

X-ray-line self-absorption and electron density determination in a laser-created plasma

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By use of a suitable target geometry, self-absorption of x-ray lines has been evidenced and measured in a laser-created aluminum plasma. Solution of the radiative-transfer equation allows inference of optical depth and electron density from plasma-expansion data.

X-ray spectral investigation has been widely used to diagnose hot and dense plasmas¹ which are to be considered as not optically thin. Knowledge of line self-absorption is essential to the interpretation of experimental spectra, giving access to plasma parameters,² such as the areal density (ρR) in imploded microballoons.³ The present paper reports a special experiment in which the target geometry⁴ allows us to measure opacity and to infer optical depths and electron density.

The experiments were performed with a Nd laser delivering 50 J in 800 ps. The beam was focused onto a thick extensive planar silica target in which a small bar of aluminum had been embedded, Fig. 1. SiO_2 and Al were chosen because of their similar initial densities and nuclear charges ensuring nearly identical hydrodynamical behaviors; therefore, aluminum is kept within silica during the plasma expansion.⁵ The Al bar was 500 μm in length, 45 μm in width, and 1 μm in thickness, which is much larger than the ablation depth.⁶ The focal laser spot (diameter of 350 μm) was centered on the bar. The mean laser irradiance reached $6 \times 10^{13} \text{ W cm}^{-2}$.

As we were concerned with x-ray emission and absorption, the plasma radiation was analyzed by means of two identical spectrographs in the two main directions of the aluminum bar: transverse (T) and longitudinal (L), Fig. 1. The spectral dispersion was achieved through the use of flat TIAP crystals, and each spectrograph was equipped with a

15- μm -width slit providing a spatial resolution along the direction of the plasma expansion; spectra were recorded on Kodirex films.

Figure 2 shows spatial dependence of energies emitted in the main K lines of H and He-like Al ions viewed in the (L) and (T) directions versus the distance from the initial target position. In a first analysis, it is clearly seen that resonance lines ($1s-2p$, $1s^2-1s2p$) are self-absorbed in the longitudinal direction. For the other lines self-absorption is minimal, as the underdense plasma is almost optically thin, except near the target. We have not measured the $1s^2-1s3p$

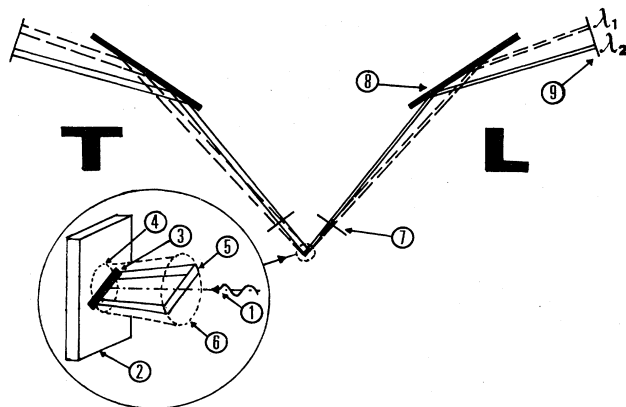


FIG. 1. Experimental setup: ① laser beam; ② silica target; ③ small bar of aluminum; ④ focal spot; ⑤ aluminum plasma; ⑥ silica plasma; ⑦ spatial resolution slit; ⑧ TIAP crystal; ⑨ film.

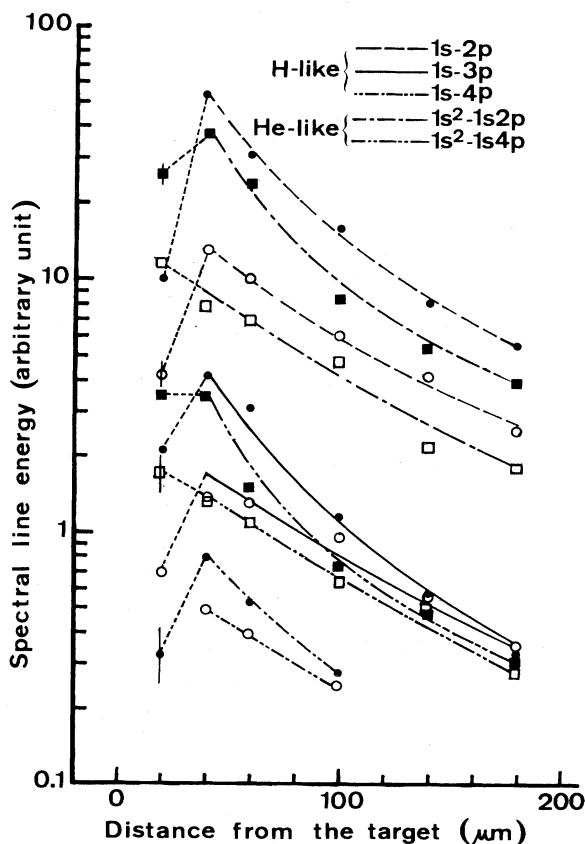


FIG. 2. Energy of aluminum lines E_0 vs the distance from the target. Solid points are transverse measurements and open points longitudinal measurements.

line because of mixing with the $1s^2-1s2p$ Si line. The reduction of line intensity observed close to the target might be due to the effects of a rapid drop in plasma temperature and of the absorption by a cold dense plasma formed by the focal spot wings.

