Hard and Soft X-ray Line emission from High-Z Multiply Ionized Ions Influenced by Dielectronic Recombination and Polarization from HEDLP DE-NA0003877

Radiation from High Energy Density Pulsed Power Plasma DE-NA0003047

A.S. Safronova (PI) and V.L. Kantsyrev (co-PI)

University of Nevada, Reno

Poster HEDP-36 by Chris Butcher et al
Poster HEDP-37 by Ryan Childers et al
Poster HEDP-38 by Amandeep Gill et al

2020 Stewardship Science Academic Programs (SSAP) Symposium
Washington Marriott Wardman Park Hotel, Washington DC, February 26-27, 2020
Two research faculty, a research scientist, and a researcher were involved in and fully (or in part) supported by the projects.

Four graduate students were involved in and supported (fully or in part) by the projects under supervision of Prof. Alla Safronova and two experimental students under supervision of Prof. Victor Kantsyrev.
Collaborations

- John Giuliani, Nicholas Ouort (Naval Research Laboratory)
- David Ampleford, Adam Steiner (Sandia National Laboratories, Albuquerque)
- Ryan McBride, Ron Gilgenbach (University of Michigan)
- Donald Umstadter (University of Nebraska, Lincoln, LaserNetUS facility)

Recent graduates

published collaborative papers in 2019

- Kimberly Schultz (LANL, Jan. 2018 - present, see 2019 SSAP Annual, p. 24)
- Emil Petkov (Karle’s fellow at NRL, June 2018 – present)
Objectives of the HEDLP project

- The goal of this HEDLP project is a comprehensive study of hard and soft x-ray line emission from high-Z multiply ionized ions including such important processes in plasmas as dielectronic recombination and line polarization.

- The new effort within the project focuses on the hard x-ray characteristic radiation which is believed to be caused by inner-shell ionization of neutral atoms by non-thermal electron beams propagating through the cold thermal plasma. Such hard x-ray characteristic radiation has not yet been studied in detail in pulsed power plasmas but mostly in laser produced plasmas.

- Such studies are very important for the achievement of better understanding of non-thermal plasmas and electron beams in general and from Z-pinches in particular and for development of efficient x-ray sources and new diagnostics of both ”hot” HEDLP and warm dense matter.
OUTLINE

- Hard x-ray characteristic lines from high-Z materials from pulsed power plasmas

- Introduction and Background
  - Time evolution of characteristic L-shell lines of Tungsten (W)
  - Development of a new hard X-ray source to study characteristic lines
  - Understanding mechanisms driving K-shell emission in non-thermal HEDLP of iron (Fe)

- Progress in studying X-ray line polarization

- Modeling of X-ray line emission from high-Z multiply ionized ions (Xenon HEDL Plasmas)

- Study of Complex Planar Wire Arrays on UM’s MAIZE
Introduction: Hard x-ray characteristic lines from high Z materials from pulsed power plasmas

Recently, hard x-ray characteristic lines from high Z materials produced from pulsed power plasmas have been studied*:

- as signatures of hot electrons
- Mo and Ag Kα emission from nested wire arrays on SNL-Z (Ampleford et al, 2015, Hansen et al, 2014)

Experiments were reported demonstrating the transition from thermally-dominated K-shell line emission to non-thermal, hot-electron-driven inner-shell emission for z pinch plasmas on the Z machine. While x-ray yields from thermal K-shell emission decrease rapidly with increasing atomic number Z, it was found that non-thermal emission persists with favorable Z scaling, dominating over thermal emission for Z=42 and higher (hv ≥ 17keV). Initial experiments with Mo (Z=42) and Ag (Z=47) have produced kJ-level emission in the 17-keV and 22-keV Kα lines, respectively.


