High Energy Density Physics 26 (2018) 73–80

Contents lists available at ScienceDirect

High Energy Density Physics

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

Properties of laser-produced GaAs plasmas measured from highly resolved X-ray line shapes and ratios

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ARTICLE INFO

Keywords:
X-ray spectroscopy
Plasma diagnostics
Laser-produced plasmas
Hard X-ray spectra

ABSTRACT

The properties of hot, dense plasmas generated by the irradiation of GaAs targets by the Titan laser at Lawrence Livermore National Laboratory were determined by the analysis of high resolution K shell spectra in the 9 keV to 11 keV range. The laser parameters, such as relatively long pulse duration and large focal spot, were chosen to produce a steady-state plasma with minimal edge gradients, and the time-integrated spectra were compared to non-LTE steady state spectrum simulations using the FLYCHK and NOMAD codes. The bulk plasma streaming velocity was measured from the energy shifts of the Ga He-like transitions and Li-like dielectronic satellites. The electron density and the electron energy distribution, both the thermal and the hot non-thermal components, were determined from the spectral line ratios. After accounting for the spectral line broadening contributions, the plasma turbulent motion was measured from the residual line widths. The ionization balance was determined from the ratios of the He-like through F-like spectral features. The detailed comparison of the experimental Ga spectrum and the spectrum simulated by the FLYCHK code indicates two significant discrepancies, the transition energy of a Li-like dielectronic satellite (designated *t*) and the calculated intensity of a He-like line (*x*), that should lead to improvements in the kinetics codes used to simulate the X-ray spectra from highly-charged ions.

1. Introduction

Spectroscopic diagnostic techniques have been developed for the detailed analysis of the H-like and He-like transitions and the associated Li-like dielectronic satellite transitions from hot laboratory and solar plasmas for the elements up to Fe [1–6]. The high resolution spectra were recorded by spectrometers utilizing Bragg reflection crystals. In this paper, the spectroscopic analysis techniques are extended to higher-energy spectra of the elements Ga and As, and the high resolution spectra were recorded by a transmission crystal operating in the Cauchois geometry.

The X-ray spectra were produced by irradiating GaAs wafer pieces using the Titan laser at Lawrence Livermore National Laboratory (LLNL). The laser pulse was designed to produce a relatively large steady-state thermal plasma with high ionization. The laser pulse had 1 µm wavelength, 3 ns duration, and was square in shape to reduce time-dependent effects. The focal spot was approximately 600 µm in diameter, the pulse energy was 770 J, and the average intensity in the focal spot was approximately 10^{14} W/cm^2. Phase plates were not used to smooth the focused intensity, and X-ray images indicated numerous small hot-spots distributed across the focal spot. The intensity in the hot-spots was at least several times higher than the average intensity, and this resulted in the generation of energetic non-thermal electrons during the laser-plasma interaction. The energetic electrons created 1 s vacancies and K shell X-ray transitions in the plasma ions and also propagated into the cold material outside the focal spot and generated characteristic K shell transitions from the neutral atoms.

An accurate energy scale was established from the well-known energies of the characteristic transitions in the cold (and stationary) Ga and As atoms outside the focal spot, and the transitions from the highly-charged plasma ions were found to be blue-shifted by the bulk non-thermal plasma motion toward the spectrometer. The electron density, electron temperature, non-thermal electron energy and fractional abundance, and ionization balance were determined by comparing the experimental and calculated spectral line ratios. After accounting for the spectral line broadening mechanisms, the turbulent plasma motion

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https://doi.org/10.1016/j.hedp.2018.02.002
Received 2 February 2018; Received in revised form 10 February 2018; Accepted 16 February 2018
Available online 17 February 2018
1574-1818/

was measured from the residual line widths. Thus a full range of plasma properties was determined from the high resolution K shell spectra.

The high resolution experimental spectra were compared to spectra simulated by the FLYCHK and NOMAD codes. The comparisons with the FLYCHK code revealed two significant discrepancies, the transition energy of one of the Li-like Ga dielectronic satellites (designated *t*) and the calculated intensity of one of the He-like Ga transitions (*x*). These results should enable the improvement of the kinetics codes used to simulate the K shell spectra from highly-charged ions.

2. Cauchois spectrometer

The spectrometer employed a transmission crystal in the Cauchois geometry [7] that was developed and tested at the National Institute of Standards and Technology (NIST) prior to the experiments at the Titan laser facility as described in [8]. The quartz crystal was 70 mm long, 40 mm wide, and 0.2 mm thick. The (101) planes were parallel to the 40 mm × 0.2 mm ends of the crystal slab, and the diffraction was from the (301) planes that were at an angle of 23.51° to the (101) planes. The crystal was bent to a 0.5 m radius of curvature, and the large convex surface of the crystal faced the X-ray source. The image plate detector was placed on the Rowland circle where the spectral lines are focused and source broadening is minimal. The energy coverage was tunable by rotating the crystal as described in [8].

