Effect of Velocity Gradients on X-Ray Line Transfer in Laser-Produced Plasmas

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Resonance lines of hydrogenlike aluminum ions emitted from a high-power laser-produced plasma have been recorded using a novel ultrahigh-resolution double-crystal x-ray spectrometer. The resolution provided by this instrument allows, for the first time, well resolved emitted line profiles and positions to be measured as a function of observation angle. Interpretation of the measured line shapes, positions, and intensities requires simulations which include the transfer of radiation in a plasma with a large velocity gradient.

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During the expansion of high-power laser-produced plasmas (LPPs) very large velocity gradients are produced of, typically, $10^9\ s^{-1}$. These gradients increase the probability of escape of x-ray resonance line photons because of the Doppler-decoupling mechanism. The mechanism is an important contributor to the successful operation of recombination-pumped extreme ultraviolet (XUV) lasers [1–8] because reabsorption of the resonance line photons pumps the lower laser level, reducing the population inversion. Enhanced probability of escape due to high velocity gradients is also found in astrophysical plasmas, and many workers (starting with Sobolev [9–15]) have tried to calculate line transfer in this situation.

Previous workers have viewed LPPs parallel and perpendicular to the laser beam in the soft XUV regime, but these experiments are dominated by two dimensional effects, and no detailed comparisons with sophisticated radiation transfer models have been attempted. Data obtained observing parallel to the laser have yielded bulk Doppler shifts, but, again, little information on line transfer [16–18]. The effect of observation angle on relative intensity in the soft x-ray (keV) regime has also been investigated, but the resolution was insufficient to record the effect on line shapes and positions [19]. More recently it has been noted that the range of Doppler shifts due to the velocity gradient in a LPP broaden and shift the peak of optically thick lines, though these XUV measurements were made with comparatively poor spectral resolution ($\lambda/\Delta\lambda \sim 1700$), and no absolute shifts in the peak of the lines could be inferred [20].

We describe here the first experiments to measure with high resolution the line shape, intensity, and position of an x-ray resonance line emitted by a laser-produced plasma as a function of observation angle. These line features can only be understood by considering the transfer of radiation through the plasma with its high velocity gradient. We have performed simulations showing that the combination of the velocity gradient (which alters the escape factor), the emission and absorption profile as a function of distance from the target surface, and the position-dependent line broadening mechanisms conspire to produce asymmetric line shapes, the intensity and position of which are a strong function of observation angle. Experimental observations of these angle-dependent features using a novel x-ray spectrometer show remarkable agreement with calculations. We describe first the experimental arrangement and results and go on to describe the numerical model used to simulate the experiment.

The measurements were obtained by use of the vertical dispersion variant of the double-crystal spectrometer (DCS). The DCS, described in detail elsewhere [21–23], is a two-crystal instrument with extremely high spectral resolution and dispersion. For these experiments we calculate a spectral resolution of 6400, and a dispersion of 6.4 $\mathrm{m\AA\,mm^{-1}}$ at line center on film at a distance of 10 cm from the source. The DCS also affords a degree of spatial resolution in a direction perpendicular to the dispersion plane, which in this case was 7 μm. More detailed information about the theory of the instrument can be found in the work of Renner and Kopecky [21].

The experiment was performed using the neodymium glass laser VULCAN at the Rutherford Appleton Laboratory. A single beam containing 80 J of 0.53 μm light in a pulse of 1.2 ns (FWHM) was incident normally onto a 10 μm thick 500 μm diameter aluminum foil. The focal spot diameter on target was 200 μm, giving an incident intensity of $3\times10^{14}\ \mathrm{W\,cm^{-2}}$.

The experimental arrangement is shown schematically in Fig. 1. The DCS was fitted with two ADP crystals ($2d = 10.64$ Å). It was mounted on a rotation stage whose axis of rotation was aligned with the center of the aluminum foil to within $\pm 30\ \mu$m. The line shifts were measured in the following way. A series of laser shots was taken with a given laser energy and focal spot size. For each shot in the series, the angle between the DCS and the incident laser (the angle ψ in Fig. 1) was varied