*The importance of the development of non-thermal x-ray sources was also highlighted in Plenary talk FR1.00001 by Daniel Sinars (SNL)
Recently, hard x-ray characteristic lines from high Z materials produced from pulsed power plasmas have been studied:

- **as a new hard x-ray spectroscopic diagnostic technique**

for the direct measurement of the ionization distribution in warm dense plasmas using W L emission generated by the NRL’s Gamble II pulsed power machine (Seely et al, 2013, Pereira et al, 2017)

J.F. Seely et al, ”Tungsten L transitions line shapes and energy shifts resulting from ionization in warm dense matter”, High Energy Density Physics 9, 354 (2013)

Background: “cold” characteristic W L lines

The strongest W L transitions, energies, and relative intensities (modified Table 1 from Seely et al, 2013). Line identification and experimental energy levels are from Deslattes et al, 2003 and Bearden, 1967.

J.F. Seely et al, ”Tungsten L transitions line shapes and energy shifts resulting from ionization in warm dense matter”, High Energy Density Physics 9, 354 (2013)
Background: hard X-ray characteristic L lines from W pulsed-power plasmas

Characteristic X-ray W L-shell lines occupy the energy range from 8 to 12 keV and in pulsed power plasmas were collected first from exploded wire plasmas on Gamble II generator more than 40 years ago (Burkhalter et al, 1977). Since then, the studies were focused mainly on spatially resolved hard X-ray spectroscopy.

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The strongest W L transitions, energies, and relative intensities (modified Table 1 from Seely et al, 2013).

<table>
<thead>
<tr>
<th>Line</th>
<th>Levels</th>
<th>Transitions</th>
<th>Energy (eV)</th>
<th>λ (Å)</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lα₂</td>
<td>L₃M₄</td>
<td>2p3/2 – 3d3/2</td>
<td>8335.3</td>
<td>1.487</td>
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<td>Lα₁</td>
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<td>L₁M₂</td>
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<tr>
<td>Lβ₁</td>
<td>L₃M₄</td>
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<td>1.282</td>
<td>55.6</td>
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<tr>
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<td>L₁M₃</td>
<td>2s1/2 – 3p3/2</td>
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<tr>
<td>Lγ₁</td>
<td>L₂N₄</td>
<td>2p1/2 – 4d3/2</td>
<td>11,286.0</td>
<td>1.098</td>
<td>10.45</td>
</tr>
</tbody>
</table>

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J.F. Seely et al, ”Tungsten L transitions line shapes and energy shifts resulting from ionization in warm dense matter”, High Energy Density Physics 9, 354 (2013)
Spatially resolved hard X-ray spectra (1 – 2.4 Å) from W X-pinches (Zebra shot 4951)

$m=564 \, \mu g/cm$, $I=1 \, MA$
$E_{Bolo} = 6kJ$, $I_B=45.3 \, kA$
Time evolution of radiation from Tungsten (W) Double Planar Wire Arrays (DPWA) and Nested Cylindrical Wire Arrays (NCWA)

All W wire arrays considered here had 16 W wires:

- **DPWA**: 8/8, wire $\phi=7$ $\mu$m, Inter-wire gap $\text{IWG}=0.7$ mm, Inter-planar gap $\text{IPG}=3$ mm, $m=119$ $\mu$g/cm
- **NCWAs**: 8/8, wire $\phi=5$ $\mu$m, Inner/Outer 6/13 mm, $m=61$ $\mu$g/cm
Temporal evolution of characteristic L-shell emission from W and what it has to do with electron beams?

For another examples of temporal evolution of characteristic K-shell emission form mid-atomic-number wire loads in Z-pinch plasmas, see:

Time evolution of hard x-ray characteristic lines from W Nested CWA* (Zebra shot #1805)

- Bolo energy = 16 kJ.
- Implosion time = 101 ns.
- Almost no M-shell W spectra were recorded by the KAP crystal spectrometer.
- Mostly non-thermal x-rays.
- Timing of time-gated W L lines before the x-ray burst.

