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L-shell absorption measurement and simulation of x-ray-heated constrained material*

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Using the newly-designed multi-layered target, we obtain a homogeneous Al sample plasma at high density, low electron temperature, and in near local thermodynamic equilibrium. L-shell resonance absorption lines of Li-like and Be-like ions, as well as satellites are clearly observed. Transition arrays such as 2s–3p, $2s^2$–2s3p and 2s2p–2p3p are identified. We present the calculation method based on the unresolved transition array model, and we compare the measured transmission spectrum with the calculated results. The electron temperature of the constrained sample plasma is determined to be 34eV with a variation of ±2eV.

Keywords: L-shell absorption, photoexcitation photoionization, inverse bremsstrahlung
PACC: 5225P, 5250J

1. Introduction

The theoretical and experimental investigation of x-ray absorption characteristics is an active field of research with applications in astrophysics, inertial fusion and x-ray laser production. In the past two decades, K-shell absorption of laser plasma has been of particular interest. A series of experiments has been carried out on high-power laser facilities.[1−5] These experiments have been successful insofar as they have provided more information about the plasma than was previously known. The main absorption mechanisms include photoexcitation (bound–bound transition), photoionization (bound–free transition) and inverse bremsstrahlung (free–free transition). However, few works have dealt with the L-shell absorption of a plasma, which is much more complicated.

Basically, the backlight and the sample plasma are the two key problems of x-ray absorption measurements. For the unique character of pseudocontinuous emission spectrum, samarium, gold, bismuth and neodymium are mostly used as the backlight materials. Gold is chosen here because we have previously investigated its emission.[6−10] It is the O-band unresolved transition arrays that provide a relatively smooth spectrum in the range of interest. It is easy to obtain a sample plasma by directly irradiating the target with a laser beam, as done by Balmer *et al.*[11] The drawback is obviously due to the existence of steep gradients of electron temperature and density in the laser plasma. The x-ray fluxes can heat materials volumetrically and homogeneously, at a higher density and lower temperature. An isothermal plasma in local thermodynamic equilibrium (LTE) is formed and expands uniformly and, if it has a right aspect ratio, essentially in one dimension.

In this paper, we present a detailed measurement and analysis of L-shell absorption with the newly-designed multi-layered target. The experiment set-up is described in Sec.2. The calculation method based on the unresolved transition array (UTA) model is presented in Sec.3. The analysis of the results is presented in Sec.4.

2. Experimental set-up

The principle of our experiment is similar to that of the measurements of K-shell absorption carried out by Chanais-Popovics.[12] In the present case, we are interested in a different energy range, namely the L-shell absorption. Figure 1 shows a schematic diagram of the experimental set-up, displaying different parts

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of the target. The first layer, gold, directly irradiated by the coming laser, acts both as a backlight source for the absorption measurement and as a radiative heater of the Al sample layer. Gold has been chosen because its O-band UTAs provide a relatively smooth spectrum in the range 4.0–7.0nm, which can be absorbed by AlIX and AlX ions. The thickness of the Au layer is determined from a compromise between the need for incomplete laser ablation and maximum x-ray conversion efficiency at the irradiance of 10^{13}w/cm^2, which can create a predominantly Li-like and Be-like ion sample plasma. The Al sample layer is buried between two Formvar (CH) layers, which are transparent to x-ray, so that they can constrain the Al sample and keep it flat.

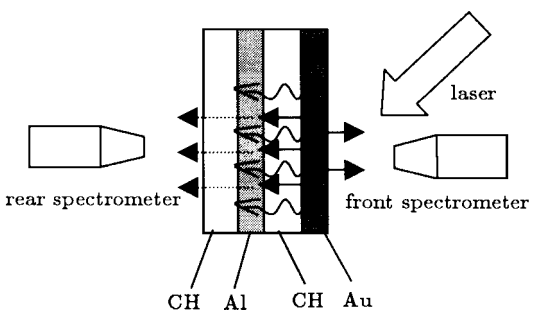


Fig.1. Schematic diagram of the experiment set-up.

The experiment was performed at the China Academy of Engineering Physics (CAEP) using the main beam of the 'XingGuang II' high-power laser facility. Random-phase plates designed for 0.35μm wavelength are used to produce a smooth laser energy distribution. The main beam delivers about 25 joule energy in a pulse of 700ps full width at half maximum (FWHM) providing irradiance up to 7.0×10^{13}w/cm^2 on the target. The diagnostics consists of two pinhole cameras and two varied-line-space grating spectrometers (1200 lines/mm). One pinhole camera is set by the side of the target for monitoring the expansion of the sample, and the other pinhole camera is used to monitor the focal spot. The front grating spectrometer records the unattenuated Au spectrum with the soft x-ray sensitive film 5FW, and the rear one records the absorption by Al L-shell transitions. The film is scanned with a photodensitometer. The average density of the edge film is taken as the background. With the background and self-emission subtracted, the film density is converted to the measured intensity using the calibrated x-ray response of the 5FW film. The transmission spectrum is obtained by comparing the unattenuated x-ray spectrum and the sample plasma absorption spectrum, as shown in Fig.2.