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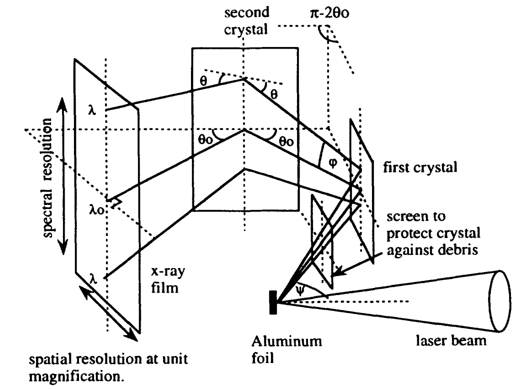

FIG. 1. A schematic diagram of the experiment. The CDS disperses the x rays in the vertical direction, while yielding spatial resolution at unit magnification perpendicular to the dispersion direction. For each laser shot the instrument was rotated coaxially around the aluminum foil, altering the angle of observation with respect to the laser beam, ψ. The x-ray line, of wavelength λ, is recorded on both sides of a central point shown as λ_0, and is defined by $\lambda = \lambda_0 \cos\varphi$. Refer to Ref. [21] for further details of the instrument.

by rotating the instrument around the axis containing the target, and the x-ray film holder was moved transversely by approximately 2 mm, keeping the total target-to-film distance constant. The data were recorded on Kodak Industrex-C x-ray film.

Shifts in the recorded hydrogenic Ly-α resonance line ($1s\,^2S$-$2p\,^2P$) due to errors in target-to-film distance are negligible due to the high dispersion of the instrument—a combination of the 30 μm difference between rotation axes, and an estimated maximum error of 200 μm due to film shift gives rise to an error of only 0.2 mÅ. Furthermore, for the final shot of each series of laser shots we returned the spectrometer to its original angle with respect to the laser beam. In every case no detectable difference between the line positions of the first and last shot was found.

Figure 2(a) shows the spectra recorded from Al Ly-α for various angles of observation with respect to the laser beam. Film density has been converted to intensity by use of an unpublished calibration curve. The lineouts are taken from a 25 μm spatially resolved region in the center of each of the emission profiles. The variation in laser energy over the shot series was measured to be less than $\pm 10\%$. It can be seen that as the emission is viewed from angles where the plasma has a component of velocity towards the spectrometer (i.e., 30° and 60° with respect to the laser beam) there is an increase in the wavelength of the peak of the emission consistent with Doppler motion away from the target. For the 150° and 180° data (i.e., observing the emission through the target towards the laser beam) the target was 1 μm Al coated on 10 μm plastic $(CH)_n$. For these data the reduction in intensity due to the x rays passing through the cold, unablated portion of the target has been removed. The line is

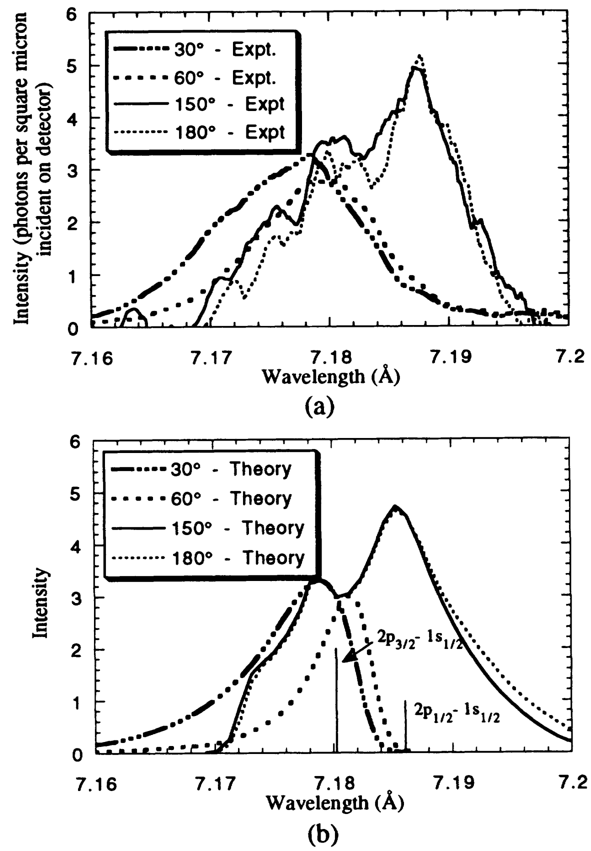

FIG. 2. (a) The measured $1s\,^2S$-$2p\,^2P$ spectral line of hydrogenic aluminum for various observation angles with respect to the laser beam and (b) MEDUSA simulations. The 30° simulated intensity has been normalized to the 30° data, although the two agree absolutely to within a factor of 2.

seen to be redshifted. Although the DCS does not record the absolute wavelength, the relative shifts and intensities shown in Fig. 2(a) are recorded accurately by the instrument. The absolute wavelength in Fig. 2(a) has been set by comparison with the simulated data described below.

