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

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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 λ) 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.

Keywords

X-ray spectroscopy; Plasma diagnostics; Laser-produced plasmas; Hard X-ray spectra

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

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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 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 $\dot{t}$) 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 $\times$ 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 $L\beta$ 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 $L\beta$ 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 $12.8 \text{ eV} \pm 1.4 \text{ eV}$ 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 $23.77 \text{ }\mu\text{m}$ and $22.03 \text{ }\mu\text{m} \pm 0.1 \text{ }\mu\text{m}$ FWHM values of the Gaussian and Lorentzian components multiplied by the 35.29 eV/mm dispersion, the contributions are 0.84 eV and $0.78 \text{ eV} \pm 0.01 \text{ eV}$, respectively. Subtracting the Lorentzian natural and TR contributions from the observed Lorentzian line width, the result is $-0.78 \text{ eV} \pm 1.4 \text{ eV}$ 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 $4.75 \text{ eV} \pm 0.02 \text{ eV}$ 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 $250 \text{ }\mu\text{m}$ 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 $125 \text{ }\mu\text{m}$ 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 absolute accuracy of ± 0.5 eV. The identification of the spectral features from the highly-charged plasma ions was performed using simulated spectra from the FLYCHK code [13].

The resolving power of the spectrometer as fielded in the Titan target chamber was determined from the widths of the Ga and As $K\alpha_2$ transitions which are well isolated from other spectral lines. Voigt profiles were fit to the experimental lines, and the FWHM values of the Gaussian and Lorentzian components are listed in Table 1. The natural lifetime line widths (2.53 ± 0.33 eV for Ga $K\alpha_2$ and 3.04 ± 0.40 eV for As $K\alpha_2$) were subtracted from the measured Lorentzian widths. The spatial resolution of the MS image plate when scanned at the Titan facility with 25 μm steps was measured from the edge transfer function (ESF) recorded by directly exposing a Pb plate having a smooth edge to an irradiated GaAs target. The FWHM values of the Gaussian and Lorentzian components were $83.9 \mu\text{m} \pm 2.3 \mu\text{m}$ and $7.7 \mu\text{m} \pm 3.4 \mu\text{m}$, respectively, and these values were multiplied by the dispersion and were removed from the measured $K\alpha_2$ line widths. As listed in Table 1, the resultant Lorentzian widths were zero within the uncertainties in the measurements, and the resultant Gaussian widths are attributed to the intrinsic broadening by the diffraction crystal as fielded in the Titan target chamber. The intrinsic crystal broadening is Gaussian with FWHM values $5.14 \text{ eV} \pm 0.23 \text{ eV}$ derived from the Ga $K\alpha_2$ line and $5.11 \text{ eV} \pm 0.21 \text{ eV}$ derived from the As $K\alpha_2$ line. These values are slightly larger than the $4.75 \text{ eV} \pm 0.02 \text{ eV}$ intrinsic crystal broadening measured during the spectrometer testing phase, and the difference probably results from the relatively large Gaussian contributions (and uncertainties) from the spatial resolution of the MS image plate, a factor of 3 to 4 larger than the Gaussian component of the TR spatial resolution. In addition, the 4.75 eV measurement during the NIST testing phase is considered to have higher accuracy because of the controlled laboratory conditions and the much higher count level resulting from long spectrum integration time.

4. Ga He-like and Li-like spectrum analysis

The Titan spectra were initially analyzed by non-LTE steady state modeling of the Ga He-like transitions and the Li-like satellites using the FLYCHK kinetics code [13]. Numerous spectrum simulation runs were performed by varying the electron temperature, hot electron energy and fractional abundance, and electron density. Based on order of magnitude estimates of the electron temperature and density of expanding plasmas produced by the Titan laser, the electron temperature was varied from 900 eV to 2000 eV and the electron density from 10^{18} cm^{-3} to 10^{20} cm^{-3} . Based on the estimated 10^{15} W/cm^2 hot-spot intensity and the formula in [14] for the hot electron energy generated during the laser-plasma interaction, the hot electron energy was varied from 30 keV to 70 keV and the fractional abundance up to 0.04.

Opacity effects are negligible owing to the large transition energies (9.5 keV to 9.7 keV) and fast radiative decay rates of the Ga He-like and Li-like transitions. Over the range of assumed electron density and temperature, Stark broadening is also negligible. It is assumed

that the electron and ion temperatures are equal owing to the fast electron-ion equilibration time (less than 1 ps).

