X-Ray Thomson-Scattering: Incisive Probe for Warm, Dense Matter

Field of view
HOPG/XRFC

Backlighter
1-ns drive
$10^{16}$ W/cm$^2$

Drive beams

Pinhole aperture

$\text{Cl Ly}_\alpha$
(2.96 keV)

Cu

Liquid deuterium

54th Annual Meeting of the American Physical Society
Division of Plasma Physics
Providence, RI
29 October–2 November 2012
X-ray Thomson scattering* (XRTS) is a primary diagnostic for high-energy-density-physics (HEDP) experiments

- The conditions of dense plasmas are probed with XRTS, especially warm, dense matter with $T_e \sim T_F$ and the ratio of potential energy to kinetic energy of the ions greater than unity

- The elastic and inelastic x-ray scattering features are spectrally resolved
  - scattering from electrons (noncollective) \( \rightarrow T_e, Z \)
  - scattering from plasmons (collective) \( \rightarrow n_e \)
  - elastic scattering \( \rightarrow \) structure of matter

- A review of XRTS experiments is presented
  - inertial confinement fusion (ICF)
  - radiation heated
  - shock heated and compressed
  - proton heated
  - laboratory astrophysics (radiative shocks and planetary interiors)

Many XRTS experiments need spatially resolved spectral measurements.

XRTS research involves many international collaborations
Collaborators for XRTS experiment
of shocked liquid deuterium

K. Falk,2 G. Gregori,2 P. B. Radha,1 S. X. Hu,1 T. R. Boehly,1
B. Crowley,2,3 S. H. Glenzer,4 O. L. Landen,4 D. O. Gericke,5
T. Doeppner,4 D. D. Meyerhofer,1* C. D. Murphy,2 T. C. Sangster,1
and J. Vorberger5

1Laboratory for Laser Energetics, University of Rochester, Rochester, NY
2Department of Physics, University of Oxford, Oxford OX1 3PU, UK
3Atomic Weapons Establishment, Reading, UK
4Lawrence Livermore National Laboratory, Livermore, CA
5Centre for Fusion, Space and Astrophysics, Department of Physics,
Warwick University, Coventry, UK
*also, Depts. of Mechanical Engineering and Physics and Astronomy,
University of Rochester
Outline

- Motivation
- XRTS
- Experiments
X-ray Thomson scattering* (XRTS) is a primary diagnostic for HEDP experiments.

Penetrating x rays are needed to probe dense plasmas.

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

\[ T_e \text{ (eV)} \]

\[ \Gamma_{ee} = 1 \]

\[ \Gamma_{ee} = 2 \]

\[ \theta = \frac{k_B T_e}{E_F}, \quad E_F = \frac{\hbar^2}{2m_e} (3\pi^2 n_e)^{2/3} \]

\[ \Gamma_{ee} = \frac{e^2}{4\pi\varepsilon_0 \overline{d} k_B T_e}, \quad \overline{d} = \left(\frac{4\pi n_e}{3}\right)^{-1/3} \]

Diagnosing the shock heated and compressed-shell conditions in an ICF target is an ideal XRTS application.

**Triple-picket, direct-drive design for the NIF**

The minimum energy needed for ignition depends on the plasma conditions in the fuel layer ($P_{\text{fuel}}$), which can be diagnosed with XRTS.

\[ E_{\text{min}} \sim \frac{\alpha^{1.8}}{V_{\text{imp}}^{5.8}} \]

(minimum laser energy for ignition)\(^2,3\)

Minimize \( \alpha \rightarrow \alpha = \frac{P_{\text{fuel}}}{P_{\text{Fermi}}} \)

---


XRTS can provide accurate measurements of conditions in HEDP plasmas designed for planetary science

- Outstanding physics issues
  - Metallization of hydrogen (pressure, temperature?)
  - H/He phase separation
  - Magnetic-field generation
Outline

• Motivation
• XRTS
• Experiments
The properties of dense plasmas can be diagnosed with XRTS

Ion–ion correlations
- scattering as a function of the scattering angle exhibit peaks that are representative of the structure (diffraction)

Electron–electron correlations
- scattering as a function of energy describes either single-particle dynamics or correlated plasmons

1. Ion–ion correlations
2. Electron–electron correlations

Elastic scattering (diffraction) is used to test the degree of correlation between ions.

