Stellar-Relevant Emission-Based Opacity Experiments at the Orion Laser Facility

HEDS Seminar Series

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Madison E. Martin on behalf of Orion team
The Orion team is large, interdisciplinary, and international

**LLNL:**
- Greg Brown (PI, experiment lead)
- Mark Foord (theory lead)
- Madison E. Martin (design lead)
- Ronnie Shepherd
- Mike MacDonald
- Klaus Widmann
- Antonia Hubbard
- Carlos Iglesias
- Daniel Aberg
- Michael Kruse
- Duane Liedahl
- Paul Grabowski
- Rich London
- Joe Nilsen
- Mehul Patel
- Dylan Cliche
- Howard Scott
- Bob Heeter
- Heather Whitley

**AWE:**
- Dave Hoarty (PI)
- J. Morton
- S. Richardson
- Colin Brown
- B. Foote
Outline

- Motivation
- Experimental Platform
- Recent Fe Campaign
- Modeling Approaches
  - Radiation Hydrodynamics modeling
  - Atomic kinetics and radiation transfer calculations
- Ongoing & Future Work
- Summary
Opacity is an important physical property in the energy transport of HED systems and requires experimental validation of theory

- Radiation hydrodynamic design calculations rely on energy transport models that include material opacities as either theoretically based formulas or tables.
- High energy density (HED) systems can include a large range of ionization stages which may require statistical methods.
- Experimental validation of opacity theory is needed.
- Disagreements between solar observations and models may be mitigated by increased opacity\[1\]
  - Bailey et al.\[2\]: measured iron opacity values 30-400% larger than predicted.

Figure adapted from London et al., APS, DPP, 2013.
Buried layer targets heated by short pulse lasers can be used to infer opacity

- Laser → hot electrons → heat target → x-ray emission
- High $T$ at solid density
- Measure specific intensity ($I_{\nu}$)
- Dopant (e.g. Mg) used to infer $T$ and $\rho$ from emission
- Infer opacity ($\kappa_{\nu}$):
  \[
  \kappa_{\nu} = -\ln \left( 1 - \frac{I_{\nu}}{B_{\nu}(T)} \right) / \rho \Delta l
  \]
- We are currently focused on directly comparing simulated emission spectra with measured emission spectra ($I_{\nu}$)
  - explore sensitivities to modeling assumptions
  - understand plasma evolution
We use Orion Laser Facility at Atomic Weapon Establishment (UK) to access HED conditions

- Orion is a combined long and short pulse facility delivering:
  - 10 long-pulse beams (500J each, 0.1-10ns, 335nm)
  - 2 short-pulse beams (500J each, 500fs, 1054nm)

- 1 short-pulse beam has been converted to green operation to increase pulse contrast (200J, 500fs, 527nm)
- 200 J is achieved using two independent doubling crystals

Orion provides access to a portion of phase space that is complementary to other facilities
We recently conducted an Fe Campaign with well characterized buried layer targets

- Characterized using:
  - PIXE (proton induced X-ray emission)
  - EDX (electron beam)
  - Profilometry

- Metrology results for FeS layer
  - layer thickness ($174 \pm 12$) nm
  - composition: Fe 60.2 at%, S 39.8 at%
  - areal density:
    - Fe: $61 \pm 4 \, \mu g \, cm^{-2}$
    - S: $23 \pm 2 \, \mu g \, cm^{-2}$

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**Cartoon of target Assembly & Shot Orientation**

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parylene-N</td>
<td>3</td>
</tr>
<tr>
<td>FeS</td>
<td>0.16</td>
</tr>
<tr>
<td>KCl</td>
<td>0.06</td>
</tr>
<tr>
<td>C</td>
<td>0.015</td>
</tr>
<tr>
<td>Parylene-N</td>
<td>3</td>
</tr>
</tbody>
</table>

**Incident side of 2ω LASER**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δt</td>
<td>1 ps</td>
</tr>
<tr>
<td>energy</td>
<td>~ 165 J</td>
</tr>
<tr>
<td>Focus</td>
<td>100 µm</td>
</tr>
<tr>
<td>Irradiance</td>
<td>~ 2 x10^{18} W/cm²</td>
</tr>
</tbody>
</table>
We cover several bandwidths from several angles to ensure that the plasmas is well diagnosed

- For these shots, we fielded:
  - 2 time - resolved spectrometers:
    - Temperature inference
  - 4 time - integrated spectrometers:
    - Emission of interest (Fe L-shell)
    - Temperature & Density
  - 1 Pinhole Camera (GXD):
    - uniformity