Fig. 5(a) compares the experimental spectrum produced by the plasma's Li-like and He-like Ga from 9.54 keV to 9.64 keV with the spectrum calculated by FLYCHK normalized to the strongest transition. The experimental spectrum was derived by subtracting the background produced by the numerous blended transitions from the lower charge states as seen in Fig. 4. The experimental spectrum is blue shifted with respect to the energy scale established by the Ga and As characteristic transitions from the cold and stationary atoms outside the focal spot. In Fig. 5(b) the experimental spectrum is shifted by -10 eV and is in good agreement with the simulated spectrum. The 10 eV shift results from the bulk plasma motion toward the spectrometer with velocity 3.1×10^7 cm/s which is reasonable for the hydrodynamic expansion of a laser-produced plasma. The simulated spectrum was not shifted because of the high accuracy of the FLYCHK calculated energy of the Ga He-like $1s^2 \ ^1S_0 - 1s2p \ ^1P_1$ resonance transition (labeled *w* in Fig. 5), 9628.4 eV as compared to the previously calculated value 9628.2 eV [15] and the previous experimental value 9627.5 ± 0.7 eV [16].

The spectrometer's high resolution enables the identification of numerous He-like transitions and Li-like dielectronic satellites as indicated in Fig. 5 where the transition designations are from [1]. The vertical dashed lines below the spectra indicate the FLYCHK calculated transition energies and intensities. A Voigt profile was convolved with each spectral line which included the effects of Gaussian intrinsic crystal broadening, Gaussian and Lorentzian MS detector broadening, Lorentzian lifetime broadening derived from the radiative decay rates, and Gaussian ion temperature broadening (assuming the ion temperature is equal to the electron temperature). The most intense peak of the calculated spectrum was normalized to the corresponding peak of the experimental spectrum.

In Fig. 5(b), two discrepancies are apparent near the Li-like satellites *t* and *m* and the He-like transition *x*. Comparison of the FLYCHK satellite energies with those calculated by the Cowan code [17] indicates good agreement except for the satellite *t* which in the Cowan code has 0.7 eV higher energy than *m*. By placing the *t* satellite 0.7 eV on the high-energy side of *m* and arbitrarily increasing the *x* intensity by a factor of 2, the simulated FLYCHK spectrum is in excellent agreement with the experimental spectrum as shown in Fig. 5(c). The Li-like *t* transition is $1s^2 2s \ ^2S_{1/2} - 1s2p2s \ (^3P)^2P_{1/2}$ and the *m* transition is $1s^2 2p \ ^2P_{3/2} - 1s2p^2 \ ^2S_{1/2}$. The $1s^2 \ ^1S_0 - 1s2p \ ^2P_2$ He-like *x* transition is an M2 type transition with enhanced intensity resulting primarily from electron-collisional population transfer from other singly-excited He-like levels.

After the corrections were made to the *t* and *x* transitions calculated by the FLYCHK code, each simulated Ga spectrum, calculated with variable electron temperature, electron density, and hot electron component, was compared to the experimental spectrum. The Pearson correlation coefficient is calculated for the two spectra, and the correlation for the case of 50 keV hot electron energy and 0.02 fractional abundance is shown in Fig. 6. In general, for fixed hot electron energy and abundance, the correlation is a strong function of the electron temperature and a weaker function of the electron density. The best-fit electron temperature tends to decrease with increasing hot electron energy and abundance. The highest correlation

occurred for the following plasma properties with fitting uncertainties: $1100 \text{ eV} \pm 100 \text{ eV}$ electron temperature, $1 \times 10^{19} \text{ cm}^{-3} \pm 50\%$ electron density, $50 \text{ keV} \pm 20 \text{ keV}$ hot electron energy, and 0.015 ± 0.005 fractional abundance. The spectrum calculated with these optimum plasma parameters is shown in Fig. 5.

