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X-ray emission of a xenon gas jet plasma diagnosed with Thomson scattering

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Abstract- We present the results of a benchmark experiment aimed at validating recent non-local-thermodynamic-equilibrium (NLTE) calculations for the emission properties of high-Z multicharged ions in hot plasmas. X-ray and XUV spectra emitted in a xenon laser-produced gas-jet plasma were simultaneously recorded. Measurements of the electron and ion densities and electron temperature by Thomson scattering diagnostics allowed direct comparisons with predictions of a NLTE collisional-radiative model for the charge-state distribution. The experimental spectra were also compared to calculations provided by this model, run for the plasma conditions measured with the Thomson scattering diagnostic.

1. Introduction

NLTE atomic physics calculations of the X-ray emission of heavy elements can be benchmarked against well-characterized experimental data. In a previous study [1], X-ray spectra of laser-heated xenon gas jet plasma have been reproduced by calculations based on the super transition array (STA) concept. In this new experiment, the spectral range has been extended to the XUV domain, especially to test the $\Delta n=0$ transitions. X and XUV experimental spectra were measured in a laser-heated xenon gas jet plasma, in which plasma parameters were deduced from electronic and ionic Thomson scattering (TS) spectra. The X ans XUV spectra were compared to calculations performed with the AVERROES/TRANSPEC NLTE collisional-radiative superconfiguration code [2], using the TS experimental plasma parameters.

2. Experimental set-up

The measurements were performed in a xenon *(*Z=54) laser-heated sonic gas jet, wich was emitted from a 1 mm diameter nozzle. A frequency-doubled (λ=0.53 µm) laser beam of the Nd:glass nanosecond LULI facility was focused at the center of the gas jet with an $f/2.5$ lens equipped with a random phase plate providing a 160 µm full width at half maximum focal spot diameter. The laser pulse shape was quasi-gaussian with a 650 ps duration at half-maximum and the intensity on the target was around 10^{14} W/cm^2. At a pressure of 6.6 bar and a distance of 1.3 mm from the nozzle, the ion density was 4.6 10^{18} cm^{-3} on the jet axis. An $f/3$ lens was set at 45° from the heating beam to collect the Thomson scattering signal. Both ionic and electronic Thomson spectra were recorded on streak cameras. A time-integrated space-resolved x-ray spectrograph, equipped with a TlAP crystal, recorded spectra over the spectral region 9-16 Å. XUV spectra were recorded in the 10-140 Å spectral range, with a 5000 lines/mm transmission grating spectrograph equipped with a 3.6 ° grazing incidence gold mirror. These spectrographs were set at 90° from the laser axis, as shown in Fig.1. X and XUV spectra were recorded on DEF film and on a cooled CCD camera, respectively.

