Suprathermal electrons in kJ-laser produced plasmas: M-shell resolved high-resolution x-ray spectroscopic study of transient matter evolution

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Abstract. Hot electrons are of key importance to understand many physical processes in plasma physics. They impact strongly on atomic physics as almost all radiative properties are seriously modified. X-ray spectroscopy is of particular interest due to reduced photoabsorption in dense matter. We report on a study of the copper Kα X-ray emission conducted at the ns, kJ laser facility PALS, Prague, Czech Republic. Thin copper foils have been irradiated with 1ω pulses. Two spherically bent quartz Bragg crystal spectrometers with high spectral and spatial resolution have been set up simultaneously to achieve a high level of confidence in the spectral distribution. In particular, an emission on the red wing of the $K\alpha_2$ transition (λ = 1.5444 Å) could be identified with complex atomic structure calculations. We discuss possible implications for the analysis of non-equilibrium phenomena and present first atomic physics simulations.

1. Introduction

The study of suprathermal electrons in hot and dense matter is of fundamental interest for the understanding of many physical processes, namely in fusion sciences. Simulations are challenging due to the non-equilibrium physics involved.

Hot electrons have also large impact in atomic physics as almost all radiative properties of the matter are seriously modified. This in turn provides the possibility for their detailed characterization. Hot electrons ionize atomic inner-shells as described in equation (1.1). The use of a high-resolution spectrometer allows hot electrons tracing *via* the induced Kα X-ray emission (see equation (1.2)). Time evolution is related to the different ionization stages (different values of X and Y). Thus, the line intensity of the Kα transitions provide potentially information about the transient hot electron fraction (f_{hot}).

$$K^2L^XM^Y + e^-_{hot} \rightarrow K^1L^XM^Y + 2e^- \quad (1.1)$$
$$K^1L^XM^Y \rightarrow K^2L^{X-1}M^Y + h\nu_{K\alpha} \quad (1.2)$$

2. Experimental Setup

The PALS is an iodine gas laser capable to deliver about 0.7kJ of energy on target at 1ω. Its pulse duration is approximately equal to 350ps with a 80µm focal spot diameter. In the present experiment the laser has been used in 1ω mode at λ=1315nm. With intensity of about 10^{16} W/cm^2 on the target, the laser beam can create hot plasmas and K-shell X-ray emission observable in a single shot.

2.1 Target

Copper (thickness: 1 to 6µm) has been chosen as the target for this experiment. Mid- Z-elements, like copper (Z=29), offer the possibility to observe almost all ionization states in X-ray spectra during the transient plasma evolution. Copper ionization energies are located in a range which allows the bulk plasma electrons with temperature (0.1 < E (keV) < 10) to successively ionize outer-shell electrons. Furthermore, the hot electron temperature ($T_{hot} \approx 85$ keV) is largely sufficient to ionize the K-shell. Kα emission is then created.

2.2 Geometry

In this experiment, the spherical crystal has been chosen to increase the signal level on a detector and in the same time to provide spatial resolution without slit. Two quartz Bragg crystals $22\bar{4}3$ (2d=2.024Å) with a curvature radius R=150mm have been employed as dispersive elements. Photographic films (Kodak Industrex AA-400) were used as detectors. The spectral resolution is $\Delta\lambda/\lambda \approx 5000$ and the spatial resolution is about 15µm.

Two X-ray spectrometers (called FSSR) are implemented at two different observation angles as shown in Figure 1. One spectrometer is placed almost parallel to the target surface (± 0.5°) in order to provide spatial resolution along z-axis. The second one is placed at an angle of 57° to simplify its implementation inside the chamber. Having two high-resolution spectrometers with two detectors inside the chamber gives a very good confidence level about the obtained results.

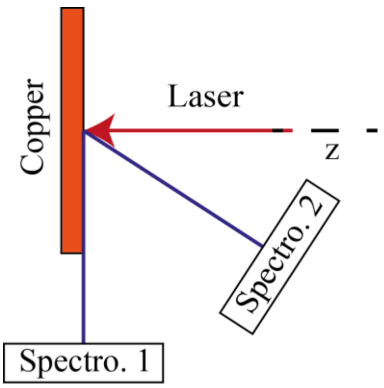

Figure 1. Experimental setup

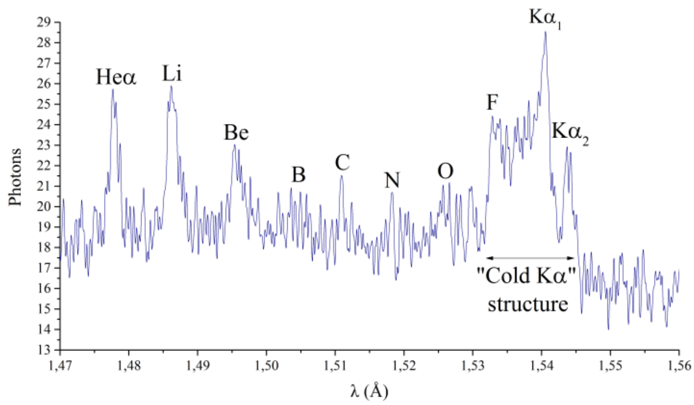

Figure 2. Single shot X-ray spectrum, shot #46406, FSSR 1

Figure 2 shows a X-ray spectrum taken in a single shot (#46406). As can be seen, a strong overlap of many transitions emitted by M-shell ionization states between 1.545 > λ(Å) > 1.53 creates the "cold Kα structure". In addition to this structure, all lines of L-shell ionization states of copper can be identified (indicated by the letters above the different visible peaks, eg., C for C-like etc.).

