Journal of Quantitative Spectroscopy & Radiative Transfer 187 (2017) 20–29

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

K-shell X-ray spectroscopy of laser produced aluminum plasma

Channprit Kaur [a,b], S. Chaurasia [a,*], A.K. Poswal [c], D.S. Munda [a], A.K. Rossall [d], M.N. Deo [a], Surinder M. Sharma [a]

[a] High Pressure & Synchrotron Radiation Physics Division, Bhabha Atomic Research Centre, Mumbai 400085, India
[b] Homi Bhabha National Institute, Mumbai 400094, India
[c] Atomic & Molecular Physics Division, Bhabha Atomic Research Centre, Mumbai 400085, India
[d] International Institute for Accelerator Applications, University of Huddersfield, Queensgate, Huddersfield HD1 3DH, UK

ARTICLE INFO

Article history:
Received 9 May 2016
Received in revised form
26 August 2016
Accepted 29 August 2016
Available online 13 September 2016

Keywords:
Laser produced plasma
K-shell X-ray spectrum
Plasma parameters
Angular distribution

ABSTRACT

Optimization of a laser produced plasma (LPP) X-ray source has been performed by analyzing K-shell emission spectra of Al plasma at a laser intensity of 10^{13}–10^{14} W/cm^2. The effect of varying the laser intensity on the emissivity of the K-shell resonance lines is studied and found to follow a power law, $I_x=(I_L)^\alpha$ with α=2.2, 2.3, 2.4 for He$_\beta$, He$_\gamma$, He$_\delta$ respectively. The emission of these resonance lines has been found to be heavily anisotropic. A Python language based code has been developed to generate an intensity profile of K-shell spectral lines from the raw data. In theoretical calculations, the temperature is estimated by taking the ratio of the Li-like satellite (1s^{2}2p–1s2p3p) and the He$_\beta$ (1s^2–1s3p) resonance line and the ratio of the He-like satellite (1s2p–2p^2) and the Ly$_\alpha$ (1s–2p) resonance line. To determine the plasma density, stark broadening of the Ly$_\beta$ spectral line is used. Simulation was carried out using the FLYCHK code to generate a synthetic emission spectrum. The results obtained by FLYCHK are T_e=160 eV, T_h=1 keV, f=0.008, $n_e=5\times10^{20}$ cm^{-3} and the analytical model resulted T_e=260–419 eV and n_e=3x10^{20} cm^{-3}.

1. Introduction

Laser produced plasma (LPP) is a brilliant source for X-ray production. The high density and temperature of plasma produced by focusing a high power laser makes it an ideal media for production of X-ray sources. These X-rays have several applications in various fields of science. These X-ray sources can be used as a probe for the study of high density phenomenon by using them as a back-lighter in extreme matter physics [1] which allows us to determine the opacity of materials [2]. Opacity plays a key role in radiation diffusion modeling of stars [3] and in inertial confinement fusion (ICF) for accurate modeling of radiative hydrodynamics. The use of these LPP X-rays in X-ray radiography of shocked material which is opaque to optical light [4,5], lithography [6], X-ray microscopy [7], radiobiology [8], photo pumped X-ray lasing, efficient soft X-ray emission for indirect drive fusion scheme [9] etc. shows its importance. Optimization of these X-ray sources is essential for the development of effective and compact X-ray sources. The X-ray line spectra emitted from hot dense plasmas provide an important diagnostic tool to infer local plasma parameters such as temperature, density and ionization states. Many authors have successfully theoretically and experimentally analyzed the spectra [10,11] emitted from dense plasmas of various materials irradiated with intense laser pulses. K-shell spectra, including resonance lines of Hydrogen (1s–np, $n>2$) and Helium (1s^2–1snp, $n>2$) like ions (H-like and He-like) along with associated satellites are particularly interesting

* Corresponding author.
E-mail address: pgshivanand@gmail.com (S. Chaurasia).

http://dx.doi.org/10.1016/j.jqsrt.2016.08.020
0022-4073/© 2016 Elsevier Ltd. All rights reserved.

because the spectrum is relatively simple and easy to model. High precision numerical calculations of various atomic characteristics make these spectra a convenient tool for the investigation of physical processes occurring in the solar corona [12].These resonance lines, also known as ionic lines, are due to the transition of electrons in highly charged species present in plasma such as H-like, He-like etc. There has been considerable interest in satellite emission appearing on the long wavelength side of resonance lines. These satellites, arising from doubly excited configurations, are particularly useful as a diagnostic tool because they are less sensitive to opacity effects. The relative intensity of these satellites to their parent resonance line provides a valuable diagnostic for the measurement of various plasma parameters. These dielectronic satellites of spectral lines of multiply charged ions have been investigated actively during the last several years [13–15]. There are also several calculations have been done using a multi-configuration Dirac–Fock method with the addition of quantum electrodynamics as well as Breit corrections to estimate density and temperature of plasmas using Li-like ions of mid Z [16,17]. In general, the X-ray emission from a planar target irradiated with an intense laser is considered as isotropic and several models use this basis. It has been shown that there is a large deviation from the isotropic nature of Bremsstrahlung X-ray flux due to a change in plasma opacity with respect to target normal [18].