An interpretation of the results can be done through the solution of the radiation transfer equation assuming that the plasma is homogeneous in temperature and in total ion density along the two lines of sight. Also assuming an identical spectral profile P_ν for emission and absorption and neglecting induced emission we deduce the total energy E_0 of a line of frequency ν_0 emerging out of a plasma of length X , of surface dS in a solid angle $d\Omega$:

$$E_0(X) = dS d\Omega \frac{e\nu_0}{k\nu_0} \int [1 - \exp\{-\tau_{\nu_0}(X)P_\nu/P_{\nu_0}\}] d\nu, \quad (1)$$

where ϵ_{ν_0} , k_{ν_0} , and $\tau_{\nu_0}(X) = k_{\nu_0}X$ are, respectively, the emissivity, the absorption coefficient, and the optical depth at the line center. Though the plasma is homogeneous, the population of the excited states can depend on the photon density if there is absorption. Nevertheless, because of the particular geometry, the aluminum plasma is practically optically thin in one dimension (T). Therefore collisional excitation prevails over photoexcitation. So, the choice of a uniform source function $\epsilon_{\nu_0}/k_{\nu_0}$ is justified in a first analysis.

In the experimental density and temperature ranges, line broadening is essentially due to Doppler and quasistatic Stark effects. So, we approximate the resulting profile as the convolution of Gaussian and Holtsmarkian⁷ profiles whose full widths at half maximum (FWHM) are⁸

$$\Delta\nu_G = \nu_0(2kT_i/Mc^2)^{1/2}, \quad (2)$$

$$\Delta\nu_H \approx (6.64\hbar z_p^{1/3}/\pi m z_e)(n_i^2 - n_f^2)N_e^{2/3},$$

where z_p and z_e are, respectively, the charges of the perturber and of the emitter, n_i and n_f are the quantum number of the initial and final states, M is the ion mass, N_e is the electron density, and T_i is the ion temperature. Then the line profile can be written as

$$P_\nu = \frac{0.711}{\Delta\nu_H} \int_{-\infty}^{\infty} \frac{\exp(-2.77x^2)dx}{1 + [2|rx - (\nu - \nu_0)/\Delta\nu_H|]^{5/2}}, \quad (3)$$

where $r = \Delta\nu_G/\Delta\nu_H$ is the convolution parameter.

As the point of interest is absorption, we consider the ratio of the energies $E_0(L)$ and $E_0(l)$, where L and l are the plasma lengths in longitudinal and transverse directions, respectively; from (1) and (2), this ratio depends only on r , $\tau_{\nu_0}(L)$, and on the length ratio L/l ,

$$\frac{E_0(L)}{E_0(l)} = \frac{l}{L} \frac{\int [1 - \exp\{-\tau_{\nu_0}(L)P_y/P_{y0}\}] dy}{\int [1 - \exp\{-\tau_{\nu_0}(L)P_y l/P_{y0}L\}] dy}, \quad (4)$$

where $y = (\nu - \nu_0)/\Delta\nu_H$.

Figure 3 shows this dependence for $L/l = 8$ (deduced from the initial dimensions of the aluminum plasma). Note that a Holtsmarkian profile ($r=0$) is less absorbed than a Gaussian one ($r=\infty$) for the wings of the former spread farther.

For an experimental value of the line energy ratio (Fig. 2), we deduce from Fig. 3 a set of couples $\{\tau_{\nu_0}(L), r\}$ that are compared to the theoretical one, knowing that

$$\tau_{\nu_0}(L) = \pi r_0 c f N_e \theta L P_{\nu_0} / \langle z_p \rangle \quad (5)$$

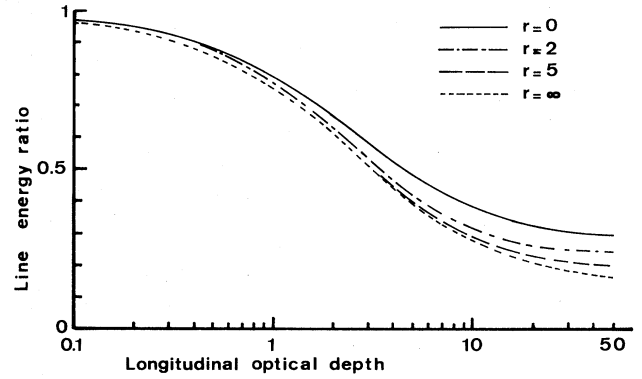


FIG. 3. Theoretical value of $E_0(L)/E_0(l)$ vs the longitudinal optical depth $\tau_{\nu_0}(L)$ for different values of the convolution parameter r and for $L/l = 8$.

where r_0 is the classical electron radius, f is the oscillator strength of the transition, and θ the relative abundance of the emitting ion.

