

K-shell spectroscopic diagnosis of suprathermal electrons at fusion-relevant environmental conditions

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Abstract. Fast-electron-induced changes in the ion charge distribution lead to a substantial modification of radiative properties of x-ray emitting systems. We report Cu K-shell spectra emitted from 1.5- μm -thick Cu foils irradiated by laser intensities up to $5 \times 10^{16} \text{ W/cm}^2$ using the fundamental and frequency tripled radiation of the Prague iodine laser system PALS, i.e., at conditions characteristic for laser spikes anticipated in the shock ignition scheme. The emission of the lower-ionization-stage ions observed as a fine structure merged with the Cu $K\alpha_{1,2}$ doublet and spectral lines corresponding to transitions in He-like to Ne-like Cu atoms were identified. The spectra analysis based on a combination of MULTI2D hydrodynamic modelling of the plasma evolution and its emissivity synthesized by collisional-radiative code FLYCHK provides information on distribution of hot electron fractions at low plasma temperatures. The procedure used for interpretation of experimental data contributes to a development of alternative methods for diagnosis of suprathermal electrons.

1. Introduction

Generation of fast electrons accompanying high-intensity laser-matter interaction, their transport and energy deposition in a near-solid density material with a varied degree of ionization represent one of the key issues for realization of diverse schemes of inertial confinement fusion [1]. Non-Maxwellian electrons strongly affect properties of x-ray emitting plasma systems, in particular their radiative losses, spectral line intensities, ratios, and shapes (including appearance of non-diagram lines and satellites accompanying parent transitions) [2]. Advanced methods of x-ray imaging spectroscopy thus offer a direct experimental technique for studying the distribution of hot electrons in plasmas.

The purpose of the reported research is to contribute to a development of suprathermal electron diagnostics based on a detailed study of K-shell emission of mid-Z elements. The conditions of the experiment with Cu foils irradiated by fundamental and frequency tripled radiation of the iodine laser PALS, i.e., at variable coupling parameter $I\lambda^2$ (where I and λ are the intensity and wavelength of the laser radiation), are close to those characterizing laser spikes in the shock ignition fusion scheme [3].

In general, fast electrons are generated due to combined effects of stimulated parametric processes in the lower density plasma and resonance absorption near the plasma critical surface. A survey of recent spectroscopic experiments studying the hot-electron-energy deposition and target-heating effects via Cu K-shell emission can be found in papers [4,5]. In contrast to these studies, we present x-ray spectra covering a broader range of photon energies with considerably higher spectral resolution.



The observed fine structure is interpreted in terms of suprathermal electron effects. We compare the measured data with synthetic spectra produced using MULTI2D hydrodynamic modeling of the plasma evolution [6] post-processed by collisional-radiative code FLYCHK [7] and discuss implications for hot electron diagnosis.

2. PALS experiment

The experiment was carried out using the first ($\lambda_1 = 1.315 \mu\text{m}$) and third ($\lambda_3 = 0.438 \mu\text{m}$) harmonics of the PALS laser [8]. The radiation with maximum energy of 450 J, pulse duration of 0.25 ns and focal spot radius of $35 \mu\text{m}$ was incident normal to the surface of a $1.5\text{-}\mu\text{m}$ -thick Cu foil. The maximum intensity of $4.7 \times 10^{16} \text{ W/cm}^2$ delivered on the target using the first laser harmonic (1ω) corresponds to the coupling parameter $I\lambda^2 = 8 \times 10^{16} \text{ W}\mu\text{m}^2/\text{cm}^2$.

The spectral emission was observed tangentially to the target surface by using a x-ray spectrometer with a crystal of quartz (223) spherically bent to a radius of 150 mm. The spectrometer was aligned to cover the photon energy range of 7.9 – 8.5 keV and provided 1D spatial resolution of $14 \mu\text{m}$ in the direction of the target normal. The spectra were recorded on x-ray film Kodak Industrex AA400, scanned with a table-top scanner, calibrated with respect to experimental geometry and tabulated Cu $K\alpha_{1,2}$ transitions (8047.78 and 8027.83 eV, respectively) and recalculated to intensity scale using the film characteristic curve.

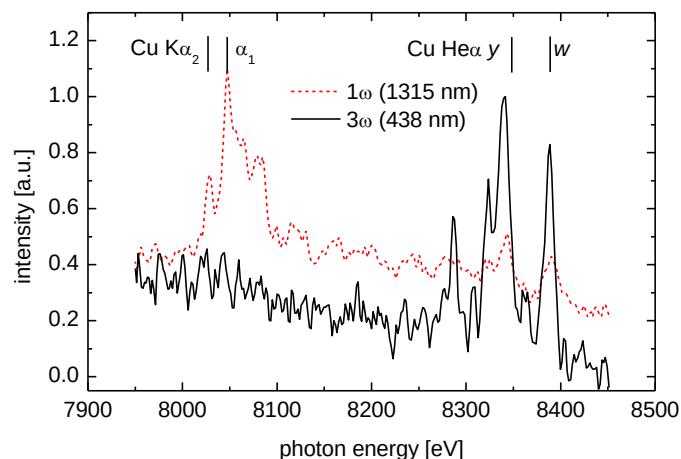


Figure 1. Comparison of Cu K-shell spectra recorded using 1ω and 3ω laser radiation.

