Inferring the Electron Temperature of Shocked Liquid Deuterium Using Inelastic X-ray Scattering

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Summary

Inelastic x-ray scattering is a powerful diagnostic for equation-of-state measurements

- The electron temperature ($T_e$) of the shocked deuterium is inferred from the spectral line shapes of the noncollective x-ray scattering.

- Initial results from the new cryogenic experimental platform are consistent with DRACO 2-D simulations.
  - $T_e \sim 10$ eV at $P \sim 10$ Mbar

Future experiments will combine inelastic x-ray-scattering observations with shock-velocity measurements to infer $n_e$, $T_e$, $Z$, $\rho$, and $P$ of the shocked deuterium.
Collaborators

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The shell adiabat is an important parameter for inertial confinement fusion (ICF)

- Shell adiabat \( \alpha = \frac{P_{\text{fuel}}}{P_{\text{Fermi}}} \)
- The shell adiabat of the target is mainly controlled by the shock-wave strength.

Motivation for measuring low adiabat (\( \alpha \sim 1 \) to 3) plasma conditions in shocked deuterium:

\( E_{\text{min}} \sim \alpha^{1.8} \) (minimum laser energy for ignition)*,**

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A laser-ablation–driven shock wave is launched in a planar liquid-deuterium target creating warm dense matter.

Uniform conditions with \( n_e = 2.0 \times 10^{23} \, \text{cm}^{-3} \) (\( \rho \sim 0.8 \, \text{g/cm}^3 \)) and \( T_e = 22 \, \text{eV} \) are predicted.

\( J. \, A. \, \text{Delettrez et al.}, \, \text{Phys. Rev. A} \ 36, \ 3926 \ (1987) \).
An experimental platform to study inelastic x-ray scattering\textsuperscript{1} from shocked deuterium has been demonstrated.

The $T_e$ of the shocked deuterium is inferred from the spectral line shapes of the noncollective x-ray scattering.

Inelastic x-ray scattering is a powerful diagnostic for high-pressure ($P > 10$ Mbar) EOS research, which is inaccessible to optical shock-velocity measurements.
$T_e$ is inferred from the Doppler-broadened Compton-downshifted peak of the noncollective x-ray scattering for $T_e > T_F^*$

Calculated x-ray scattering from electrons ($\alpha_s \sim 0.6$)

- $\theta = 90^\circ$
- $\lambda_0 = 4.188 \, \text{Å (Cl Ly}_\alpha)$
- $T_e = 22 \, \text{eV}$
- $n_e = 2.0 \times 10^{23} \, \text{cm}^{-3}$, $Z = 1$

Compton downshifted energy (eV)

$$\Delta E_c = \frac{\hbar^2 k^2}{2m_e} \quad k = \frac{4\pi}{\lambda_0} \sin\left(\frac{\theta}{2}\right)$$

- $\theta$: scattering angle
- $\lambda_0$: wavelength of probe

Scattering parameter

$$\alpha_s = \frac{1}{k\lambda_D}$$

$\alpha_s < 1$ noncollective $\rightarrow$ x rays scatter from individual electrons $\rightarrow T_e^*$

$\alpha_s > 1$ collective $\rightarrow$ x rays scatter from plasmons $\rightarrow n_e^{**}$

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Noncollective x-ray scattering from shocked deuterium has been observed

Noncollective x-ray scattering

$n_e = 0.4 \times 10^{23} \text{ cm}^{-3}$

$Z = 0.6$

$T_e (\text{expt.}) < T_e (1-D) = 22 \text{ eV}$:
X rays are scattered from shocked and unshocked deuterium.
Initial results from the new cryogenic experimental platform are consistent with DRACO* 2-D simulations.

\[ T_e (1-D) = 22 \text{ eV} \rightarrow T_e (2-D) = 5 \text{ to } 15 \text{ eV} \rightarrow T_e (expt.) \sim 10 \text{ eV} \]

\[ Z (1-D) = 1 \rightarrow Z (2-D) \sim 0.5 \text{ to } 0.8 \rightarrow Z (expt.) \sim 0.6 \]

Summary/Conclusions

Inelastic x-ray scattering is a powerful diagnostic for equation-of-state measurements

- The electron temperature \( T_e \) of the shocked deuterium is inferred from the spectral line shapes of the noncollective x-ray scattering.

- Initial results from the new cryogenic experimental platform are consistent with DRACO 2-D simulations.
  - \( T_e \approx 10 \text{ eV} \) at \( P \approx 10 \text{ Mbar} \)

Future experiments will combine inelastic x-ray-scattering observations with shock-velocity measurements to infer \( n_e, T_e, Z, \rho, \) and \( P \) of the shocked deuterium.