The procedure used is the following: As electron density is low in plasma expansion, T_e and θ are deduced in a first step from nonabsorbed lines (i.e., $1s-3p$; $1s^2-1s4p$) by using a coronal ionization model, Fig. 4; expecting T_i equals T_e in the analyzed plasma region T_i and θ are introduced in Eqs. (2), (3), and (5). So, only one value of the density allows the fitting of experimental and theoretical ratios $E_0(L)/E_0(l)$. Secondly we check the coronal temperature to be in good agreement—mostly with an accuracy better than 10%—with the temperature picked out of a collisional-radiative ionization equilibrium model.⁹ If this is not the case, the above procedure is run once again with a tempera-

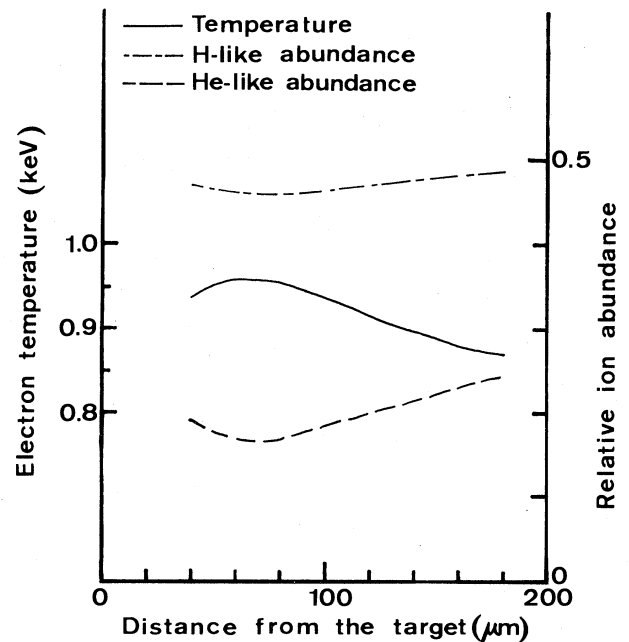


FIG. 4. Electron temperature and relative ion abundance vs the distance from the target.

ture equal to the average of the two previous temperatures. L is measured experimentally and L/l is kept constant according to hydrodynamical theories and experiments describing plasma expansion.¹⁰

The spatial variations of N_e and $\tau_{\nu 0}(L)$ inferred from experimental data for the resonance lines of both H and He-like ions are shown in Fig. 5. These two determinations of density give quite similar results confirming the validity of the interpretation method. With regard to the convolution parameter, it comes out from the results that r values range from 3 to 10 showing a predominant Doppler effect on line broadening. On the other hand, the uncertainty of one-line energy measurements is of the order of 10%, corresponding to an accuracy better than 60% on $\tau_{\nu 0}(L)$ and N_e .

Actually the plasma density and the source function are not homogeneous in the longitudinal direction. To evaluate the influence of a density gradient on the determination of the mean value of N_e and $\tau_{\nu 0}(L)$, we have modified the model by introducing in the complete transfer equation a Gaussian spatial density profile of FWHM L , only for the case of a pure Doppler broadening (a convolved profile for any r has not been introduced because of too-long computations). Comparison with the previous calculations gives density and optical depth reduced by 30% and 20%, respectively.

Finally, we must point out that our calculated density is about 1.5 times lower than the value deduced from the intercombination to resonance line ratio⁹ taking account of opacity effects even in the (T) direction.

In summary, by use of a suitable target geometry providing an anisotropic x-ray emission, we have evidenced self-absorption of x-ray lines. By comparison with theoretical optical depth, electron density in an expanding plasma has been inferred. Such a method is another way of determining densities whose values are comparable to those deduced from the intercombination line method.

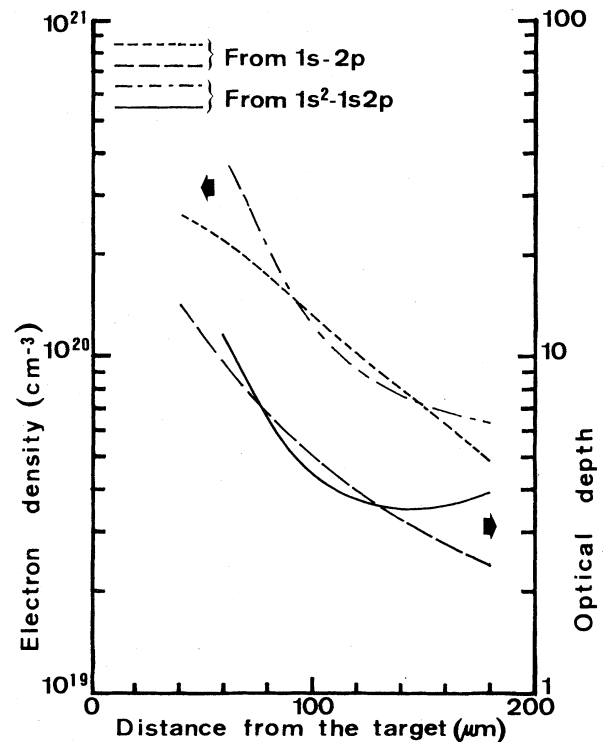


FIG. 5. Spatial dependence of optical depths $\tau_{\nu 0}(L)$ of Al ions' resonance lines and electron density deduced from absorption.

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