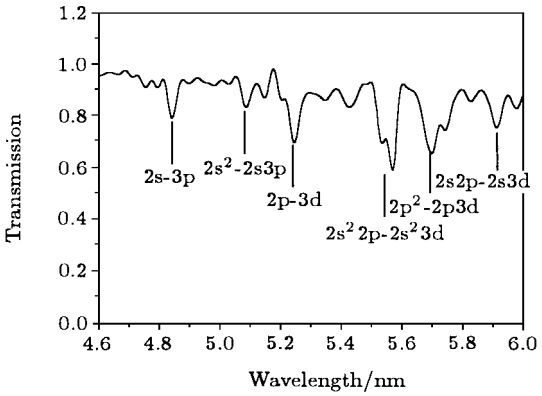


Fig.2. Normalized experimental transmission spectrum.

3. Calculation model

In a one-dimensional homogeneous plasma, the radiation transfer equation can be simplified as

$$F(\hbar\omega) = \frac{I(\hbar\omega)}{I_0(\hbar\omega)} = \exp(-\alpha(\hbar\omega)L), \qquad (1)$$

where $I_0\hbar(\omega)$ and $I(\hbar\omega)$ are the incident and transmitted x-ray intensity, respectively. L is the path length traversed by the light through the plasma. In the configuration average approximation, the frequency-dependent absorption coefficient $\alpha(\hbar\omega)$ can be written as

$$\alpha(\hbar\omega) = \sum_i \left[\sum_{c,c'} N_{i,c}\sigma^{bb}_{i,c,c'}(\hbar\omega) + \sum_c N_{i,c}\sigma^{bf}_{i,c}(\hbar\omega) \right] + N_e\sigma^{ff}(\hbar\omega), \qquad (2)$$

where i indicates the ionic stage, $N_{i,c}$ is the number of ions of configuration c per unit volume, and N_e is the number density of free electrons. $\sigma^{bb}_{i,c,c'}(\hbar\omega)$ and $\sigma^{bf}_{i,c}(\hbar\omega)$ are the photoexcitation and photoionization cross sections, respectively. $\sigma^{ff}(\hbar\omega)$ is the free–free absorption cross section, which can be calculated by the simple Kramers formula with the Gaunt factor.

For the case of LTE plasma, the population densities of configurations satisfy the Boltzmann–Saha equations

$$N = \sum_{i,c} N_{i,c}, \qquad (3)$$

$$N_e = \sum_{i,c} Z_i N_{i,c}, \qquad (4)$$

$$\frac{N_{i+1}N_e}{N_i} = \frac{U_e U_{i+1}}{U_i}\exp[-(\phi_i - \Delta\chi)/\kappa_B T], \qquad (5)$$

where N is the total ion number density, Z_i is the efficient charge of the corresponding ion, and U_i and U_e are the partition functions of the ion and free electron, respectively. ϕ_i is the ionization potential and $\Delta\chi$ is the depression of ionization limit caused by the plasma environment restricting the number of bound states available.

The photoexcitation cross sections are calculated from the single-electron transition properties. Under the configuration average approximation, the frequency-dependent cross section can be written as

$$\sigma^{bb}_{i,c,c'} = \frac{\pi h e^2}{mc} f_{i,c,c'} l(\hbar\omega), \tag{6}$$

$$\sigma^{bf}_{i,c} = \frac{\pi h e^2}{mc} \sum_{\alpha} q_\alpha \frac{\mathrm{d}f_\alpha}{\mathrm{d}\varepsilon}, \tag{7}$$

where $l(\hbar\omega)$ is the lineshape function. In general, it is a convolution of Gaussian and Lorentzian profiles. $f_{i,c,c'}$ is the configuration average oscillator strength. The transition energy is assumed to be approximately the same for all lines of the transition arrays. $\mathrm{d}f_\alpha/\mathrm{d}\varepsilon$ is the density of oscillator strength. q_α is the occupation number of orbital α. The summation runs over all the subshells.

According to quantum defect theory, the photoexcitation and photoionization processes can be treated in a unified manner.[13] The infinite bound and adjacent continuum states with the same angular momentum and parity can form a channel, in which the quantum defect varies smoothly with the excitation energy. Therefore, with several benchmark points, the relevant transition energy from the initial state to the final channel can be obtained conveniently by interpolation. Based on the method described above, we calculate the predicted transmission spectra of Al plasma at different temperatures. The mass density of the sample plasma is $0.01\pm0.002\mathrm{g/cm^3}$, obtained from the radiograph of the pinhole camera. Figure 3 shows the calculated results versus the experiment data. Here, the path length is L=3.2μm, and an instrumental width of 0.01nm is used to convolute the spectra in our calculation.

