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Spectral analysis of K-shell X-ray emission of magnesium plasma produced by ultrashort high-intensity laser pulse irradiation

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Abstract. Spectral analysis of K-shell X-ray emission of magnesium plasma, produced by laser pulses of 45 fs duration, focussed up to an intensity of $\sim 10^{18}$ W cm^{-2}, is carried out. The plasma conditions prevalent during the emission of X-ray spectrum were identified by comparing the experimental spectra with the synthetic spectra generated using the spectroscopic code Prism-SPECT. It is observed that He-like resonance line emission occurs from the plasma region having sub-critical density, whereas K-α emission arises from the bulk solid heated to a temperature of 10 eV by the impact of hot electrons. K-α line from Be-like ions was used to estimate the hot electron temperature. A power law fit to the electron temperature showed a scaling of $I^{0.47}$ with laser intensity.

Keywords. X-ray spectroscopy; K-shell spectra; plasma diagnostics; ionic line radiation.

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1. Introduction

Spectral analysis of the K-shell X-ray emission of plasma produced by intense laser pulses is often used to derive diagnostic information [1] of electron temperature, density, ionization states and expansion velocity of the plasma. In particular, the spectral analysis of K-shell X-ray emission from plasma produced by the ultrashort, high-intensity laser pulses is one of the most effective tools to understand the underlying complex laser–matter interaction processes, and to optimize the plasma X-ray source for high flux of ultrashort duration X-ray photons [2]. For instance, the most important feature of the K-shell X-ray emission spectrum of such a plasma is the presence of the characteristic K-α radiation which is due to the generation of hot electrons during the ultrashort, high-intensity laser–matter interaction. The generation and propagation of the hot electrons, which is of big concern due to preheating of pellet undergoing compression for the inertial confinement fusion, can be inferred from the quantitative analysis of the X-ray spectrum. In such a plasma, the X-ray emission occurs from the high density over-critical region since the laser energy is deposited during the laser pulse duration that is much shorter than the hydrodynamic time scales of plasma expansion and hence a heated region of solid density is created. However, pre-pulses invariably associated with the chirped pulse amplification-based intense femtosecond laser system produce long density scale length plasma which may modify the interaction mechanism, resulting in X-ray emission from sub-critical region of the plasma. This modifies the X-ray spectrum, thereby makes K-shell X-ray spectroscopy technique of vital importance to monitor and to provide clues to control the laser–matter interaction conditions.

High-resolution K-shell emission in the 1–2 keV energy range from the plasma produced by the ultrashort, high-intensity laser pulses has both the inner-shell X-ray line (K-α, K-β, L-α, etc.) as well as ionic X-ray line emissions (He-α, Ly-α) from thermal plasma. These line radiations are of immense importance as monochromatic X-ray source for providing diagnostic information. Under optimized conditions, the duration of the inner-shell X-ray line radiation is of the order of the laser pulse duration which makes it suitable to be used as X-ray probe in time-resolved X-ray diffraction studies. The conversion efficiency and the duration of the K-α radiation are governed by the generated hot electron spectrum which in turn depends on the laser irradiation parameters such as intensity, pulse duration, pre-pulse, etc. as well as the target material [3]. On the other hand, the ionic line emission [4] is due to the electronic transitions in the highly charged ionic species (H-like, He-like) present in the plasma heated to a high temperature. The spectral and temporal characteristics of such radiation depend on the plasma parameters, viz. electron density, temperature, average degree of ionization, and opacity of the hot plasma medium. Analysis of the inner-shell and ionic line radiation can be used as diagnostics to infer the plasma conditions in the experiment. In this paper, we present a spectral analysis of K-shell X-ray emission spectrum of magnesium plasma produced by laser pulses of 45 fs duration focussed to an intensity of $\sim 10^{18}$ W cm^{-2}. The plasma conditions prevalent during the emission of X-ray spectrum are identified by comparing the experimental spectra with the synthetic spectra generated by the spectroscopic analysis code PrismSPECT [5].