<table>
<thead>
<tr>
<th>Diagnostic</th>
<th>Crystal</th>
<th>Filters</th>
<th>Sees</th>
<th>View Angle</th>
<th>Front/Back</th>
</tr>
</thead>
<tbody>
<tr>
<td>AXIS 608</td>
<td>RAP</td>
<td>8 μm Be</td>
<td>Fe L</td>
<td>25°</td>
<td>F</td>
</tr>
<tr>
<td>AXIS 609</td>
<td>CsAP</td>
<td>16 μm Be</td>
<td>S K</td>
<td>65°</td>
<td>B</td>
</tr>
<tr>
<td>OHREX-I</td>
<td>Quartz</td>
<td>51 μm Be</td>
<td>Fe K</td>
<td>19.3°</td>
<td>F</td>
</tr>
<tr>
<td>OHREX-I</td>
<td>KAP</td>
<td>51 μm Be</td>
<td>Fe L</td>
<td>19.3°</td>
<td>F</td>
</tr>
<tr>
<td>HBS</td>
<td>CsAP</td>
<td>8 μm Be</td>
<td>Fe L</td>
<td>70°</td>
<td>F</td>
</tr>
<tr>
<td>MK II</td>
<td>CsAP</td>
<td>16 μm Be</td>
<td>S, Cl Heα, Lyα, S β-lines</td>
<td>76°</td>
<td>F</td>
</tr>
<tr>
<td>Titan</td>
<td>PET</td>
<td>16 μm Be</td>
<td>S, Cl, K k-shell</td>
<td>76°</td>
<td>B</td>
</tr>
<tr>
<td>GXD</td>
<td>...</td>
<td>8 μm Be</td>
<td>Imaging</td>
<td>20°</td>
<td>B</td>
</tr>
</tbody>
</table>
Measurements require lots of calibration, which is completed at both LLNL and AWE

- **Crystals:**
  - AWE: X-ray tube/Excaliber w/ double crystal spectrometers
  - LLNL: EBIT w/ quantum calorimeter (ECS)

- **Filters:**
  - LLNL: EBIT with ECS
  - AWE & LLNL: Profilometry

- **Image Plate:**
  - AWE: X-ray Tube/Excaliber sources
We use two main modeling approaches

**HYDRA**\(^{[1]}\):
- Parametric heating source
- Target and laser parameters
- Opacity model
- Radiation transport methods
- Electron conduction model

**Cretin**\(^{[2]}\):
- Single pair of plasma conditions
- Time dependent atomic kinetics
- Optical depth effects
- Line shapes
- Radiation transfer effects

- evolution of plasma conditions
- post-process for simulated emission

- Simulated emission
- Ionization
- charge state distributions

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\(^{[2]}\) H. A. Scott, JQSRT 71, 689 (2001)
We use a 1D radiation-hydrodynamics modeling methodology to study sensitivities

**Design parameters**
- laser energy
- laser pulse shape
- target dimension

**Observe effect on:**
- Temperature
- Density
- Emission
- Opacity

**HYDRA**
- Opacity model
  - LTE versus non-LTE
- Radiation transport model
- Electron conduction model

**YORICK**
- Calculate radiation transport along a specified ray

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Martin et al., POP 24, 022705 (2017)
Martin et al., HEDP 26, 26-37 (2018)
HYDRA was used to model buried layer targets

- Assume 1-Dimensional geometry
- Opacity is modeled using HYDRA DCA package
  - Relies on super-configuration-based atomic models
- Energy source
  - Do not model laser rays or hot electrons
  - Deposit internal energy (J/g) uniformly in target and proportional to laser pulse (conversion efficiency)

Martin et al., POP 24, 022705 (2017)
Parametric energy source is tuned to reach a similar peak electron temperature inferred for a specific experimental shot.

Internal FY21 Milestone Report: LLNL-TR-820896
Including nonlocal thermal transport effect may improve modeling

- Nonlocality parameter (Kn) is used to assess whether non-local transport is important
  - $Kn = \frac{\lambda_C}{L_T}$
  - $L_T = \frac{T}{|\nabla T|}$ (electron temperature gradient length scale)
  - $\lambda_C$ (thermal collisional mean free path)

HYDRA includes a nonlocal electron transport package to model electron thermal conduction for strongly driven plasmas
  - Extension of Schurtz, Nicolai, and Busquet (SNB) non-local thermal transport model[1]

Nonlocal transport predicts slightly lower peak temperature and a wider range of conditions over the layers.
Ray tracing is used to study sensitivity of simulated emission for various assumptions

Assuming steady-state NLTE atomic kinetics has a small impact on average $T_e$ in FeS Layer but slightly increases S ionization.

Average $T_e$ in FeS Layer

Emission at time of peak $T_e$ in FeS Layer
(1 degree from target normal)

Average S Charge State:
15
15.1
Ray tracing is used to compare multiple models to experimental data

Both non-LTE and LTE models have reasonable agreement with the time-integrated Fe L-shell data

Peak average $T_e \sim 1.4$ keV at 2 ps
Parametric energy source is tuned to reach a similar peak electron temperature inferred for a specific experimental shot.
We have decent agreement with the Fe L-shell but have discrepancies with the K-shell spectra.