*See also the Invited talk by A.S. Safronova et al at the 2019 IEEE Pulsed Power and Plasma Science Conference (PPPS 2019, Orlando, FL, June 23-28, 2019)
Time evolution of hard x-ray characteristic lines from W Nested CWA (Zebra shot #1804)

- Bolo energy = 18.4 kJ.
- Implosion time = 94 ns.
- The highest estimated e-beam current for wire array loads of 210 kA.
- Almost no M-shell W spectra were recorded by the KAP crystal spectrometer.
- Mostly non-thermal x-rays.
- Timing of time-gated W lines after the x-ray burst.
Time evolution of radiation from W Double PWA

Zebra shot #1972: Bolo energy = 27.5 kJ, implosion time = 85 ns, early timing of time-gated hard x-ray spectroscopy
Time evolution of hard x-ray characteristic lines from W DPWA (Zebra shot #1972)

- Bolo energy = 27.5 kJ.
- Shorter Implosion time = 85 ns.
- The estimated e-beam = 21.7 kA.
- Some of non-intense M-shell W spectra were recorded by the KAP crystal spectrometer radiating from hot spots, for one near cathode in particular.
- Early timing of time-gated W L lines before and just after the x-ray burst.
W L line intensity ratios behave very differently in time for W DPWA and W NCWAs. W DPWA ratios are surprisingly close to the “cold atom” (dashed lines on the left) and warm dense matter results (within the red box) near the x-ray burst. W NCWA ratios substantially deviate from warm dense matter as well as from “cold atom” results during the x-ray burst but are closer before (-10 and -5 ns) and after (+17 ns and +27 ns) the x-ray burst. The results for the intensity ratios of the lines with the same lower level in L-shell, for example, La2/La1 (L_3M_4/L_3M_5), are of particular interest, because they indicate which upper levels in M-shell are depleted during the x-ray burst due to excitation/ionization dynamics.
W L line intensity ratios behave very differently in time for W DPWA and W NCWAs.

W DPWA ratios are again surprisingly close to the “cold atom” (dashed lines on the left) and warm dense matter results (within the red box), near the x-ray burst in particular.

W NCWA ratios are also close to warm dense matter as well as to “cold atom” results during the x-ray burst for $L\alpha_1/L\beta_1$ ratios but deviate from them substantially for the $L\beta_1/L\gamma_1$ ratios which can be caused by high uncertainties for this particular ratio.
One of the main objectives of our research is to study the hard x-ray characteristic radiation which is believed to be caused by inner-shell ionization of neutral atoms by non-thermal electron beams propagating through the cold thermal plasma. Such hard x-ray characteristic radiation as well as its polarization properties has not yet been studied in detail in pulsed power plasmas.

To accomplish this goal, we have developed a hard x-ray source based on a vacuum diode with laser-plasma cathode triggering dubbed “Sparky-HXRS” (or Sparky Hard X-Ray Source). This design is great for producing monochromatic x-rays while keeping the production of bremsstrahlung low in comparison.

The vacuum diode consists of a planar Copper (Cu) or Titanium (Ti) slab as a cathode and a conical point-tip anode made of Brass, or Tungsten (W) with a Brass or Ti holder, in a vacuum chamber evacuated to <10^{-5} Torr. The cathode slab revolved on a rotating motor system. The figures to the right show the machine vacuum chamber, anode-cathode within the vacuum chamber, and the two anode shapes used (conical point-tip and conical extended point-tip).
A Study of the Generation of Hard X-ray Characteristic Lines from Pulsed Power Sources (Poster HEDP-36, cont’d)

- Diagnostics implemented on Sparky-HXRS included an absolutely calibrated filtered PCD and cross-calibrated Si-diodes featuring a wide range of x-ray cutoff energy filters (from >1.4 keV to > 15 keV), and spatially resolved x-ray spectrometers with a convex LiF crystal harder x-ray regions, or a convex KAP crystal for softer x-ray regions.

- Analysis of these x-ray diode signals revealed prominent x-ray production in the >8 keV region, with an x-ray pulse duration of ~20 ns at FWHM on the main peak. A pre-pulse forms with a pulse duration of ~30 ns at FWHM.

- Characteristic L-shell W x-ray spectral lines were successfully produced, as well as K-shell Cu lines from all anodes.