2. Experimental details

Experiments were carried out with femtosecond pulses of 45 fs (FWHM) duration, obtained from a Ti:sapphire laser (800 nm) system operating at 10 Hz rep-rate. X-ray emission spectrum from planar magnesium target was recorded, with a spectral resolution of 0.013 Å, in the wavelength range of 9 Å to 10 Å using an in-house developed X-ray crystal spectrograph coupled with X-ray CCD camera. Figure 1 shows the X-ray spectrum of magnesium plasma recorded at an intensity of 4×10^{17} W cm^{-2}. In this figure the spectral lines are identified as He-α resonance transition Mg XI $1s^{2}\,{}^{1}S_0$–$1s\,2p\,{}^{1}P_1$ at $\lambda = 9.17$ Å, He-α intercombination transition Mg XI $1s^{2}\,{}^{1}S_0$–$1s\,2p\,{}^{3}P_{1,2}$ at $\lambda = 9.23$ Å, the *j-k* dielectronic satellite lines of the Li-like transitions at $\lambda = 9.32$ Å, K-α emission

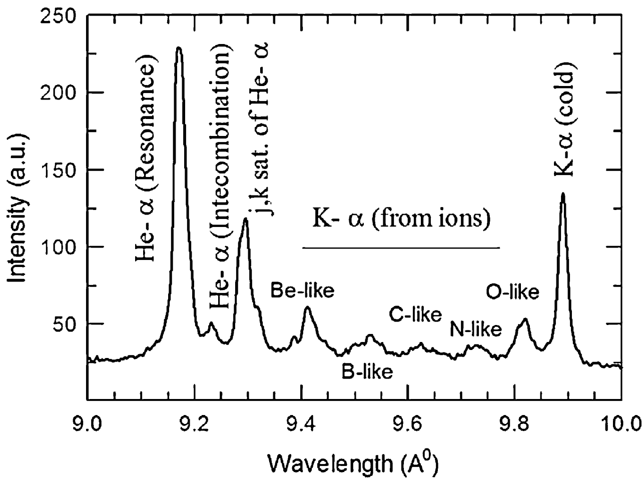

Figure 1. Experimental X-ray emission spectrum of the magnesium plasma recorded at an intensity of 4×10^{17} W cm^{-2}.

cold Mg atoms at 9.87 Å, respectively. A relative smaller intensities shifted K-α emission from Be-like, B-like, C-like, N-like, O-like Mg ion are also observed to the lower wavelength side of K-α emission from cold Mg atoms. These lines are produced by the interaction of hot electrons with ions present in the low-temperature pre-plasma.

3. Spectral analysis

The X-ray spectrum was recorded with a time-integrated X-ray spectrograph. As the plasma undergoes rapid hydrodynamical evolution, the observed X-ray spectrum corresponds to the time- and space-averaged value of density and temperature of the plasma. Modelling of X-ray spectra at each distinct condition of temperature and density, in space and time, will require the use of sophisticated computer simulations coupled with plasma hydrodynamic codes including radiation transport. Nevertheless, most of the important features can be realized by approximating the plasma to be of some geometrical shape, and making certain simplifying assumptions on the spatial variations of plasma density and temperature. For example, hot electrons are emitted during the laser pulse and the inner shell line emission originates mainly from the dense bulk of the target which is heated to a temperature of few tens of eV by the hot electrons generated during the interaction process.

Spectroscopic analysis and modelling of K-shell spectrum of Mg plasma produced by the interaction of femtosecond laser pulses has been carried out using the spectral analysis code PrismSPECT. It generates K-shell emission spectra based on either steady-state or time-dependent plasma conditions. User inputs are: range of densities, temperatures, and size of the plasma. PrismSPECT allows the user to specify specify the thermodynamic equilibrium such as plasma in local thermodynamic equilibrium (LTE) or a plasma not in the local thermodynamic equilibrium (NLTE), and the expansion geometry (planar or spherical) to be used in the spectra calculations. Time-dependent calculations allow the

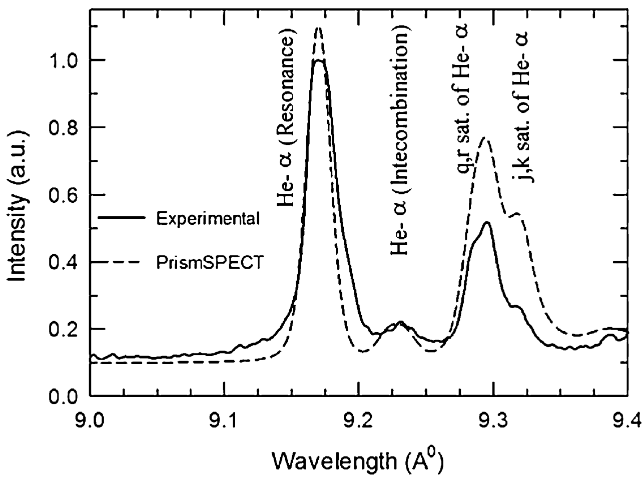

Figure 2. Experimental and synthetic spectra of Mg in the region around the He-α resonance line.

user to specify the time duration over which the ionic populations are to be calculated for the user specified temperatures and densities.