3. Data analysis

A LSJ-split Hartree-Fock calculation (including intermediate coupling and configuration interaction) allows the correlation of the experimental data. This code based on the work of Cowan [1] associated with a spectrum synthesizer module of the MARIA-code [2] has been used. Here, a gaussian profile has been employed with a line width that mates the experimental observation. Populations have been described by a Boltzmann distribution law. Line identification can be realized via equation (3.1).

$$I_{\omega}^{a} = \sum_k f_k \sum_{i,j} g_j^{(k)} A_{ji}^{(k)} e^{-E_j^{(k)}/kT_e} \phi_{ji}^{(k)}(\omega, \omega_{ji}^{k}) \quad (3.1)$$

The index (k) indicates different ionization states (k=0,1...,29) and f_k is a relative population factor for each ionization state "k" which is associated with the population of levels $n_k = const.\cdot f_k$. The index j corresponds to the upper-level and i to the lower-level, g_j is the statistical weight, E_j the energy, A_{ji} the spontaneous transition probability and ϕ_{ji} the line profile.

3.1 High-charge states

Figure 3 compares the theoretical calculation for Kα L-shell (and He-like) copper ionization states (and satellites) emission with the experiment. Correlation of this data is generally good and the presence of the lines corresponding to all ionization states of copper and their Kα emission in the spectrum indicates that hot electrons are present during the whole lifetime of the plasma. Then, line intensity ratios can give detailed information on the evolution of the hot electron fraction inside the plasma.

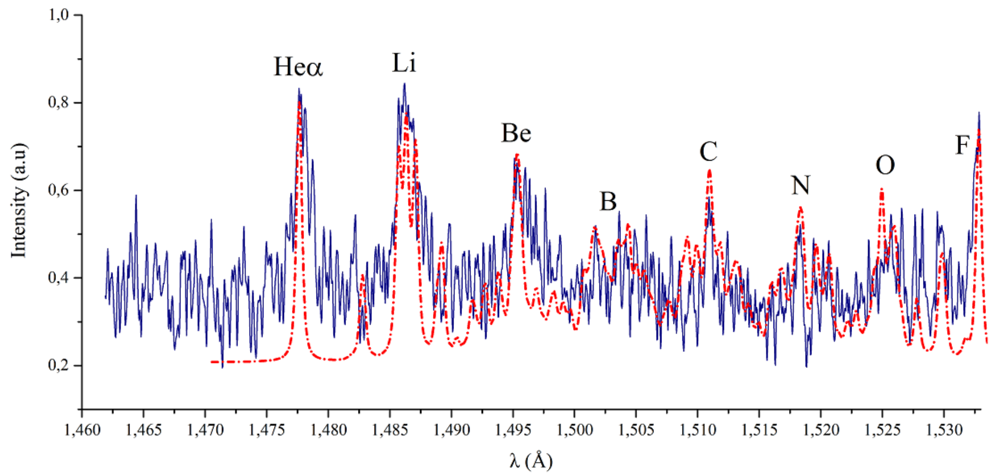

Figure 3. 1ω experimental (solid) and theoretical (dash) spectra (shot #46406, FSSR 1)

3.2 "Cold" structure

The Kα structure corresponds to lines generated by low ionization states and is designated as "cold structure" as these states originate from low temperature plasmas. However, the study of these transitions is challenging due to the complexity of configurations involving M-shell electrons. Figure 4a shows the comparison between the positions of $K\alpha_1$ and $K\alpha_2$ lines for all M-shell ionization states. Two groups can be separated. Ionization states involving 3d-shell electrons have almost all the same $K\alpha_1$ wavelengths (group D). On the contrary, 3p/3s-shell lines are much more separated (group P/S).