Analysis of the spatially resolved emission away from the target surface shows it falls to a half intensity point at a distance ~0.5 of the focal spot diameter away from the surface, indicating that the data should be quasi 1D. The numerical model used to simulate the experiment is based on a modified version of the 1D Lagrangian hydrodynamic code MEDUSA which includes time-dependent average-atom nonlocal thermodynamic equilibrium atom physics [24]. The effect of optically thick line reabsorption on level populations is taken into account by use of escape probabilities which include the effect of the large velocity gradient [24] (an approximation which is in good agreement with detailed line transfer calculations [7]). This part of the calculation provides densities, temperatures, velocities, and ionic populations in each Lagrangian cell. A detailed multifrequency line transfer model in the laboratory frame is then used to calculate the observed hydrogenlike Lyman-doublet line emission. Within each cell in which the photons originate, the model calculates the population in the $2p_{1/2}$ and $2p_{3/2}$ states from the average-atom populations using the technique described in [24] together with the assumption of statistical equilibrium between all the $n=2$ levels. Absorption profiles in one cell are Doppler shifted relative to the emission profiles in a different cell because of the velocity difference between the cells. A Doppler profile is used for each component of the doublet with a width calculated from the ion temperature predicted by MEDUSA. Simulations show that the effect of using Voigt or Stark profiles, which include the effects of electron collisional lifetime and Stark broadening, is negligible. A more detailed description of this model is currently being prepared for publication elsewhere, although it is similar in principle to techniques used by others to predict realistic line shapes in laser-produced plasmas [20].

The results of the simulations at an absorbed irradiance of 10^{14} W cm^{-2} are shown in Fig. 2(b). The absolute predicted and observed intensities agree to within approximately a factor of 2. It can be seen that there is remarkable agreement with the experimental data. The unshifted line positions of the doublet are shown. The code predicts the maximum ion temperature of the emitting plasma to be $\sim$700 eV, leading to a thermal Doppler broadening of 2.8 mÅ (FWHM); the linewidths and shifts observed are much larger than this, demonstrating the importance of bulk Doppler motion. The simulations also show that for the front side emission (observation angles of 30° and 60°) the red side of the line is relatively independent of observation angle, whereas the blue is not. Furthermore, the relative position, intensity, and degree of line reversal in the rear side (150° and 180°) data are also in excellent agreement. More detailed analysis of these data is the subject of further work, although the excellent agreement between code and experiment at this stage is encouraging. We believe the discrepancies between code and experiment in the slopes of the red side of the line are because the experiment is not purely one dimensional. This issue will be addressed more fully in a future publication.

The code predicts that at the time of peak emission, at the unshifted position of the peak of the $2p_{3/2}$-$1s_{1/2}$ component, the maximum optical depth normal to the target surface is 9 when absorption by the $2p_{1/2}$-$1s_{1/2}$ component is included, and only 6 if not. If the Doppler decoupling is not taken into account the optical depth increases to 36. The predicted velocity gradient at this time in a direction normal to target surface is 4×10^9 s^{-1}. Simulations show that the angle dependent line shape and intensity are sensitive to the irradiance on target, and hence the resultant velocity gradient. Of the simulations performed, only those close to the experimental absorbed irradiance match both the experimentally observed intensity and line shapes. Calculations for a static plasma show markedly different line shapes from those observed. Thus the effect of velocity gradients is critical to the observations. Artificially setting the escape factor to unity in the average atom model results in a lower population of the upper level of the transition and a reduction in intensity by a factor of about 12, whereas the absolute experimental intensities are within a factor of 2 of the calculated values with the escape factor included in the calculation of the ionic populations.

In conclusion, this work shows the first high-resolution spectra of line profiles and relative positions in an expanding laser-produced plasma as a function of observation angle. The peak positions, intensities, and salient features of the measured line profile, requiring experimental spectral resolution in excess of 6000, can only be simulated by accounting for the Doppler shift of the expanding material in the calculation of radiation transfer, and absolute intensities are consistent with the escape factor approximation; such results cannot be obtained by simply using models based on homogeneous slabs of plasma.

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