Both models have reasonable agreement with Fe L-shell but overpredict the Fe K-shell emission.
We have decent agreement with the Fe L-shell but have discrepancies with the K-shell spectra.

Both models underpredict S He-\(\alpha\) and S Ly-\(\alpha\) but the higher temperature model overpredicts Cl He-\(\alpha\), Cl Ly-\(\alpha\), and K He-\(\beta\).
We used 1D Cretin models to study sensitivities for comparison with data and other spectral codes including those used for temperature inference.

**Plasma Conditions**
- For fixed density:
  - $Te = 0.8\text{--}1.4$ keV
- 1D slab of FeS (areal density conserved)
- Less expensive and not dependent on assumed heating in rad-hydro

**Cretin\cite{1}**
- No radiation transfer
- With radiation transfer
- Optical depth effects
- Ti effects

**Compare with Data and other Spectral Codes**
- Measurement
- SCRAM (used for $Te$ inference)
- ENRICO (non-LTE code)

**Output**
- Ionization
- Charge state
- Emission

\[1\] H. A. Scott, JQSRT 71, 689 (2001)
Including radiation transfer has a small effect on average ionization but a larger effect on concentration of the main ionization stages of S.

Average ionization vs Te

- FeS $\rho=2$ g/cc
- Fe
- He-like
- Li-like
- Be-like
- S
- w. RT
- H-like
- He-like
- bare
- w/o RT

S ion fractions vs Te

- bare
- H-like
- He-like
- w/o RT
- Li-like
- w. RT

RT = radiation transfer
Simulated emission for OHREX line of sight demonstrates sensitivity of Fe K-shell emission to temperature

Fe He-alpha region for Te = 1.2 to 1.8 keV

OHREX spectrum of Orion shot 11219 OHREX

Optical depth at line center ~10
The He-like w line is better matched by a reduced areal density and He-like y line is better matched by a lower ion temperature.

**Effect of layer thickness on Fe He$_{\alpha}$ lines**

- He-like w
  - Thickness/nominal: 0.1, 0.15
  - Data

- He-like y
  - E = 6600 eV
  - Te = 1.8 keV

**Effect of T$_i$ on y line profile**

- He-like y
  - T$_i$ = 1.2, 1.8
  - Data
  - E = 6600 eV
  - Te = 1.8 keV; areal density 15% of nominal
The best match to the OHREX data requires $T_e = 1.8$ keV, $T_i = 1.2$ keV, and areal density that is 15% of nominal.
Ultimate goal is to use a coupled methodology to characterize heating as informed by measurements

- **HYDRA**
  - Predict plasma conditions

- **Assumed energy deposition**
  - Parameterized in:
    - Time
    - Spatial dimension(s)

- **Compare Measured and Synthetic Data**
  - Emission
  - Opacity

- **Cretin**
  - Simulate multiple diagnostic signals

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Ongoing and future work is done in parallel and coordinated across Orion team

- **Modeling and Design**
  - Complete predictions and analysis of FY22 campaign using current HYDRA and Cretin models [Martin et al.]
  - Extend HYDRA models to include 2D effects [R. London, et al.]
  - Replace ray trace with post-processing using Cretin for simultaneously constraining plasma evolution and atomic kinetics by comparing simulated and measured spectra [D. Cliche, et al.]
  - Improve understanding of sensitivities of the Orion platform using our best available models [Martin, et al.]

- **Experimental**
  - Continue to improve calibration of spectrometers [Brown, MacDonald, Shepherd]
  - Complete software development to more efficiently reduce data and aid with preliminary analysis during future FY22 campaign [MacDonald]
  - Continue to develop multiple-temperature inference algorithm [MacDonald and Liedahl]
  - Complete installation and testing of STOHREX to provide time-resolved density diagnostics [Brown, et al.]

- **Theory**
  - Complete predictions and analysis of FY22 campaign using NLTE models (eg. SCRAM, ENRICO, Cretin) [Foord, et al.]
  - Improve accuracy, convergence, and speed of ENRICO [Foord, et al.]
  - Generate NLTE tables as part of Autonomous Multiscale SI [Gaffney et al.]
Summary

- Experimental validation of opacity theory is needed for HED conditions
- Short pulse lasers can be used to conduct opacity measurements
- We have conducted Fe emission experiments at AWE’s Orion Laser Facility
- A previously developed 1D HYDRA methodology was used to study sensitivities to radiation transport, non-local electron transport, and assumed atomic model
- Cretin was used to investigate radiation transfer and plasma conditions on ionization and emission
- We have only discussed a small fraction of the ongoing work associated with this campaign and milestone