Using the NIST continuous slowing down model for the propagation of energetic electrons through solid-density materials [18], the range of 50 keV electrons in solid-density GaAs is $22 \text{ }\mu\text{m}$. Thus the hot electrons are created in the focal spot by the interaction of the laser irradiation with the plasma, propagate through the plasma, and generate 1 s vacancies and K shell radiation in the highly-charged ions in the 1100 eV thermal plasma as well as additional ionization of outer-shell electrons. The 50 keV electrons also propagate into the solid-density GaAs outside the focal spot and generate 1 s vacancies in the neutral atoms and characteristic X-ray transitions. There is a blue Doppler energy shift of the transitions from the plasma ions, with respect to the energy scale based on the characteristic transitions in the stationary Ga and As atoms in the cold material outside the focal spot, of 10 eV and corresponding to plasma ion motion of $3.1 \times 10^7 \text{ cm/s}$ toward the spectrometer.

We note that in experiments using more intense Titan laser irradiation (up to 10^{21} W/cm^2), shorter pulse duration ($< 10 \text{ ps}$), and metal targets in the range of Ag to Au, the hot electron energy inferred from the K shell transitions exceeded 80 keV, and the spectra were dominated by the characteristic K shell transitions from the cold atoms and the K shell transitions from highly-charged plasma ions were absent [19]. In experiments using the LULI PICO2000 laser having 1 ps pulse duration and focused to an intensity of 10^{20} W/cm^2 , the spectra from the elements in the range Pd to W indicated hot electron energies up to 1 MeV [20]. Thus depending on the purpose of the experiment, the laser focused intensity and pulse duration are selected to produce mostly transitions from thermally-generated plasma ions (lower focused intensity and longer pulse duration), to produce mostly transitions from neutral atoms generated by the high-energy electron component (high focused intensity and short pulse duration), or to intermediate intensity and pulse duration values to produce transitions from both the thermal plasma ions and the neutral atoms as was done in the present experiment.

5. Ga spectral line shapes

The spectral features resulting from K shell transitions in the plasma ions are typically blends of numerous transitions, and the widths and shapes of the spectral features primarily result from the spread in energy of the transitions that contribute to the spectral feature. This is especially true of the spectral features from the Li-like through F-like ions. In the case of the He-like ions, there are only three intense transition w , x , and y using the letter designations of [1]. The w resonance transition is blended with nearby Li-like satellites having an $n = 3$ vacancy [6], the y transitions is blended with Li-like transitions, and only the x transition is separated from satellite transitions except for the m,t transitions. Thus only the x and m,t spectral features are useful for the determination of plasma properties from the individual spectral line widths.

Two Voigt profiles were fitted to the Ga x and m,t spectral features as shown in Fig. 7, and the measured FWHM values of the Gaussian and Lorentzian components are listed in Table 2. The natural lifetime widths calculated from the radiative decay rates are 0.001 eV for x and 0.31 eV for the m,t spectral feature. The lifetime widths and the MS detector Lorentzian widths were subtracted from the measured Lorentzian widths, and the resulting Lorentzian widths were essentially zero within the uncertainties. Subtracted in quadrature from the measured Gaussian widths are the intrinsic crystal broadening, the MS detector Gaussian broadening, and the ion Doppler broadening (calculated assuming the ion temperature is equal to the 1100 eV electron temperature). The residual Gaussian FWHM values are $0.44 \text{ eV} \pm 0.39 \text{ eV}$ for the m,t spectral feature and $2.05 \text{ eV} \pm 0.39 \text{ eV}$ for the x transition. These small but significant residual Gaussian broadenings can be attributed to a small turbulent spreading ($1 \times 10^6 \text{ cm/s}$ and $6 \times 10^6 \text{ cm/s}$) in the $3.1 \times 10^7 \text{ cm/s}$ bulk plasma velocity toward the spectrometer.

6. Simulated spectra of the lower charge states of Ga and As

The FLYCHK code uses detailed atomic level structures for the He-like and Li-like energy levels and processes, and the calculated non-LTE steady state spectra are known to have high accuracy [13]. For the lower ionization states, a hydrogenic approximation is used to generate super-configuration arrays, and the calculated spectra do not have high accuracy. Thus it is not possible to accurately analyze the spectra from the lower Ga and As ionization stages (Be-like and lower) using the FLYCHK code.

