Probing matter at Gbar pressures at the NIF

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Matter at Gbar pressure | Challenges and applications

- Interplay of Coulomb pressure and electron–degeneracy pressure
- Partial ionization, shell effects
- Difficult description of compressibility and heat capacity

Matter at Gbar pressure | Shell effects: heat capacity of aluminum

![Graph showing electronic specific heat capacity vs. temperature](image)

- **Schottky anomaly**
- **Asymptotic value Z=13**
- **Ionisation of 1s orbital**
- **Ionisation of 2s and 2p orbitals**

**Graph Details:**
- **Electronic Specific Heat** \( C_v^{\text{elec}} \)
- **Temperature** in eV

**Source:** J. C. Pain, HEDP 3, 204 (2007)
Matter at Gbar pressure | Shell effects: Aluminum Hugoniot

J. C. Pain, HEDP 3, 204 (2007)
Matter at Gbar pressure | CH Hugoniot & shell structure

\[
\frac{P}{P_0} \sim r^{-1}
\]
Experimental setup | X-ray radiography and scattering

Modified existing NIF platform (1D Convergent Ablator)

Main diagnostics:
- Streaked X-ray radiography (shock speed, mass density)
- X-ray Thomson scattering (electron temperature)

3.3-mm-diameter large LEH

Solid CH or CD spheres with Ge preheat shield

Au Hohlraum (5.75 x 9.42 mm)
Fill: 0.96 mg/cc $^4$He

Streaked Radiography

X-ray Scattering

Au shield

Zn foil 9 kev line emission

Experimental setup | X-ray radiography and scattering

Laser pulse shapes

Power (TW)

Time (ns)
Experimental setup | Target design

- Zn backlighter foil
- Au radiation shield

Capsule design with graded Ge dopant layer:
- $R_{out} = 1150 \, \mu m$
- CH (GDP)
- CH + 0.5% Ge
- CH + 1% Ge
- CH + 0.5% Ge
- 965 \, \mu m
Simulations | Parameter space

Pressure at shock front

A. L. Kritcher et al., HEDP 10, 27 (2014)
X-ray radiography | Raw data

January 03, 2013

July 01, 2013
X-ray radiography | Analysis

- Profile matching to infer
  \[ \mu(r) = \rho(r) \sigma(r) \]

- Movement of shock front with time gives shock velocity

- After shock passes marker layer, enclosed mass between shock front and marker layer is known

- Assuming constant density and constant opacity for first time step after passing marker layer: simultaneous density and opacity unfold

- As shock propagates: Using relative comparison to the first time step after passing the marker layer gives full density and opacity profile

D. C. Swift et al., in prep.
X-ray radiography | Results

Inferred opacity

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Hugoniot data

\[ \frac{\alpha}{\alpha_0} \]

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T. Doeppner et al., in prep.

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Cauble et al.

Barrios et al.

Ozaki et al.
X-ray scattering | Temperature measurement

- X-rays are scattered from plasma electrons

- **Elastic (Rayleigh):** scattering from tightly bound electrons or free electrons which dynamically follow the ion motion

- **Inelastic (Compton):** scattering from free or weakly bound electrons, mirrors electron velocity distribution → $T_e$
X-ray scattering | Spectrometer setup

High-efficiency, gated x-ray spectrometer (7.4 – 10 keV)

Calibration shot

- Cu He-α
- Cu He-β
- Zn He-α

Photon energy: 7.4 keV - 10 keV

Mounts to gated detector

Filter pack

Bragg crystal (HOPG) (10° offset from DIM- axis)

Debris shield

T. Doeppner et al., in prep.
**X-ray scattering | Raw data**

**time-resolved x-ray spectrum**

- X-ray continuum emission
- Zn source plasma and/or gold L-shell emission
- X-ray Scattering Signal
- Ungated Hard x-ray background

**streaked radiograph**

- 9.33 ns
- 8.85 ns

**Photon energy**

**space**

**time**
**X-ray scattering | Analysis: inhomogeneous sample**

Different expected X-ray scattering spectra from different radii
**X-ray scattering | Analysis: scattering signal weighting**

D. Chapman et al., in prep.

9 keV radiation
Full analysis:

- Calculate radial scattering spectrum for sample conditions
- Apply weighting maps (3D)
- Ray-tracing of weighted spectra to detector (3D)
- Compare result with measured spectrum
X-ray scattering | Results

Signal dominated by $300 \mu m \leq r \leq 500 \mu m$

at $r = 400 \mu m$ (Hydra + SESAME):
$T_e = 60$ eV
$\rho = 5.0$ g/cm$^3$
$Z_C = 3.9$

D. Kraus et al., in prep.
X-ray scattering | Bremsstrahlung continuum

- Slope sensitive to core plasma temperature:

- Fitting slope with LTE bremsstrahlung spectrum
  \( \sim \exp(-\hbar \nu/kT_e) \): \( T_e = 400 \) eV

- Fitting slope with Planck spectrum
  \( \sim \nu^3 \exp(-\hbar \nu/kT_e) \): \( T_e = 350 \) eV
CD targets | Hotspot ion temperature via DD fusion

Capsule design: CD with a graded Ge doped ablator

- CH
- CH + 0.5% Ge
- CH + 1% Ge
- CH + 0.5% Ge

Solid CD

Outgassing caused wrinkles

We attempted CD experiment with no ablator

- D + D → n + $^3$He
- $E_n = 2.5$ MeV

R_{out} = 1150 \, \mu m

<1 \, \mu m \, \text{RMS}
CD targets | Hotspot ion temperature via DD fusion

![Diagram showing CD targets and hotspot ion temperature via DD fusion](image)

- DD Rate
- Tion
- Hohlraum Component
- Capsule Component

Graph showing:
- DD Rate
- Laser Power
- Time (ns)
- $T_{rad}$ [A.U.]
- [A.U.]
CD targets | Hotspot ion temperature via DD fusion

\[ D + D \rightarrow n + ^3He \quad E_n = 2.5 \text{ MeV} \]

- neutron energy measured through time-of-flight over 18 m
- neutron energy distribution is Doppler-broadened

Hohlraum:
- \( T_{ion} = 6(2) \text{ keV} \)
- \( \text{Yield} = 1.29(10) \times 10^{10} \)

Capsule:
- \( T_{ion} = 0.5(1) \text{ keV} \)
- \( \text{Yield} = 0.1(1) \times 10^{10} \)

n-ToF Data 2-component Fit

Preliminary
Summary

- Developed and fielded an experimental platform for absolute Hugoniot measurements up to the 1 Gbar regime

- Developed dedicated tools for data analysis for this very special and demanding experimental geometry:
  - Simultaneous density and opacity unfold of time resolved radiography images
  - 3D analysis of X-ray Thomson scattering from inhomogeneous, mm scale, multi-component dense plasma samples
    Posters M–15, T–10, T. Doeppner, D. Kraus
  - ...

- First two Gbar equation of state experiments measured Hugoniot of CH up to 720 Mbar Poster T–01, J. Hawreliak

- Several approaches to experimentally constrain temperature:
  - X–ray Thomson scattering (also sensitive to ionization state)
  - DD fusion neutron yield
  - X–ray self emission spectrum
  - X–ray self emission absolute intensity Poster M–04, B. Bachmann
Outlook

- Hugoniot measurements at lower pressure (connection to NOVA data)

- Repeat of CD experiment

- Further development of temperature diagnostics

- Apply platform to different materials (HDC, ...)

- Development dedicated NIF platform for X-ray Thomson scattering