Determining Plasma Temperature Using K-line Shifts in Rapidly Heated Matter

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1. Abstract

High-intensity infrared lasers focused above 10^{18} W/cm^2 accelerate electrons to relativistic energies. These high-energy electrons heat solid matter to hundreds of eV over picosecond timescales. K-shell emission is generated by collisional ionization and can be used to study the heating process. Copper targets were irradiated with picosecond pulses from the MTW laser and the K-shell emission spectra were measured. The program *CASK* was written in *MATLAB* to compare the experimental spectra and synthetic spectra generated by the collisional-radiative code *PrismSPECT.* The experimental spectra and the measured K-line shifts are consistent with an updated version of *PrismSPECT* based on first-principles calculations. These results show that K-line shifts can be used to infer plasma temperature.

2. Introduction

Lasers are coherent, collimated pulses of electromagnetic radiation. The coherence of the radiation allows a large amount of energy to be contained within a short pulse. High-energy lasers can deliver kilojoules of energy in picosecond (10^{-12} sec) pulses, achieving intensities above 10^{18} W/cm^2. At these short pulse lengths and high intensities, laser pulses interact with solid targets before any significant hydrodynamic expansion can occur, resulting in the creation of high-temperature, solid-density plasmas [1]. Such plasmas have an inertial disassembly time of approximately ten picoseconds [2]. Over greater timescales the hot dense plasma expands and decompresses below its initial solid density state.

When a high-intensity laser interacts with a solid target, large numbers of thermal electrons are accelerated to relativistic velocities. These fast electrons couple energy to solid matter over temporal scales longer than the laser-pulse duration and spatial scales larger than the laser focal spot [3]. Energy coupling to the target occurs through direct collisions and Ohmic dissipation of the induced return current of collisional background electrons [1]. In small-mass targets, the fastest electrons escape, charging the target, but most fast electrons are electrostatically confined to the target material (Fig. 1), rapidly heating it to tens or hundreds of electron volts (1 electron volt (eV) equals 11600 Kelvin) over picosecond timescales [3]. The heating process is isochoric (i.e. at constant volume) and creates extreme conditions that are inaccessible to conventional shock-wave techniques.

At temperatures approaching 1 keV, conditions in the solid-density plasma

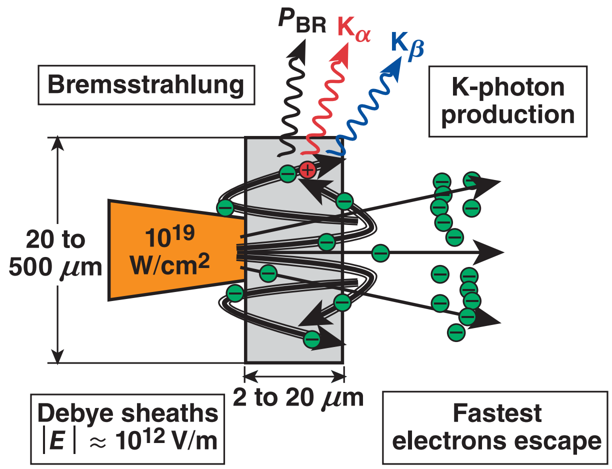

***Figure 1:** Schematic of the interaction between a high intensity laser (orange) and a thin solid metal target. Electron refluxing (recirculation) rapidly heats the solid material, creating bremsstrahlung radiation (P_{BR}) and Kα and Kβ emissions.*

are similar to those in the core of a star. Generating and measuring these extreme plasma conditions through the analysis of X-ray emission spectra fosters an improved understanding of the rapid heating process. This is important for developing high-power X-ray sources for dense-matter probing.