The single shot spectra shown in figure 1 demonstrate clearly the effect of the laser coupling parameter. Whereas at 3ω the Cu K-shell emission is governed by resonance line transitions in highly ionized atoms and their satellites (the so-called quasi-optical transitions), the 1ω laser interaction results in an increased emission of inner-shell electronic transitions in weakly ionized atoms. In accordance with this, the strongest transitions observed in 3ω -generated spectra were identified as resonance w (with photon energy 8391 eV) and intercombination γ (8347 eV) lines of He-like Cu and their Li-like satellites. In contrast, the experimental spectra recorded using the 1ω laser are dominated by x-ray emission near $K\alpha_1$ (8047.8 eV) and $K\alpha_2$ (8027.8 eV) transitions in single-ionized Cu II atoms overlapped by Cu III till Cu XX (Ne-like) emission. Complementary spectral structure observed between $K\alpha$ and $\text{He}\alpha$ lines belongs to emission from Li- till F-like copper ions; the line identification is provided in the next section.

The presence of these transitions in x-ray spectra generally indicates an occurrence of fast (suprathermal) electrons with the energy above the K-shell ionization limit of the atom in a given ionization state. Further we shall concentrate to the analysis of the 1ω -generated spectrum and to its diagnostic potential with respect to the determination of hot electron population.

3. Theoretical analysis

The importance of hot electrons for K-shell spectra formation is indicated in figure 2. The shown spectra were synthesized using the FLYCHK code [7] for the Cu plasma density of 0.894 g/cm^3 , size of $70 \text{ }\mu\text{m}$ (equal to the focal spot dimension and relevant for incorporation of reabsorption effects), two characteristic bulk plasma temperatures (200 and 1600 eV) and variable hot electron fractions $f_{HE} = 0, 10^{-4}, 10^{-3}$, and 10^{-2} . Whereas at higher plasma temperature the effect of hot electrons is more or less negligible (except the growth of the He-like resonance w and $K\beta$ line intensities at highest f_{HE}), the presence of hot electrons at lower temperatures is of paramount importance for the plasma K-shell emissivity. The shape of the emitted spectra varies in accordance with figure 2a but still more important is the variation of their intensities. To achieve the same maximum intensities for spectra emitted at $f_{HE} = 0, 10^{-4}, 10^{-3}$, and 10^{-2} , the code-predicted data had to be multiplied by a scaling factor of 3×10^{12} , 90, 9, and 1, respectively. In other words, the presence of hot electrons is decisive for observability of K-shell emission from lower ionization stages.

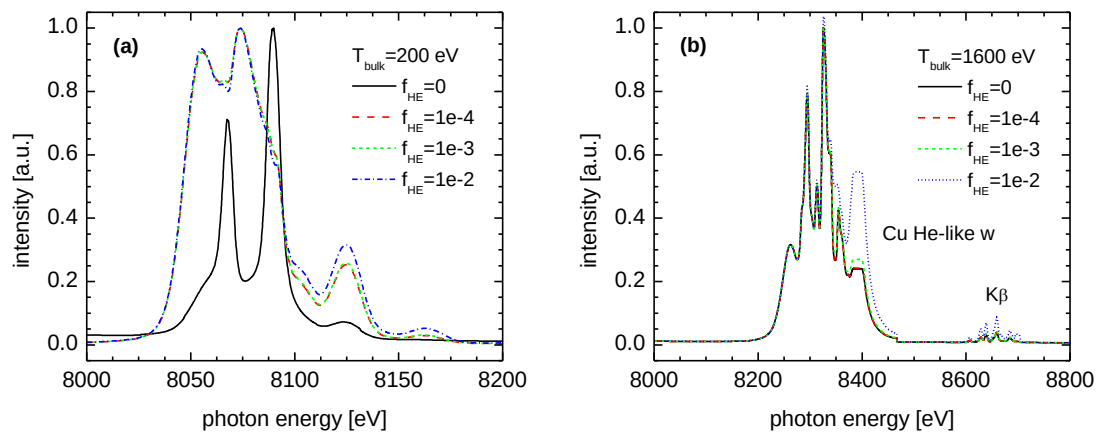


Figure 2. Spectra synthesized by CR code FLYCHK demonstrate the effect of hot electron fraction on Cu K-shell emission at bulk plasma temperature of 200 eV (a) and 1600 eV (b).