- Following up on the already promising spectroscopy results from Sparky-HXRS, further exploration is planned to study the polarization of L-shell W using this new machine.
Understanding The Excitation Mechanisms Driving K-shell Emission in Non-thermal High Energy Density Plasmas (Poster HEDP-37)

R. R. Childers¹, A. S. Safronova¹, V. L. Kantsyrev¹, D. Ampleford², R. Plotkin¹, C. J. Butcher¹

¹Physics Department, University of Nevada, Reno, NV 89557
²Sandia National Laboratories, Albuquerque, NM 87123

- New collaboration with Sandia National Laboratories

- This study focuses on the effects of hot, non-thermal electrons and high-energy photons on the ionization balance of non-thermal K-shell Fe emission in HED plasmas.

- Goals of the theoretical study include identifying the Kα and Kβ charge state distribution for each separate excitation mechanism and comparing any unique ionization patterns that arise between the two scenarios.

- Theoretical spectra produced by SCRAM and applied to experimental data from an X-pinch laboratory plasma produced on the Zebra Generator to demonstrate ionization effects of hot electron driven K-shell emission.

Also see Ryan’s work on X-ray line polarization of Mo X-pinches:
Synthetic spectra of hot electron driven non-thermal K-shell emission. Illustrates sensitivity of ionization balance to the percentage of non-maxwellian electrons in plasma.


Synthetic spectra applied to experimental X-pinich data to demonstrate viability in diagnosing hot electrons and resulting charge states for Fe plasma.

In summary, theoretical analysis was performed on the ionization effects of non-thermal K-shell excitation mechanisms in HED plasmas. It was shown that both hot electrons and photon radiation drive ionization. The latter is observed to shift the charge state more significantly than the hot electrons, per input. Future work will include attempts to approximate the relative contribution of each driving mechanism to overall non-thermal K-shell emission energy in HED laboratory and astrophysical plasmas.
Experimental results of the degree of polarization of the Ne-like Mo x-ray lines of Mo\(^{+32}\) and comparison with theoretical calculations produced using the Flexible Atomic Code (FAC).

Polarization measurements of Ne-like Mo x-ray lines excited by an electron beam at LLNL EBIT.

X-ray emission from L-shell transitions in highly charged Mo ions at an electron beam energy of 2.75 keV.

Polarization of Characteristic X-ray L-shell lines from Tungsten

- It is a well-established fact that ionization of atoms (ions) by charged particles and photons leads to the alignment of target inner-shell vacancy with the total angular momentum $J > \frac{1}{2}$.

- X-rays or Auger electrons emitted in the subsequent de-excitation demonstrates this alignment through the polarization of X-rays or through their anisotropic angular emission. What does it tell us?

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- Lines $L\alpha_1$ and $L\alpha_2$ are polarized and when produced by electron beams can be used for their diagnostics.

- It is very important to have non-polarized lines in x-ray spectropolarimetry.

- The $L\beta$ structure has four resolved lines out of which one is polarized and the rest is not, which is very useful in development of the polarization studies of W L-shell lines.

Future work will focus on modeling of the intensity ratios and polarization of W L-shell lines discussed in this talk.
Modeling of X-ray Line Emission from High-Z Multiply Ionized Ions in Xenon HED Laboratory Plasmas (Poster HEDP-38)

A. Gill¹, A.S. Safronova¹, V.L. Kantsyrev¹, A. Stafford¹, K.A. Schultz¹, E.E. Petkov², V.V. Shlyaptseva¹, R.R. Childers¹
¹University of Nevada, Reno, NV 89557, ²Naval Research Laboratory, Washington DC 20375

Objective
Modeling of experimental spectra can provide essential information on plasma parameters and electron beams. L-shell Kr x-ray spectra have been extensively studied using a previously created L-shell Kr model. Due to the substantial increase in number of configurations and transitions when going from L-shell to M-shell radiation, it is more challenging to model M-shell radiation from highly ionized high-Z gases.