In this report, experimental X-ray emission spectra from high-intensity laser-solid interaction experiments are analyzed. The experiments were carried out at the University of Rochester's Multi Terawatt Laser Facility (MTW) [4]. Thin copper foil targets were irradiated with picosecond laser pulses at focused intensities above 10^{18} W/cm^2. Fast electrons accelerated by the laser pulse were electrostatically confined inside the targets due to target charging, enabling energy to be coupled to solid-density material over picosecond timescales (Fig. 1). This electron refluxing (recirculation) generates bremsstrahlung radiation due to electron accelerations [7]. During electron refluxing, a relativistic electron may collide with an electron of a copper ion, removing it from its orbital (Fig. 2). An electron in a higher energy level

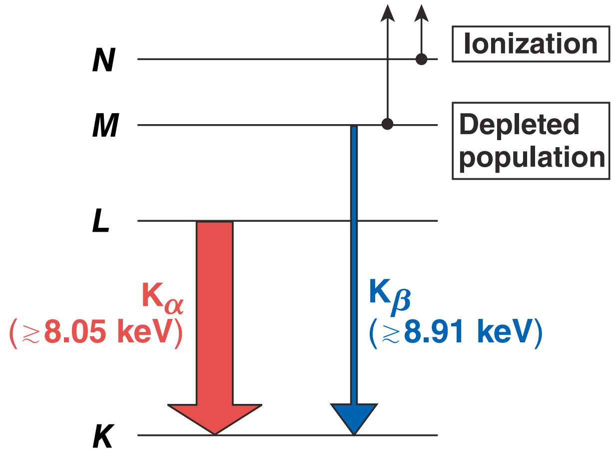

Figure 2: *Copper energy levels showing L → K and M → K electronic transitions that generate Kα and Kβ photons. Collisional ionization from the thermal background plasma depletes the outer lying shells, altering the K-shell ionization potential and reducing the Kα and Kβ photon yields.*

can transition down to fill the gap, releasing the excess energy as a photon [4]. When the gap occurs in the K shell of a copper ion, the emitted photon is a part of the K-line emission spectrum (Fig. 2).

The K-line emissions of copper are in the X-ray range. A transition from the L shell to the K shell produces Kα emission and a transition from the M shell to the K shell produces Kβ emission (Fig. 2). Changes in plasma temperature affect the energy difference between shells, with higher plasma temperatures resulting in larger energy differences. K-line photons emitted from a copper ion will have a higher frequency and thus higher energy as the temperature of the plasma increases. This increase in energy causes the K-line emission spectrum to be shifted toward higher energies if plotted with the energy of detected photons as the independent variable and signal strength as the dependent variable. Measuring the energy shifts of K-spectra and comparing them to atomic physics calculations allows the plasma temperature to be inferred.

An X-ray spectrometer measured the copper Kα and Kβ emission spectra from the heated material. Analysis of the time-integrated copper Kα and Kβ emission lines allowed the plasma temperature to be inferred by comparing the spectra to theoretical predictions from the atomic physics code *PrismSPECT* [5]. The K-shell emission spectra predicted by *PrismSPECT* were used to understand how the Kα and Kβ spectral lines shift with increasing plasma temperature. The *PrismSpect* model predictions based on first-principles (Hartree-Fock) calculations [6] reproduced the experimental Kα and Kβ emission spectra when the plasma temperature was assumed to increase as a linear function of time.

The report is organized as follows: Sec. 3 describes the atomic physics code *PrismSPECT*, Sec. 4 presents the data analysis, Sec. 5 shows the data comparison with *PrismSPECT* model predictions, and Sec. 6 provides a summary and conclusions.

3. PrismSPECT

PrismSPECT is an atomic physics (collisional-radiative) code used to simulate the atomic level populations of plasmas over a range of conditions represented by specified parameters, such as plasma density and temperature [5]. *PrismSPECT* generates the spectra that result from these plasmas. *PrismSPECT* can run both steady-state simulations and time-dependent simulations over a timescale defined by the user. In a steady-state simulation, the temperature of the plasma remains constant over an identified time period. Time-dependent simulations vary the plasma temperature as specified by the user (e.g., as a linear increase with time).

These spectra can be combined to produce a time-integrated emission spectrum for a particular simulation.

PrismSPECT predictions, calibrated against experimental measurements made by Tanis *et al* [5], accurately reproduce copper Kα emission spectra. In contrast, *PrismSPECT* has shown insufficient accuracy for reproducing copper Kβ emission spectra [2]. Prism Computational Sciences, Inc., has recently developed a new model for Kβ emission based on first-principles (Hartree-Fock) calculations [6]. These new model calculations aim to correctly predict the Kα and Kβ emission spectra from hot dense copper plasmas. They predict the same copper Kα energy shift as the original *PrismSPECT* model, but a much larger Kβ energy shift. However, these shifts have not been tested against experimental data. This report compares experimental emission spectra from high-intensity laser-solid interactions with the synthetic spectra generated by these new model predictions.