- As the plasma gets denser (or cooler) correlations among ions emerge with the formation of crystalline structure.
The microscopic characterization of warm, dense matter is inferred from inelastic scattering

1. Ion–ion correlations
   - scattering as a function of the scattering angle exhibit peaks that are representative of the structure (diffraction)

2. Electron–electron correlations
   - scattering as a function of energy describes either single-particle dynamics or correlated plasmons

Inelastic x-ray scattering probes the electron-velocity distribution function

Noncollective Thomson scattering ($\lambda_{\text{scatter}} < \lambda_s$)

Optical laser

$\lambda_{\text{scatter}} = \lambda_0$

$E_0 \uparrow \downarrow$

$\lambda_{\text{scatter}} = \lambda_0 [1 \pm (v/c)\sin(\theta/2)]$

X-ray Compton scattering

X-ray source

$E_s$

$p = h\nu'/c$

$p = mv$

$\lambda_{\text{scatter}} = \lambda_0 [1 + 2(h\nu/mc^2)\sin^2(\theta/2) \pm (v/c)\sin(\theta/2)]$

Boltzman distribution

Scattering on free electrons

Wavelength

Intensity

Compton peak

Raleigh peak

$T_e^{1/2}$

$\lambda^*$

$\lambda_0$

Solid-density plasma

Scattering on free and weakly bound electrons

$T_{e,F}^{1/2}$

$\nu_e$

$\nu_0$

Wavelength

Photon energy
Collective inelastic x-ray scattering is used to diagnose the electron density

\[ \alpha = \frac{\lambda^*}{2\pi \lambda_s} = \frac{1}{k\lambda_s} \]

\[ k = |k| = 4\pi \frac{E_0}{\hbar c} \sin(\theta/2) \]

- \( \alpha < 1 \): scattering from electrons (noncollective) \( \rightarrow T_e, Z \)
- \( \alpha > 1 \): scattering from plasmons (collective) \( \rightarrow n_e \)

\[ \omega_{\text{plasmon}} \sim \omega_{\text{plasma}} = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}} \]

Outline

• Motivation
• XRTS
• Experiments
The first noncollective XRTS experiment diagnosed isochorically heated Be on OMEGA

Noncollective scattering from radiatively heated Be

Noncollective XRTS

Collective XRTS was first demonstrated using isochorically heated Be on OMEGA.

Collective scattering from radiatively heated Be

25 μm Au cone, 4 mm long

20 distributed Pump Beams
t = 0 ns; 3ω, E = 10 kJ in 1 ns

7 Backlighter Beams
t = 0.5 ns; 3ω, E = 3.5 kJ in 1 ns

Be target (1.3 mm x 0.6 mm)

Graphite (HOPG) Spectrometer mosaic focusing mode

XRTS was applied to a laser-driven, shock-heated, and compressed CH foil on OMEGA

Shock heated and compressed CH foil

1-D simulation

The Compton energy downshift is observed to be greater for the larger scattering angle.

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

\( \theta \): scattering angle

\( \lambda_0 \): wavelength of probe

(Zn He\(\alpha\) \(\sim\) 1.3 Å \(\sim\) 9.0 keV)

\[ \Delta E_C = 178 \text{ eV (for } 90^\circ) \]
\[ = 267 \text{ eV (for } 120^\circ) \]

---

An electron temperature of 10 to 20 eV was inferred from noncollective XRTS.

Br dopant in plastic increased the elastic scattering component.

A planar cryogenic target was developed to measure noncollective XRTS from shocked liquid deuterium.

A 90° scattering geometry is used.

2-D hydrodynamic simulations are consistent with the experimental results.

Spectral imaging would greatly benefit this experiment.

Scattering angle will be decreased from 90° to 40° to measure collective XRTS and infer electron density.

Shocked liquid deuterium experiment with 40° scattering geometry.