The spectrum shown in figure 1 clearly establishes the existence of three distinct plasma regions. He-like resonance line (together with their satellites) originates from the thermal plasma. The strong cold K-α line indicates that a large number of hot electrons are produced. The weak K-α line from ions suggests the presence of low-temperature plasma. Figure 2 shows the experimental and computed spectra of the region around the resonance line. The spectrum was computed by time-dependent solution of rate equations considering NLTE equilibrium. Least-squares comparison of normalized PrismSPECT spectrum with the experimentally observed spectrum yields a best fit for plasma condition with electron temperature $T_e = 130$ eV and electron density $n_e \sim 5.4 \times 10^{20}$ cm^{-3}. The calculated parameters are justified since the ionization equilibrium time [4] for He-like species is of the order of a few ps. Therefore, the region of the above line emission is the subcritical plasma expansion region having a high temperature of ~130 eV. Next, it can be noted that the spectral width of dielectronic satellite lines of the Li-like transitions (q, r and j, k) is much smaller than that calculated by PrismSPECT. It shows that the emission region of these spectral lines has a much smaller density.

The ratio of He-α resonance line and intercombination line intensity was used for estimating electron density [1]. The electron temperature was measured using the intensity ratio of dielectronic satellites j, k to the resonance line [1]. We have experimentally studied the dependence of X-ray emission spectrum as a function of laser intensity in the range of 10^{16}–10^{18} W cm^{-2}. The laser intensity was varied by changing the laser energy keeping the focal spot size fixed. Figure 3 shows the variation of the derived electron densities from the measured X-ray line intensity ratio as a function of the laser intensity. It is noted that the electron density decreases with the increase in laser intensity. This can be understood by considering the pre-pulse activity ahead of main laser pulse [6]. The pre-pulse intensity increases with the increasing laser intensity. The pre-plasma is formed by the high pre-pulse intensity and it expands faster with the increasing laser intensity and hence has lower density.

The spectrum around K-α emission from cold Mg atoms was calculated by the time-dependent collisional-radiative model by considering the electron distribution function to be a bi-Maxwellian. This distribution assumes that one group of electrons referred to as thermal electron has a temperature T_e while another group called hot electron has much higher temperature T_{hot}. Figure 4 shows the experimental and the computed spectra of the region around the K-α emission. The best fit was for the plasma condition with temperature $T_e = 10$ eV, $T_{hot} = 130$ keV (hot electron fraction = 0.01) and electron density $n_e = 4.4 \times 10^{22}$ cm^{-3}. The K-α emission from O-like ions is the signature of a low-temperature

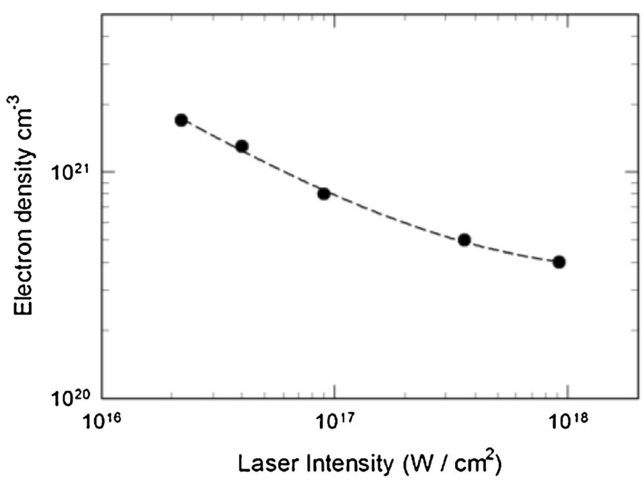

Figure 3. Derived electron densities as a function of the laser intensity. The line is drawn to guide the eye.