Previous Work
The previously created L-shell Kr model was benchmarked with x-ray spectra produced from dense plasma focus (Petkov et al.), reversed polarity gas puff (Shlyaptseva et al.) and laser-irradiated gas jet experiments on both the Leopard laser at UNR (Kantsyrev et al.) and the Titan laser at Lawrence Livermore National Laboratory (Schultz et al). Examples of such experiments are illustrated below. Comparisons show agreement between experimental and theoretical spectra.

Fig. 1. The experimental spectrum (blue) from reversed polarity gas puff Kr experiment in Japan fit with the theoretical spectrum (red) using modeling parameters electron temperature 500 eV, electron density 10¹⁹ cm⁻³, and fraction of hot electrons (f) at 1% (Shlyaptseva et al.).

Fig. 2. The experimental spectrum (blue) from laser-irradiated gas jet Kr experiment on Leopard laser at UNR fit with the theoretical spectrum (red) using modeling parameters: electron temperature 400 eV and electron density 10²¹ cm⁻³ (Kantsyrev et al.).

Fig. 3: The experimental spectrum (blue) from laser-irradiated gas jet Kr experiment on the Titan laser at LLNL with the theoretical spectrum (red) using modeling parameters: electron temperature 640 eV and electron density 5x10¹⁸ cm⁻³ (Schultz et al.).
Highlights of the new Xe M-shell model:
- added transitions, particularly for Ar-like to Ca-like
- 3d-4f transitions were added to Sc-like to V-like ionization stages.
- removed some configurations which are not very abundant in certain ionization stages within the wavelength range 9Å to 15Å.

Summary
There is marked improvement in the new Xe model in fitting the lower wavelength ionization stages, such as Ti-like and V-like. However, the simultaneous high intensity of lines from ionization stages from Ar-like to Co-like suggest a non-uniform plasma, see below for an example of a single electron temperature and density comparison.

Fig. 4. Experimental x-ray spectrum from a laser-irradiated gas jet Xe experiment on the Titan laser at LLNL fit with both the old and new M-shell Xe models.

Future Work
We continue to make improvements to the newly created model by adding 3p-4d transitions to the ionization stages of interest which will improve lower wavelength fitting. In addition to modeling of Xe spectra from laser irradiated gas jets at Titan at LLNL, we will apply this model to the newly developed DPF Sparky device at the UNR, where experiments with pure and mixed Krypton and Xenon gases are anticipated.

Fig. 5. The Xe experimental spectrum (blue) from laser-irradiated gas jet experiment on the Titan laser at LLNL fit with the theoretical spectra (red) using the newly created model, with a single electron temperature (350 eV) and density (10^21 cm^-3).
Big surprise was the ability to implode not only W DPWAs but also PWAs of complex geometry, where the outer planes were from mid-atomic-number wire materials (Alumel, mostly Ni) and the inner plane was from alloyed Al 5056 (mostly Al).

Note high reproducibility of the Triple PWA shots on MAIZE

Current for this experiment was 520 kA with a 210 ns rise time. Radiation detecting diodes suggest an implosion time of 238 ns after current start which is close to 233 ns which is the time predicted by the Wire Ablation Dynamics Model (WADM).
Shadowgraphy for this experiment began at 50 ns and continued to 160 ns with 10 ns intervals. The simulation to the right is the predicted evolution of the array by the WADM. A precursor fully comes into existence in the 70 ns frame and continues until 110 ns where the plasma becomes too dense for the laser and self emission becomes dominant in the center.
SUMMARY/ACKNOWLEDGEMENTS

- Hard x-ray characteristic lines from high-Z materials from pulsed power plasmas have been studied with focus on:
  - Time evolution of characteristic L-shell lines of W;
  - The development of the new hard x-ray source;
  - Understanding mechanisms that driving K-shell emission in non-thermal HEDLP of iron (Fe).

- Progress in studying x-ray line polarization is highlighted.

- Modeling of x-ray line emission from high-Z multiply ionized ions in HEDLP is accomplished for Xenon laser-produced plasmas.

- Future work in all above mentioned directions of the project is discussed.

- Study of radiation and implosion dynamics of complex Planar Wire Arrays on UM’s MAIZE.

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ICOPS 2021

JUNE 20TH – 24TH, 2021

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