Backlighter beams

Parylene D foil

Ta aperture plate

Cu cryo cell

Polyimide window

Liquid deuterium

Be window

X-ray scattering axis

Detector

Cu cryo cell

Au slit plate

Drive beams

Volumetric backlighters will be used to increase backlighter intensity.
Compressed CH and Be shells were imploded on OMEGA and diagnosed with XRTS

Spherical direct-drive implosion

The adiabat \( \left( P_{\text{fuel}}/P_{\text{fermi}} \right) \) and the ion-ion coupling parameter were diagnosed with XRTS.

---

The adiabat and the ion–ion coupling parameter were inferred from the XRTS measurements.

\[
\text{adiabat} = \frac{P_{\text{final}}}{P_{\text{Fermi}}}
\]

\[
\Gamma_{ii} = \frac{(Ze)^2}{(4\pi\varepsilon_0 a k_B T_i)}
\]

\[
a = \left(\frac{4}{3\pi n_i}\right)^{-1/3}
\]

Ultrafast x-ray thomson-scattering was used to probe ionic structure of shock compressed LiH on Titan

The amount of liquid carbon was diagnosed with elastic x-ray scattering from a proton-heated target.
A radiative shock wave in Ar was diagnosed with XRTS on OMEGA

![Ar radiative shock experiment diagram](image)

- Ten drive beams
- Eight probe beams
- 20-μm thick Be drive disk
- 400-μm viewing slit
- Gated Thomson spectrometer (HOPG)
- 50-μm-thick Mn x-ray source
- Ar gas-filled acrylic "shock tube"
- Au shield

![Energy spectrum graph](image)

- Best fit: $T_e = 34$ eV
- $T_e = 50$ eV
- $T_e = 20$ eV

*A. J. Visco, et al., PRL. 108, 145001 (2012).*
The University of Michigan and LANL have deployed an imaging spectrometer for XRTS on OMEGA.

Spatially resolved XRTS ($dx \sim 50 \mu m$) was recorded.

Gamboa et al., to be presented at the 19th Topical Conference on High Temperature Plasma Diagnostics, Monterey, CA 6–10 May (2012).
Summary/Conclusions

X-ray Thomson scattering* (XRTS) is a primary diagnostic for high-energy-density-physics (HEDP) experiments

- The conditions of dense plasmas are probed with XRTS, especially warm, dense matter with $T_e \sim T_F$ and the ratio of potential energy to kinetic energy of the ions greater than unity

- The elastic and inelastic x-ray scattering features are spectrally resolved
  - scattering from electrons (noncollective) $\to T_e, Z$
  - scattering from plasmons (collective) $\to n_e$
  - elastic scattering $\to$ structure of matter

- A review of XRTS experiments is presented
  - inertial confinement fusion (ICF)
  - radiation heated
  - shock heated and compressed
  - proton heated
  - laboratory astrophysics (radiative shocks and planetary interiors)

Many XRTS experiments need spatially resolved spectral measurements.

Experimental data on liquid fraction is used to validate equation-of-state models

\[ I_{sc} = C I_0 \left[ V_s S_s^{tot}(k) + V_l S_l^{tot}(k) \right] \]

\[ \frac{V_l}{V_{tot}} = \left( \frac{I_{hot}}{I_{cold}} - 1 \right) \left( \frac{S_l^{tot}}{S_s^{tot}} - 1 \right) \]

The correct modeling of the liquid content at high pressures in carbon-rich planets has implications on the predicted magnetic fields.

The electron temperature in the shocked region is higher than in the radiative precursor.

The predictive capability of radiative shock waves is validated in the laboratory with XRTS and x-ray radiography.

A spatial resolution of \( \sim 10 \ \mu m \) for spectral measurements would greatly benefit many XRTS experiments.

- General-use spectral imaging diagnostic
- Development of brighter backlighters
- Improve accuracy of target alignment
  - install foreground lighting on OMEGA Target Viewing System

OLUG could help to develop specifications for next-generation XRTS measurements on OMEGA.
XRTS is a noninvasive probe

Compared to absorption spectroscopy, no tracer layers are required for XRTS.