In this paper, a detailed study of the K-shell X-ray emission spectrum generated by 30 J, 500 ps Nd: Glass laser, focused to an intensity of 10^{13}–2×10^{14} W/cm^2 is presented. The angular dependency of K-shell resonance lines flux of the Al plasma has been studied by rotating the target normal with respect to detector.

2. Experimental setup

The experiment was carried out using Nd: Glass laser which provides an output energy of 30 J per pulse with pulse duration of 500 ps. The laser was incident on a 10 mm thick Al slab and focused to a spot size of 120 μm using an f/5 lens, yielding a peak intensity of 2×10^{14} W/cm^2. The experimental chamber was evacuated to a pressure 4×10^{-5} mbar. An X-ray crystal spectrometer using a Thallium Acid Phthalate (TAP) crystal placed at 45° with respect to laser axis was used for the line emission studies in spectral range of 5.5–7.5Å which enabled us to measure He-β, γ, δ, ε and H-like lines. These resonance lines are due to Al XII, Al XIII and Al XIV ions. Two stacked aluminized polycarbonate foils (Alexander Vacuum Research, Inc., trade name: B-10) having 1/e cutoff of 0.9 keV were used to prevent the scattered visible light from entering the plasma chamber. The TAP crystal spectrally resolves X-ray emission from the laser produced plasma, these reflected X-rays were detected by X-ray CCD camera (Model VISION 4M, from Rigaku innovative) having resolution of 25 mÅ. To obtain a wide range of X-ray energies, the spectrum crystal is mounted on a motorized Z-stage which can move up and down by 15 mm. By changing the height of the crystal with respect to the plasma we are able to cover a spectral range of 5.5–7.5Å. A schematic of the crystal spectrometer along with the experimental setup is shown in Fig. 1a. A sample image of one recorded X-ray spectrum is shown in Fig. 1b. The X-ray spectra were analyzed using a code developed by our group using Python software. To facilitate the angular distribution studies, the target was mounted on motorized X–Y–Z–θ stages. The angular distribution of K-shell resonance lines with associated its satellites and Al XII, Al XIII and Al XIV ions are studied by mounting the X-ray crystal spectrometer and Thomson parabola spectrometer (TPS) at 45° from the laser axis when target normal and laser axis are collinear. The TPS is kept fixed in position and the target is rotated to study the angular distribution of K-shell resonance lines. Care was taken to correct the irradiation profile after each rotation and the laser was s-polarized to negate any effects due to resonance absorption.

Two ion collectors are installed at an angle of 22.5° and 45° with respect to target normal to measure the ion temperature and plasma expansion velocity. The schematic of ion collector is shown in Fig. 1c. Our ion collector is the simplest and most common type of probe with a plane collector and a grid for ion and electron separation. The separation is done by means of a static field that exists between the grounded grid and the biased (negative) collector, which will solve the problem of the contribution of secondary electron emission and as the Faraday cup has a large area, it can be placed far away from the target to give better resolution. The grid also separates primary electrons from the ions to be measured. The ion collector signal can be written as

$$I_{coll}(t) = \frac{U_c(t)}{\left\{\varepsilon R_{load}\left[1+\frac{\bar{\gamma}(t)}{\bar{z}(t)}\right]\right\}} = \frac{ed[N(t)\bar{z}(t)]}{\bar{z}(t)} \quad (1)$$

where I_{coll} is the ion current in the entrance grid for a given moment, $\bar{\gamma} = \sum_j \gamma_j n_{i,j} / \sum_j n_{i,j}$ and $\bar{z} = \sum_j z_j n_{i,j} / \sum_j n_{i,j}$ are the average secondary ion electron emission coefficient and the average charge state of the ions, respectively, $n_{i,j}$ is the density of the jth ion species ($j=0$ corresponds to neutral particles), $U_c(t)$ is the voltage amplitude of the collector signal on oscilloscope, $N(t)$ is the number of ions reaching the charge collector and R_{load} is the load resistance, ε is transparency of entrance grid. The time distribution of ion charge Q can be written as

$$\frac{dQ}{dt} = \frac{ed[N(t)\bar{z}(t)]}{dt} \rightarrow I_{coll}(t) = \frac{U_c(t)}{\left\{\varepsilon R_{load}\left[1+\frac{\bar{\gamma}(t)}{\bar{z}(t)}\right]\right\}} \quad (2)$$

The factor $\left[1+\frac{\bar{\gamma}(t)}{\bar{z}(t)}\right] = 1.5$ for v $= 7 \times 10^6$ cm/sec),

$= 1.0$ for v $> 1 \times 10^7$ cm/sec,

and $= 0.5$ for intermediate velocity,

The ion velocity and energy were obtained by measuring the time of flight (TOF) spectrum of ions as shown in Fig. 1d. We have verified our measurement by comparing with the results from a TPS which provide energy spectrum of individual charge states of Al.