4. Data Analysis

X-ray spectroscopy with a highly oriented pyrolytic graphite (HOPG) crystal spectrometer was used to record K-line emission spectra from rapidly heated copper targets [8]. An example of a raw x-ray emission spectrum is shown in Figure 3. This emission spectrum was measured from a copper target irradiated with a 1-J, 1-ps pulse on the MTW Laser Facility. The x-ray signal was measured with an X-ray charge coupled device (CCD) and is time integrated. The data is spectrally resolved in the vertical direction. The copper $K\alpha_{1,2}$, Heα, and Kβ lines are shown (the Cu Heα

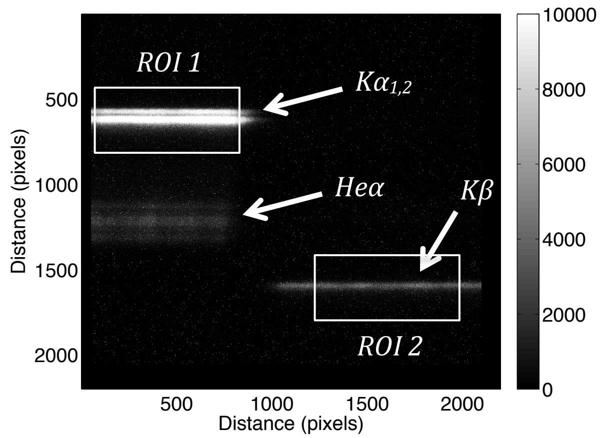

Figure 3. *Example two-dimensional X-ray emission spectrum from a copper target measured with a crystal spectrometer coupled to an X-ray charge coupled device (CCD). The copper* $K\alpha_{1,2}$*, Heα, and Kβ lines are shown. Regions of interest (ROIs) are shown. The Heα and Kβ lines have a low signal and do not reproduce well in the image.*

line emission is not considered in this study). A hard x-ray photon background generated during the laser-target interaction created the white speckle pattern in the data.

To analyze the data, a program called *CASK* was written in *MATLAB. CASK* carries out three procedures. First, the copper Kα and Kβ lines are identified and isolated into regions of interest (ROIs). Second, each ROI is given a small rotation to correct for CCD misalignment [see Figs. 4(a) and 4(c)]. Third, one-dimensional spectra are obtained from the two-dimensional ROIs by summing the signal along each row, improving the signal-to-background ratio. Figures 4(b) and 4(d) show example raw copper Kα and Kβ emission spectra plotted as a function of distance (in CCD pixels) generated by *CASK*.

In this work, two MTW shots were analyzed: shot numbers 3204 and 3189. Shot 3204 is an example of a low energy density shot with laser energy (J)/target volume (mm^3) of 2 x 10^3 J/mm^3. Shot 3189 has two orders of magnitude higher