The modeling of the experimental spectra was performed for the energy ranges between 9.30 keV to 9.65 keV for Ga and 10.50 keV and 10.90 keV for As (see Fig. 4) with the collisional-radiative code NOMAD [21]. The atomic data for NOMAD simulations were generated with the relativistic Flexible Atomic Code (FAC) [22] in the relativistic configuration approximation. For both elements the ionization stages from Mg-like to H-like ions were included with the total number of states per element of about 8500 which provided a sufficiently detailed description of both singly-excited and autoionizing states. The plasma was assumed to be optically thin and uniform.

The comparison between experimental and theoretical results proceeded in two steps. First, a wide Gaussian background was subtracted from the experimental spectra in order to emphasize strong spectral features. Then the measured integrated intensities of those features were least-square fitted against calculated intensities while varying plasma parameters such as electron temperature T_e , electron density n_e , temperature of the second Maxwellian (hot electrons) T_2 , and its fraction f_2 in a wide range. In addition to natural, Doppler, and Stark broadening, the theoretical spectra were additionally broadened with a Gaussian function of FWHM of 14 eV.

Fig. 8 presents comparisons of the best NOMAD simulations with the measured spectra of Ga (top) and As (bottom) from Fig. 4. While the positions of theoretical and experimental spectral features agree very well for As, there is a small blue shift of less than 10 eV for the measured Ga spectra. Nonetheless, the general agreement between simulations and measurements is good, especially for the strongest peaks and for the higher energies. The

lower-energy experimental spectra are due to emission from lower ionization stages that may come from other plasma volumes due to plasma non-uniformity. In addition to the total bound-bound spectrum (solid red line), Fig. 8 (bottom) also presents contributions from different ions of As. This shows that the strong features in the experimental spectrum are actually due to the similar magnitude contributions from the neighboring ions rather than from a single ionization stage. Another interesting feature of these non-Maxwellian spectra is that the strongest peaks, e.g., near 10.65 keV and 10.70 KeV for As, do not originate from the most abundant ionization stages. As shown in Fig. 8, these two peaks are primarily due to emission from N-, C-, and B-like ions with ion charges from 26 to 28. However, as follows from the calculated ionization distribution for the same plasma condition (see the inset in Fig. 8), the most populated ions are F-like ($z = 24$) and O-like ($z = 25$).

Our simulations also show that the calculated spectra display significant sensitivity to T_e as well as to T_2 and f_2 . On the other hand, their dependence on the electron density is rather weak because of the nearcoronal ionization balance. The dashed line in the top of Fig. 8 shows Ga calculations with $n_e = 10^{19} \text{ cm}^{-3}$ as compared with the $n_e = 10^{20} \text{ cm}^{-3}$ case (solid line). Indeed, the change in the spectrum is very minor.

7. Discussion

The experimental demonstration of high-resolution transmission crystal spectrometers operating in the hard X-ray region ($> 10 \text{ keV}$) has enabled the implementation of K shell spectroscopic techniques for the diagnosis of hot, dense plasmas composed of highly-charged ions of heavy elements (atomic number 31 and larger). The newly developed spectrometers employ a transmission crystal in the Cauchois geometry and utilize asymmetric diffraction, that is from planes that are not perpendicular to the crystal surface. The energy coverage is tunable by rotating the crystal, and the 2d lattice spacing and the crystal thickness are selected based on the desired dispersion, intrinsic crystal resolving power, and throughput.

The intrinsic crystal resolving power is sufficient to resolve the He-like through F-like spectral features, and in particular the He-like transitions and Li-like satellites having line ratios for determining the electron temperature, hot electron energy and abundance, and electron density. The resolution of isolated spectral lines enables the analysis of Doppler energy shifts resulting from bulk plasma motion and turbulence and potentially the analysis of ion thermal Doppler broadening. In addition, the detailed comparison of the experimental spectral line ratios with the simulated spectra provides validation of the atomic kinetics codes.

Utilizing high-resolution diffraction from the (301) asymmetric planes of a quartz crystal, the K shell diagnostic techniques were applied to the spectra from GaAs targets irradiated by the LLNL Titan laser. The electron temperature and hot electron component, electron density, and plasma bulk motion and turbulence were measured from the spectral line ratios and line widths. There are significant differences between the electron temperature derived from the He-like and Li-like line ratios and the line ratios of the lower ionization stages Be-like through F-like, 1100 eV and 1400 eV, respectively. These differences may result from

temperature and density inhomogeneities in the plasma as well as time dependent effects. In addition, the subtraction of the background, and the measurement of the line ratios above the background, is a rather subjective process. These uncertainties can be mitigated by recording time-resolved spectra and by using a spectrometer with higher spectral resolution.