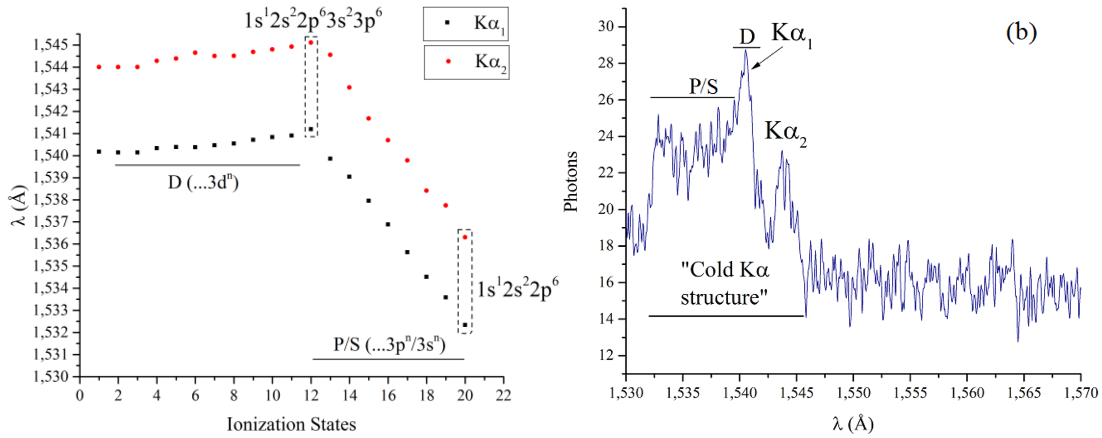

Figure 4. (a) Position of $K\alpha_1$ and $K\alpha_2$ lines for M-shell ionization states, (b) "cold structure" on experimental spectrum (#46406, FSSR 1)

Figure 4b reflects this identification in the experimental spectrum (shot #46406). The strong and narrow peak inside the structure corresponds to a very strong overlap of all lines from 3d-shell (group D) whereas the more extended structure inside the "cold structure" can be associated to the 3p/3s-shell emission (group P/S).

Figure 5a shows the simulation of emission from the states with 3d-shell configurations. States with an open shell generate lines on the red wing of the $K\alpha_2$ line. This "red wing" can be associated to the emission originating from configuration interaction and intermediary coupling. Figure 5b shows the correlation between an experimental spectrum and the simulation (each shell emission is separated for more clarity). The "red wing" seems to be present on experimental data via the enhanced slope (see arrow in figure 5) in the $K\alpha_2$ emission line.

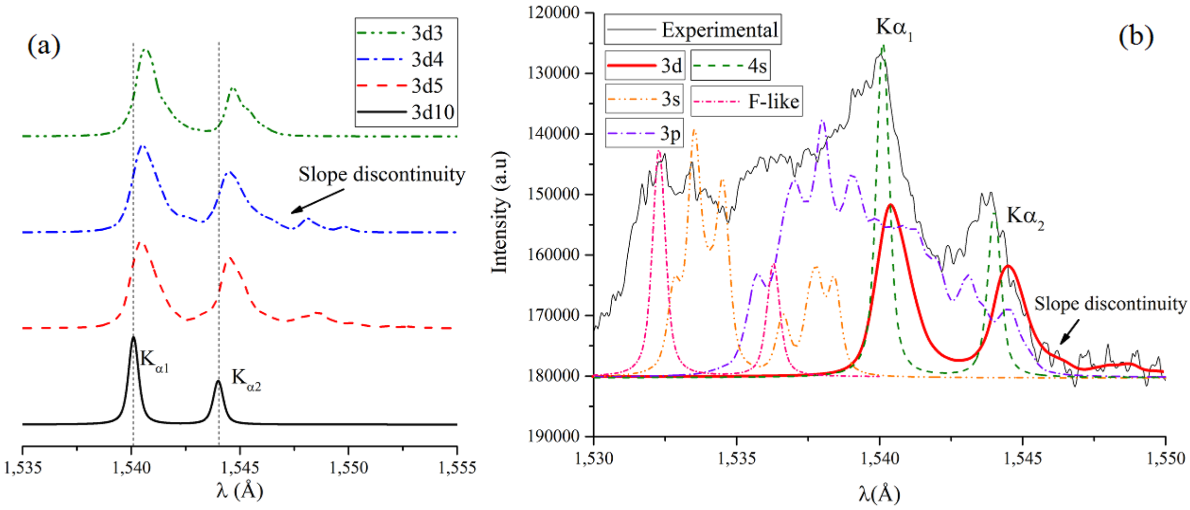

Figure 5. (a) simulations of states possessing a $K_{\alpha 2}$ red wing, (b) Sum of 5 experimental spectra (FSSR 1) and their comparison with simulations for the emission from different ionization stages

4. Conclusion

Kα lines of different ionization states (emitted at different times) can be used to visualize hot electrons during the plasma lifetime. However, this study is challenging for low ionization states due to a strong overlap between their emission lines. High-resolution spectroscopy allows to differentiate some groups of lines and their contribution inside the Kα "cold structure". Furthermore, the red wing identified in the spectra provides the possibility to resolve the contribution of some states inside the M-shell that could not be resolved otherwise.

Further analysis and experiments are envisaged to study the Kα "cold structure". Finally, these next studies should allow a verification of atomic codes describing the time evolution of hot electrons inside the plasma.

Acknowledgments

We thank all the PALS technical team for their support.

This research was performed within the LASERLAB project PALS001990, and supported by MSMT ELI Project No. CZ.1.05/1.1.00/02.0061 and CZ COST Action MP1208 Developing the Physics and the Scientific Community for Inertial Fusion.

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