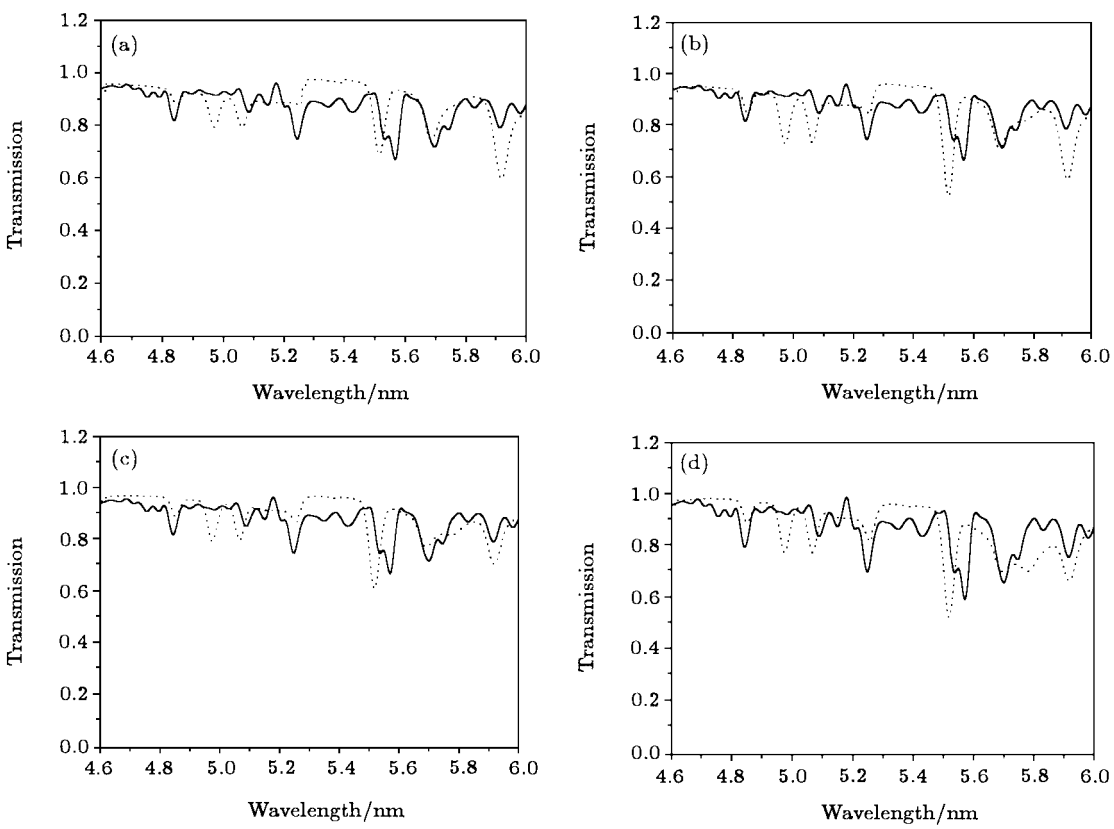


Fig.3. Experimental data versus calculations at 31eV (a), 33ev (b), 34eV (c) and 35eV (d): dotted line, calculation; solid line, experiment; with the mass density $0.01\mathrm{g/cm^3}$.

4. Discussion

The single-electron transition arrays are identified and labelled in Fig.2. From the calculated results at different electron temperatures, illustrated in Fig.3, we clearly see that the Li-like 2p–3d transition arrays do not exist at temperatures lower than 33eV. When the temperature increases to 34eV, the 2p–3d transition arrays come into existence. Except for Be-like 2sp–2s3d transition arrays, the positions of the calculated absorption have a small shift compared to the experimental data. The Be-like $2s^2$–2s3p and B-like $2s^22p$–$2s^23d$ transition arrays shift by 0.019nm and 0.025nm, respectively, towards the short wavelength side, while the Li-like 2s–3p transition arrays shift by 0.011nm towards the long wavelength side. This may be due to the fact that different configurations have different electrons and thus different correlation energies.[14] The discrepancy of the transmission spectrum intensity between the measured and calculated results is partially attributed to the calibration of the film sensitivity for a different energy range. Note that the Be-like 2s2p–2p3p transition array near wavelength 4.95nm is predicted by our calculation but is not observed in the experiment. This is because of the compensation from the self-emission and some scattered light at the position.

The electron temperature, determined by optimizing the fit for all lines at particular positions, is 34eV. Consideration of timing uncertainty increases the error, implying a temperature of 34±2eV for our sample, while the laser plasma temperature of Balmer *et al* is optimized at 250eV with a variation of ±50eV. This means that our sample plasma here is more uniform, as predicted in Sec.1. It is worth mentioning that the inverse bremsstrahlung is nearly even and the photoexcitation is much more intense than photoionization in the wavelength range 4.6∼6.0nm. So no distinguished characters of inverse bremsstrahlung and photoionization have been observed in our experiment.

In conclusion, with the newly-designed multilayered-target, we have measured the L-shell absorption of an Al plasma. The sample Al plasma was found to be uniform, at high density and low temperature. Li-like, Be-like and B-like ion transition arrays have been observed and identified. On the whole, our calculations are in agreement with the experimental data on the whole. The experimental results of the transmission spectrum compared to calculated results can be used to diagnose the temperature of plasmas. In the future, we will turn to the absorption investigation of middle-Z materials, and then the radiative opacity.[15,16]

Acknowledgments

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