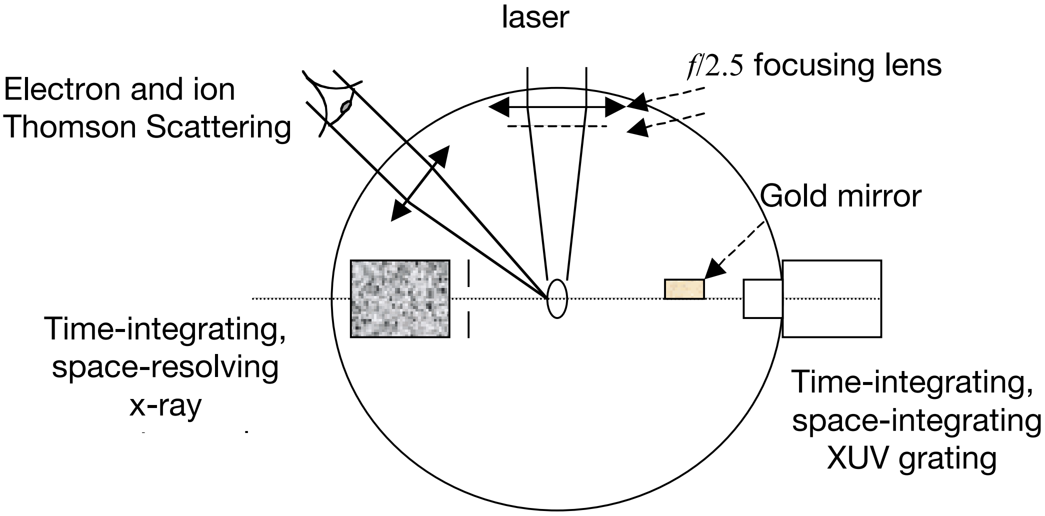

Figure 1: Geometry of the experiment

3. Results and discussion

Thomson scattering showed that plasma parameters get stationnary after a short ionisation phase. The plasma parameters, independently determined by analysing electronic and ionic Thomson spectra, were: T_e =360 eV, n_e=1.2510^{20} cm^{-3} and $<Z>$=27.

Time-integrated spectra in the 9-16 Å range were corrected for crystal [3], filters, and film [4] responses. The transmission through cold xenon remaining on the side of the gas jet has been taken into account. Fig.2 shows the comparison between the experimental spectrum and calculations performed with the code AVERROES/TRANSPEC using the plasma parameters measured with Thomson scattering. The 3p-4d transitions of ion species from Xe^{25+} (Cu-like) to Xe^{29+} (Mn-like), are quite well reproduced. The ionic balance is better reproduced when the temperature is increased to 400 eV. However, the Mn-like Xe^{29+} ions are underpopulated, taking the Co-like Xe^{27+} ion as a reference. The calculated 3d-4f Co-like feature is wider than the measured one and shifted by about 49 mÅ. The wavelength position of the Cu-like feature, measured at 14.4 Å is also not perfectly reproduced. The two intense calculated peaks between 14 and 14.5 Å, attributed to Ni-like Xe^{26+} 3d-4f features, are very well reproduced. These discrepancies are due to a lack of accuracy of the calculations, based on the STA method, compared with the high experimental spectral resolution.

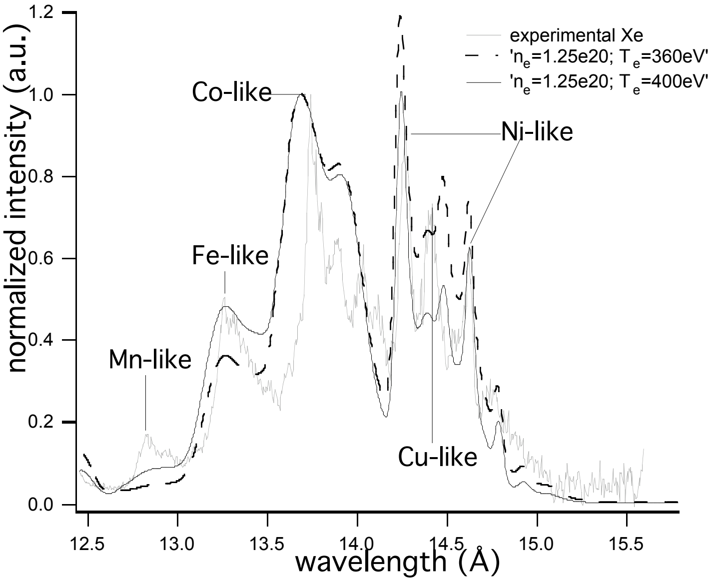

Figure 2: Comparison between experimental spectrum of Xe 3d-4f transitions and AVERROES/ TRANSPEC calculations for two temperatures (360 and 400 eV). The different ionic features are labelled by their isoelectronic sequence.

