or $\ell = 1$

Be-like satellites of the He$\alpha$ resonance lines:
- $n = 1, s$ or $\ell = 0$
- $n = 2, \ell = 1$
- $2p$–$1s$
- $h\nu = 10.13, 10.18$ keV
- $p$ or $\ell = 1$

Autoionizing states are formed primarily by dielectronic recombination.
The 1s–2p absorption lines of Ge in the ablator are visible only for $Z > 22$ or for $kT > 400$ eV.

For 0.1% Ge in CH, $0.03 \leq \rho \leq 3$ g/cm$^3$

- $n = 3$
- $n = 2$
- $n = 1$

$s$ or $\ell = 0$

$p$ or $\ell = 1$

$1s$–$3p$

$kT \leq 400$ eV
$22 \text{ (Ne-like)} \geq Z > 4 \text{ (Ni-like)}$

$kT \geq 300$ eV for Cu

$n = 3^*$ may be removed by continuum lowering

$n = 3^*$

$1s$–$3p$

$1s$–$2p$

$h\nu$

$kT \geq 400$ eV
$Z > 22 \text{ (Ne-like)}$
**PrismSPECT** is an atomic detailed configuration accounting (DCA) spectrum simulation and analysis tool

- The Ge model includes 10,205 levels from the Ne-like through fully stripped ionization species, selected from a database of 32,176 levels
  - single excitations through \( n = 10 \) and double excitations through \( n = 3 \)
  - collisional and radiative excitations and decays, autoionization, and dielectronic recombination
- The key resonance-line-emitting configurations are “spin-orbit” split
- Radiation-transport effects are calculated self-consistently for homogeneous objects with an “escape-probability” model
- Measured spectra are compared with model spectra for 7068 combinations of \( n_e, T_e, \) and \( \rho R_{\text{Ge}} \)
- Line profiles are obtained using a semi-empirical formulation by Hans Griem**

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Profiles of the critical H- and He-like spectral lines in *PrismSPECT* are obtained from the multi-electron radiator line (*MERL*) code*

\[ n_e (\text{cm}^{-3}) \]

- 2 \times 10^{22}
- 2 \times 10^{23}
- 2 \times 10^{24}
- 5 \times 10^{25}

*J. J. MacFarlane et al., High Energy Density Phys. 3, 181 (2007).*