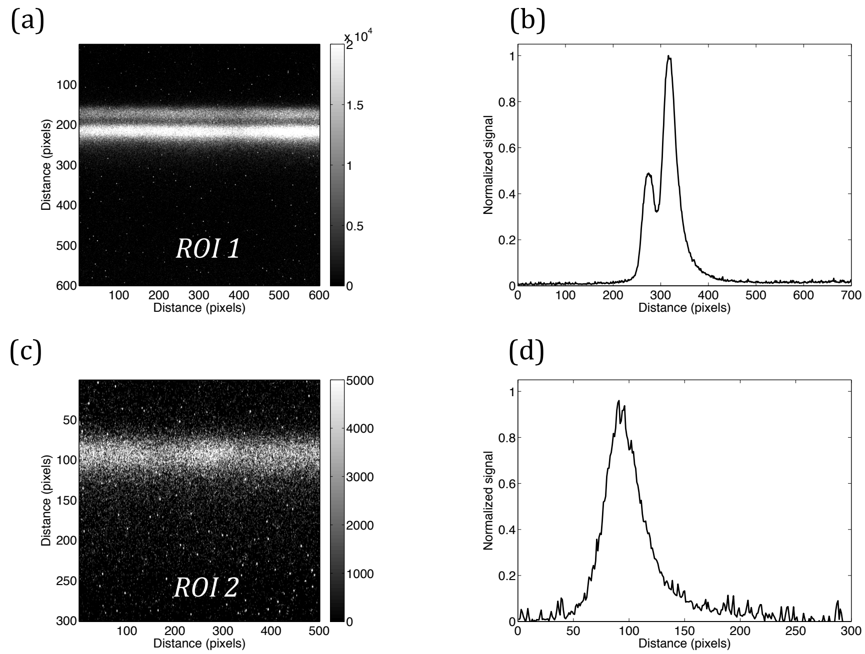

Figure 4: *(a, c) Regions of interest (ROIs) identified from the X-ray CCD data shown in Figure 3. (b, d) Raw copper K$\alpha_{1,2}$ and Kβ emission spectra, respectively, calculated from the ROIs in (a, c). This data analysis was carried out with the CASK program.*

energy density (2 x 10^5 J/mm^3). Figure 5 shows calibrated Kα and Kβ emission spectra for these shots. The spectra were calibrated by converting distance in pixels to photon energy in eV based on the known spectral separation between copper K$\alpha_{1,2}$ in cold material (20 eV). The data shows that the Kα and Kβ lines are shifted in the higher energy density target compared to the lower energy density target. Higher plasma temperatures generated this spectral shift.

5. Data Comparison with *PrismSPECT*

Using trial and error, the data from each shot was matched to synthetic spectra generated from one steady-state and one time-dependent *PrismSPECT* simulation. The time-dependent simulations used a linear temperature temporal gradient to model conditions in the solid-density plasma, each beginning at the same

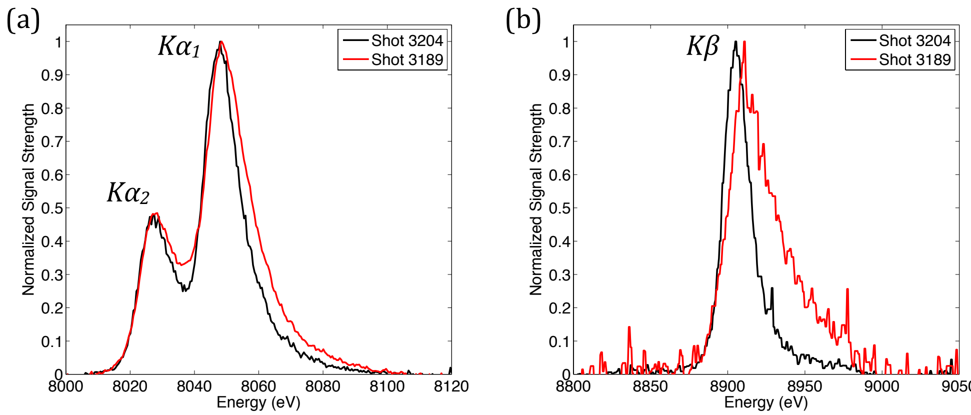

Figure 5: *Copper Kα$_{1,2}$ (a) and Kβ (b) emission spectra for Shots 3204 and 3189. Shot 3189 shows spectral shifts consistent with higher temperature plasma.*

temperature of 1 eV and increasing linearly over a 10-ps timescale to a specified final temperature that was varied between simulations, ranging from 10 eV to 350 eV. The data showed better agreement with the synthetic spectra generated from time-dependent simulations than steady-state simulations.

Figure 6 shows the measured K-shell emission spectra from Shots 3204 and 3189 and compares them with time-dependent PrismSPECT calculations. Good agreement between the measured and calculated emission spectra is found assuming peak temperatures of 10 eV (Shot 3204) and 120 eV (Shot 3189). The new *PrismSPECT* model reproduces to a good approximation the emission peaks and the falling and rising edges of the measured Kα and Kβ emission spectra. This was not the case in the original *PrismSPECT* model and provides confidence that plasma temperature can be inferred from both the Kα and Kβ emission lines. Based on the assumptions implemented, the new *PrismSPECT* model reproduces the dominant features in the K-line emission spectra of these hot dense copper plasmas.