Time-integrated XUV spectra were corrected for the gold mirror reflectivity. The correction of the CCD camera sensitivity has to be considered carefully because the CCD response is not well known around 100 Å [5]. The absorption of a layer of cold Xe gas surrounding the plasma was taken ito account, but not precisely evaluated due to the lack of space-resolution. Figure 3 shows the experimental corrected spectrum and calculations performed with the code AVERROES/TRANSPEC using the density measured with TS diagnostics and a variable temperature. First, the experiment has to be compared to the calculation performed for T_e=400 eV. The 3d-4f transitions are well reproduced, as obtained with the keV crystal measurement. The 3d-3p Co-like features calculated at 37.2 Å seem to be hidden in the plateau from 30 to 45 Å. The 3d-3p Co-like feature, measured at 49.8 Å, is reproduced by calculations with a 1.42 Å shift. This discrepancy is due to the fact that STA calculations are not optimized to be very precise in that specific spectral range. The 3p-3s Co-like structures dominate the spectrum between 50 and 75 Å. The wavelength positions of the 6-5 transitions arrays of Co-like and Ni-like ions around 100 Å are reproduced. The several differences remaining can be explained by a time-integration effect. This is demonstrated by the spectra calculated for different temperatures shown in Fig.3, which are significant of the evolution of the spectrum during the recombination of the plasma. Indeed, at low temperature, several lines are growing in the 30-45 Å and 50-75 Å regions where the experimental emission exhibits broad features. The difference between the calculated spectrum and the calculation at T_e=400 eV is certainly linked to the lack of time resolution for this XUV spectrum measurement.

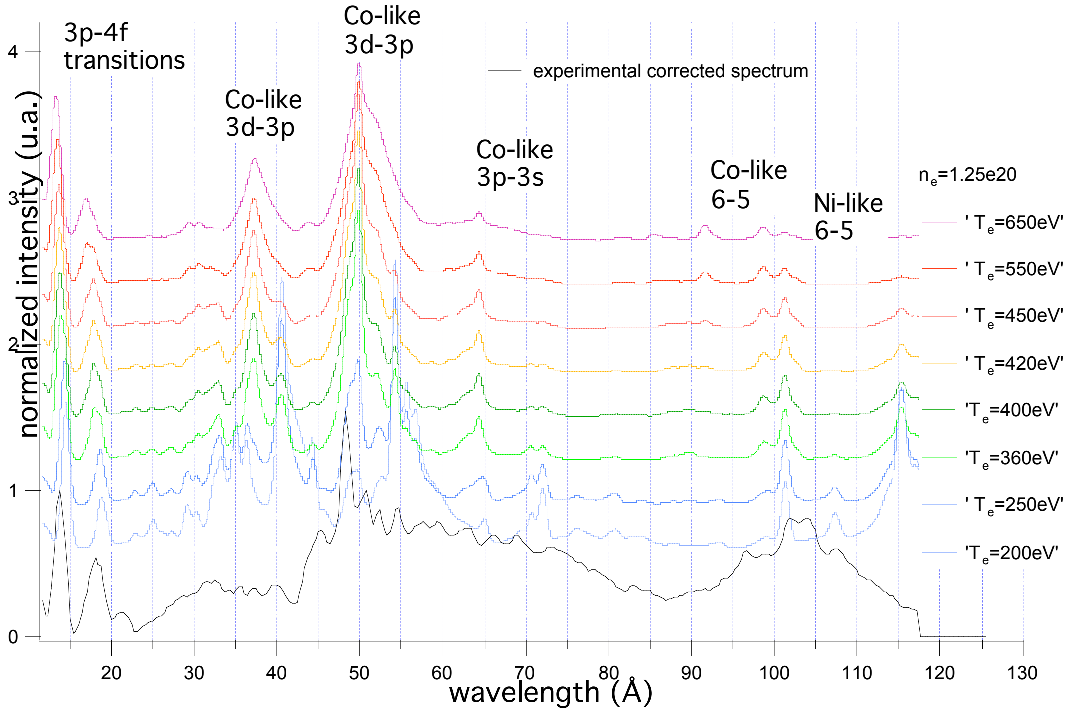

Figure 3: Comparison between the experimental spectrum of Xe and AVERROES/ TRANSPEC calculations for several temperatures (200 to 650 eV), for n_e=1.25 10^{20} cm^{-3}. The temperature given by the TS diagnostic is 400 eV.

4. Conclusion

Time-integrated experimental X and XUV spectra of xenon were recorded and reproduced with AVERROES/TRANSPEC calculations, using the plasma parameters provided by TS measurements. Experimental results provide an interesting benchmark for the NLTE atomic physics codess. The keV range spectrum is very well reproduced. We have shown that temporal integration effect can explain the discrepancies remaining in the comparison of the XUV spectrum with calculations. Next step will be to use a streak camera coupled to the XUV grating spectrograph, to evidence the time-dependence of the spectra.

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