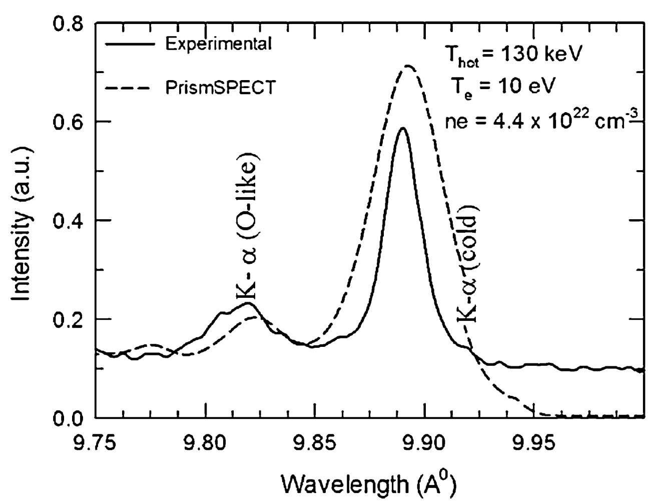

Figure 4. Experimental and synthetic spectra of the region around the cold K-α line.

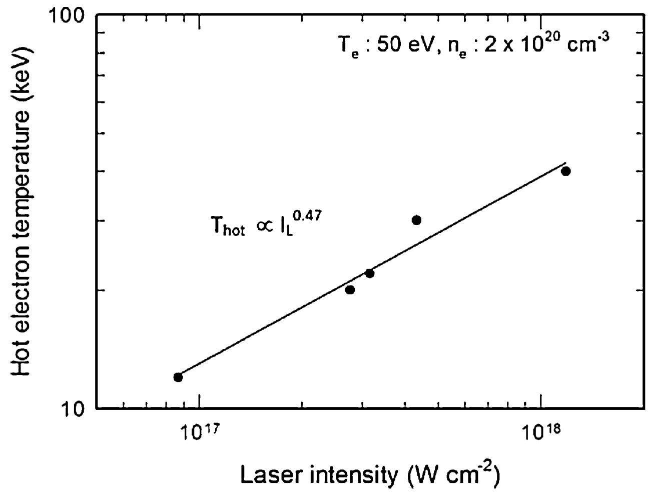

Figure 5. Derived hot electron temperature from X-ray line intensity of K-α lines from Be-like ions.

plasma produced by the heating effect of the energetic electrons penetrating the target. The best fit for the K-α from O-like ions shows that the bulk material at solid density is heated to a temperature of 10 eV. The intensity of K-α line radiation from the O-like ions can give the estimate of heating induced by the hot electron in the bulk matter. However, the reabsorption of this line in the bulk makes the estimation of hot electron temperature complicated. Nevertheless, the K-α lines from the Be-like ions, observed in spectral region between resonance line He-α and cold K-α, can be used to estimate the hot electron temperature. PrismSPECT calculations show that this line is produced by the heating effect of the energetic electrons on low-density (2×10^{20} cm^{-3}) and low-temperature plasma (<50 eV) produced in front of the target by pre-pulse [7]. Figure 5 shows the variation of the derived hot electron temperature from the measured X-ray line intensity of the K-α lines from the Be-like ions as a function of the laser intensity. A power law fit to the temperature results in scaling of $kT_e \propto I^{0.47}$ with laser intensity which is broadly in agreement with the prevailing scaling laws.

4. Conclusion

We have identified the plasma conditions prevalent during the experimentally observed K-shell X-ray emission spectrum from a planar magnesium target irradiated by a 45 fs laser of intensities varying in the range of 10^{16}–10^{18} W cm^{-2} by comparing the experimental spectra with the computed spectra generated by the spectroscopic analysis code Prism-SPECT. He-like resonance line emission is shown to occur from the plasma region with temperature 130 eV and electron density $\sim 5.4 \times 10^{20}$ cm^{-3}. K-α emission arise from the bulk solid ($n_e = 4.4 \times 10^{22}$ cm^{-3}) heated to a temperature of 10 eV by the impact of hot electrons of 130 keV energy. K-α lines from Be-like ions are used to estimate hot electron temperature resulting in a scaling of $kT_e \propto I^{0.47}$ with laser intensity.

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