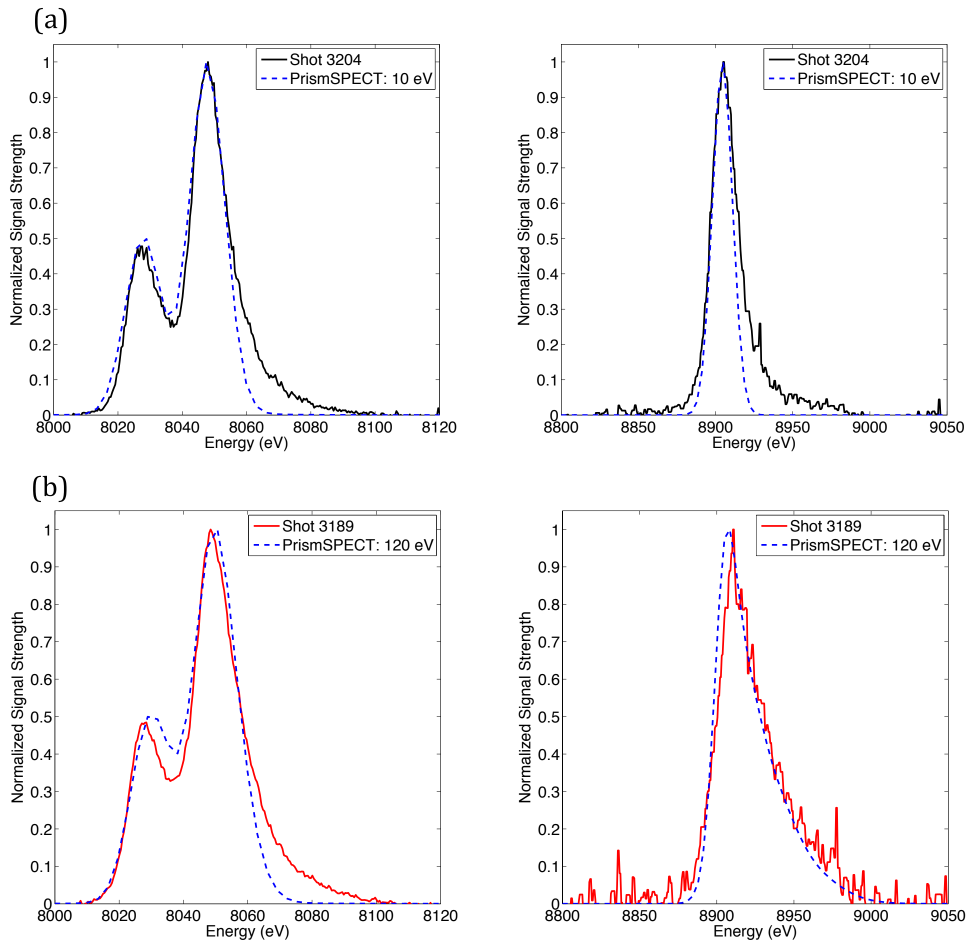

Figure 6: *Copper Kα and Kβ emission spectra for Shots 3204 (a, black) and 3189 (b, red). Emission spectra calculated by PrismSPECT (blue) for peak temperatures of 10 eV (a) and 120 eV (b).*

6. Summary and Conclusions

Experimental X-ray emission spectra were analyzed from high-intensity laser-solid interaction experiments in which thin copper foil targets were irradiated with picosecond laser pulses at focused intensities above 10^{18} W/cm^2 [4]. Fast electrons accelerated by the laser pulse refluxed inside the targets and caused K-shell emission spectra to be radiated. An X-ray spectrometer measured the copper Kα and Kβ emission spectra from the heated material. Theoretical predictions from the collisional-radiative code *PrismSPECT* [5], in the form of synthetic spectra, were obtained. *PrismSPECT* model predictions based on first-principles calculations reproduced the experimental Kα and Kβ emission spectra assuming a linear temperature temporal gradient [6]. Comparisons between the simulated and experimental spectra enabled the plasma temperature to be inferred. The *MATLAB* program *CASK* analyzed the experimental data and reduced the emission spectra for comparison with *PrismSPECT* model predictions. This work shows good agreement between the new theoretical model of K-line emission spectra for copper and the experimental results from X-ray spectroscopy measurements on MTW. An accurate model for K-line emission spectra will lead to a more precise understanding of rapid material heating at high energy densities. This work is important for the development of many applications from flash X-ray generation and laboratory astrophysics to dense-matter probing.

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