This demonstration of K shell spectroscopic diagnostic techniques indicates the potential for the development of higher energy and higher resolution transmission-crystal spectrometers that can diagnose hotter and denser plasmas produced by higher energy lasers. In particular, the ability to distinguish the ion thermal Doppler broadening from other line broadening mechanisms such as turbulence broadening and Stark broadening, for example in dense plasmas such as in Kr-doped capsules, has driven the requirement for high resolution spectrometers ($> 10,000$ resolving power) at large laser facilities such as the National Ignition Facility [23]. A transmission-crystal spectrometer using asymmetric diffraction planes similar to the one used in the present GaAs experiment and having 12,000 intrinsic resolving power (and potentially as high as 20,000 resolving power) was recently experimentally developed [24] for future laser-produced plasma experiments.

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

Fig. 2.

(a) Voigt profile (curve) fitted to the experimental (data points) W L β_3 line. (b) Difference between the fitted Voigt curve and the data points.

Fig. 3.
Schematic of the spectrometer and the experimental setup.

Fig. 4.
Spectrum from the GaAs target.

Fig. 5.

(a) Comparison of the Ga He-like and Li-like calculated FLYCHK spectrum (curve) with the experimental spectrum (data points). (b) Same comparison after shifting the experimental spectrum energy by -10 eV. (c) Same comparison after moving the calculated Li-like t satellite line to a position 0.7 eV on the high-energy side of the m satellite and multiplying the x intensity by a factor of 2.

Fig. 6. Logarithmic plot of the correlation between the experimental and calculated Ga He-like and Li-like spectra while varying the electron temperature and density in the calculation.

Fig. 7.
 (a) Two Voigt profiles (curve) fitted to the experimental (data points) Ga Li-like m,t satellite feature and the He-like x transition. (b) Difference between the fitted Voigt curve and the data points.

Fig. 8.

Comparison of measured and calculated spectra for Ga (top) and As (bottom) for $T_e = 1400$ eV, $T_2 = 30$ keV, and $f_2 = 5\%$. Solid lines in both plots are for $n_e = 10^{20} \text{ cm}^{-3}$, and dashed line for Ga is for $n_e = 10^{19} \text{ cm}^{-3}$. The different colored narrow spectral features for As correspond to contributions from different ionization stages before additional broadening (see text). The inset in the bottom plot shows ionization balance for the 10^{20} cm^{-3} case for As.

Table 1

Voigt component widths of the W L₃ and the Ga and As K α ₂ transitions.

	W Lβ3	Ga Kα2	As Kα2
Lorentzian	FWHM (eV)	FWHM (eV)	FWHM (eV)
Measured	12.80 ± 0.01	2.71 ± 0.04	3.45 ± 0.01
Lifetime	12.8 ± 1.4	2.53 ± 0.33	3.04 ± 0.40
Detector	0.78 ± 0.01	0.24 ± 0.11	0.30 ± 0.13
Resultant	-0.78 ± 1.4	-0.06 ± 0.48	0.11 ± 0.54
Gaussian	FWHM (eV)	FWHM (eV)	FWHM (eV)
Measured	4.82 ± 0.01	5.78 ± 0.03	6.08 ± 0.01
Detector	0.84 ± 0.01	2.65 ± 0.20	3.29 ± 0.20
Crystal	4.75 ± 0.02	5.14 ± 0.23	5.11 ± 0.21

Table 2Voigt component widths of the m,t and x spectral features.

	m,t	x
Lorentzian	FWHM (eV)	FWHM (eV)
Measured	0.41 ± 0.10	0.01 ± 0.10
Lifetime	0.31	0.001
Detector	0.26 ± 0.12	0.27 ± 0.12
Resultant	-0.16 ± 0.22	-0.26 ± 0.22
Gaussian	FWHM (eV)	FWHM (eV)
Measured	6.30 ± 0.10	6.61 ± 0.10
Crystal	4.75 ± 0.02	4.75 ± 0.02
Detector	2.89 ± 0.20	2.89 ± 0.20
Thermal	2.93 ± 0.07	2.93 ± 0.07
Resultant	0.44 ± 0.39	2.05 ± 0.39