Previous investigation of x-ray emission from Cu targets irradiated by intense laser beams [4,5] demonstrated that the time-integrated K-shell spectra cannot be satisfactorily modeled by considering only a single set of relevant plasma parameters (temperature, density, size and hot electron fraction). To comply with this conclusion, the plasma evolution was simulated by using the lagrangian hydrodynamic code MULTI2D [6] assuming 2D cylindrical geometry. The $1.5\text{-}\mu\text{m}$ -thick Cu foil subdivided into 30 cells in axial and 50 in radial direction was irradiated by a gaussian laser beam. To simplify the production of the final spectrum, instead of time integration over the full spatial plasma distribution the output data were interpolated onto a fixed eulerian grid and the evolution of the temperature and density at the intersection of the laser axis with the target surface was extracted.

These parameters interpolated onto 20 time steps were used for production of synthetic spectra via collisional-radiative code FLYCHK [7]. At each step, a set of simulations was performed for hot electron densities varied in the range of $10^{16} - 10^{22} \text{ cm}^{-3}$. According to the Beg scaling [9], the energy of suprathermal electrons was set to 94 keV.

The final spectra fitting was done by using an optimization code which varies the time-evolution of f_{HE} in order to obtain the best agreement of the integrated spectrum to the experimental one. In successive iterations, the code checks whether the modification of f_{HE} within any step leads to a better fit with the experimental spectra. After performing the desired modification, the code proceeds to search for the global optimum.

The comparison of the best fit theoretical spectrum with the experiment is presented in figure 3a. Since the signal to noise ratio in the measured single shot spectra was relatively low, the experimental data shown in this figure represent a sum of 6 individual spectral records taken at identic conditions.

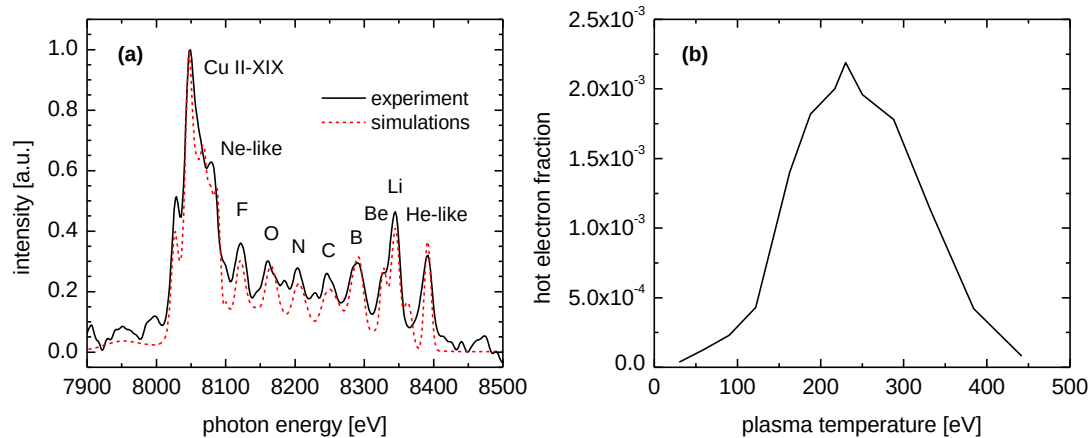


Figure 3. Comparison of experimental and synthetic spectra (a) and corresponding hot electron fractions found for the stage of low-temperature plasma emission (b).

The overall agreement of both spectra is very good. The marked peaks characterizing the principal emission of He- to Ne-like copper ions are well resolved and clearly identified. The best-fit fractions of suprathermal electrons corresponding to the plasma states in the range of bulk temperatures up to 500 eV are depicted in figure 3b. The found values of f_{HE} span between 1×10^{-4} - 2.2×10^{-3} and reach the maximum at approximately 230 eV. Outside the depicted temperature range, the values of f_{HE} cannot be univocally determined (as indicated for higher temperatures in figure 2b).

The fitting of the spectra in the photon energy range between Cu K α and He α emission can consequently be used for assessment of hot electron population in colder plasmas. The validation of this conjecture by PIC code simulations is under the progress.

4. Conclusion

By using a combination of MULTI2D hydrodynamics and FLYCHK collisional-radiative code, we have developed a model for interpretation of K-shell emission spectra emitted from Cu foil irradiated by the intense laser beam. Despite simplifications used in modeling the plasma evolution and its emissivity, we believe that the procedure used in spectra interpretation provides a viable method for determination of hot electron fraction in low temperature plasmas.

Acknowledgments

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