A spectrum from a NIST electron-bombarded W source that was recorded using a source to crystal distance of 25 cm, the same distance used in the Titan experiments, is shown in Fig. 1. The spectrum covers the W Lβ characteristic transitions from the W anode, and the energy scale having estimated ± 0.1 eV uncertainty was established from the tabulated transition energies [9]. This enabled the accurate measurement of the spectral line widths and the spectrometer resolving power. The W $L\beta_3$ line, which is isolated and unblended by other Lβ transitions, is shown by the data points in Fig. 2(a). A Voigt profile was fitted to the W $L\beta_3$ data points using the least squares technique.

As listed in Table 1, the Gaussian and Lorentzian component full width at half maximum (FWHM) values were 4.82 eV and 12.80 eV with ± 0.01 eV one-sigma uncertainties, respectively. The difference between the fitted curve and the data points is at the 0.3% level as shown in Fig. 2(b). The Lorentzian width is dominated by the 12.8 eV ± 1.4 eV natural lifetime width [10,11]. Also contributing to the line broadening was the spatial resolution of the TR image plate that was used to record the spectrum. The spatial resolution of the TR image plate when scanned at NIST was previously measured from the edge spread function [12]. Using the 23.77 μm and 22.03 μm ± 0.1 μm FWHM values of the Gaussian and Lorentzian components multiplied by the 35.29 eV/mm dispersion, the contributions are 0.84 eV and 0.78 eV ± 0.01 eV, respectively. Subtracting the Lorentzian natural and TR contributions from the observed Lorentzian line width, the result is −0.78 eV ± 1.4 eV which is effectively zero within the uncertainty of the measurements. Subtracting in quadrature the Gaussian TR contribution from the observed Gaussian line width, the result is 4.75 eV ± 0.02 eV which represents the intrinsic crystal broadening, and the resolving power at the 9.819 keV energy of the W $L\beta_3$ line is 2,070. As discussed in [8], for this transmission-crystal geometry using asymmetric diffraction planes, the intrinsic crystal broadening primarily results from the thickness of the crystal, and other broadening contributions such as rocking curve width and geometrical mis-alignments are much smaller.

3. Experimental plasma spectra

The spectrometer was fielded in the Titan target chamber with the same 25 cm source to crystal distance and the same crystal rotation angle as during the earlier testing phase. As shown in Fig. 3, the spectrometer viewed the plasma at an angle of 40° to the incident laser beam. The target was a GaAs wafer piece that was 250 μm thick and approximately 3 mm in size. The target was rotated so that the spectrometer viewed at an angle of approximately 20° to the plane of the target. A collimator fabricated from Pb plates was placed between the crystal and the target, and strong permanent magnets were housed in the collimator to deflect energetic electrons away from the crystal. A debris shield, consisting of 125 μm thick polyimide film, was placed in front of the crystal. The initial spectra were recorded on a TR (tritium detection) image plate and had low counts in the spectral lines, and the subsequent spectra (analyzed here) were recorded on an MS (most sensitive) image plate; all image plates were scanned by the LLNL/Titan scanner.

Fig. 4 shows a typical spectrum, and the Ga and As spectral features are identified. Present in the spectrum are the well-resolved $K\alpha_1$ and $K\alpha_2$ characteristic transitions from the Ga and As atoms outside the focal spot as well as the Ga $K\beta_1$ and $K\beta_2$ transitions, and these six transitions were used to establish an energy scale having an estimated

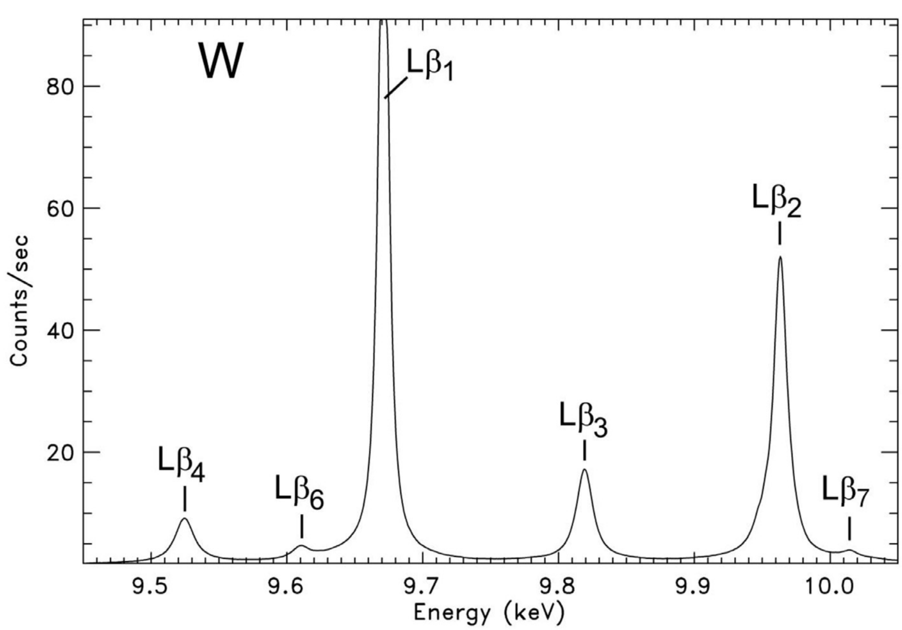

Fig. 1. Spectrum of the W Lβ lines recorded using a laboratory source.