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Search for plasma shifts of C VI, N VII, and O VIII resonance lines

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The resonance lines of the hydrogenlike ions C VI, N VII, and O VIII were observed in laser-produced plasmas with electron densities in the range 10^{21}–10^{22} cm^{-3} and electron temperatures between about 70 and 100 eV. The lines of the hydrogenlike ions were recorded photographically with a 3-m grazing-incidence spectrograph. No signigicant plasma line shift was observed.

INTRODUCTION

Spectral lines emitted by hydrogenic ions, whether they are resonance lines or not, have been reported to be shifted when excited in dense plasmas.[1–9] The studied lines were emitted by relatively low-Z hydrogenic ions, He II, Be IV, B V, C VI, and shift either to shorter wavelengths (blue shifts) or to longer wavelengths (red shifts).

As the standard Stark-broadening theories[10] when applied to hydrogenlike ions do not predict line shifts, the observed effect was first related to the formation of a time-averaged negative polarization charge overlapping the bound orbits of the radiating electrons, shielding the nuclear charge and interacting directly with the bound electrons to produce shifts of energy levels and lines. Additional shift mechanisms were proposed recently in an effort to reconcile differences between the experimental results and proposed theoretical models. A review of the older theories, dealing with the plasma polarization shift, was given by Volonté.[11] Ion quadrupole effects (second-order multipole terms in the emitter-ion perturber interaction) may yield blue shifts in the central portions of optically thin lines,[8,12] and electron collisions with relatively large angular momenta cause red shifts.[12]

In the present work the resonance lines of C VI, N VII, and O VIII were further studied in laser-produced plasmas. Use was made of the multibeam Omega laser system (at the Laboratory of Laser Energetics at the University of Rochester) to produce emitting plasmas with electron densities (N_e) in the range 10^{21}–10^{22} cm^{-3} from spherical microballoons. The lasers were operated at two wavelengths—1.06 μm and 3513 Å.

The observed resonance lines of the hydrogenlike ions do not show any shift larger than the experimental accuracy. A new analysis of the experimental data of Adcock and Griem is also presented.[13] According to the new analysis no line shift was obtained in that experiment either, and the reported shifts were due to an error in the wavelength calibration.

EXPERIMENTAL ARRANGEMENT

Two separate experimental runs were made using the Nd:glass laser of the Omega laser system at the University of Rochester Laser Laboratory at two different wavelengths. In the first experimental run the plasma source was produced by focusing 24 laser beams ($\lambda = 1.06$ μm) on microballoon targets. In this case the plasma critical density was 10^{21} cm^{-3}, while the total laser energy was in the range of 1.8–2.2 kJ. With laser pulse duration ~ 1 ns the irradiation power density at the target (a 0.41-mm-diam microballoon) was about 5×10^{14} W/cm^2.

In the second experimental run six beams of tripled frequency Nd:glass laser were focused on the microballoon targets. At laser wavelengths of 3513 Å a higher critical plasma density of 9×10^{21} cm^{-3} was obtained. In these experiments the total laser energy was in the range of 200–300 J, pulse duration also ~ 1 ns, and the irradiation intensity was $\sim 5\times10^{13}$ W/cm^2. The focus of the laser beams was adjusted to give optimally uniform illumination of the target.

The spectral lines of C VI and C V were produced either from solid polysterene spheres or from glass or plastic microballoons coated with CH$_2$-polymer shells. The sources of the N VII, N VI, and O VIII lines were glass microballoons filled with the appropriate gas. Lines of highly ionized oxygen were also emitted by the glass shell of the microballoons.

The spectra were photographed with a 3-m grazing-incidence spectrograph at 88° incidence angle. This spectrograph has been described in detail by Behring, Ugianski, and Feldman.[14] It is equipped with a 1200-lines/mm grating giving a plate factor of 0.2 Å/mm at 16 Å and 0.27 Å/mm at 34 Å. The spectra were recorded on Kodak 101-05-type photographic plates, covering the spectral region between 6 and 160 Å on a single 18-in. plate, or the region between 6 and 100 Å on a 13-in. plate. The extreme ultraviolet (XUV) radiation from the plasma is focused on the spectrograph entrance slit by a cylindrical concave mirror made of a Be strip coated with high-Z metals and bent to obtain a grazing incidence reflection in the XUV region. The design of the mirror was given in detail by Underwood.[15] Spectral lines of higher-Z elements, $Z \geq 13$, were also recorded with the same experimental arrangement. The lines of the high-Z elements were used in the calibration procedure of the plates.

The positions of spectral lines along the photographic plates were measured with a Grant comparator. Wavelength determination was made by a least-squares fit of a second-order polynomial to selected reference lines. A study of more than 20 plates taken with the same spectrograph has shown that this method of fitted second-order polynomials can be used with confidence as long as the new lines are determined by interpolation and as long as the reference and the new lines are measured on the same plate and on the same spectral track. (In the experiment of Adcock and Griem[13] five spectral tracks were recorded on each photographic plate. The spectral track with the Lyman-like lines did not include any reference lines; hence, a method of transferring a reference line was developed and the resonance lines of C VI, O VIII, and F IX were extrapolated. This method introduced serious errors as it made use of an expression with two fitted parameters which were determined on another spectral track and had no internal checks. A transfer of the Lyman lines to a track with reference lines that could be calibrated appropriately by interpolation clearly showed this error in the previous analysis.)

The standard deviation of the polynomial fit to the reference lines was always smaller than 0.010 Å. We estimated a larger standard error for the hydrogenlike ions, because of not so well-defined profiles, but even in this case we generally found $\sigma \leq 0.010$ Å.

RESULTS AND DISCUSSION

In Table I we specify all those spectroscopic plates which were used to measure the wavelengths of the various hydrogenlike and heliumlike ion lines. The appropriate high-Z elements used for the plate calibration are also listed there. Shifts of the high-Z nonhydrogenic ion lines are assumed to be negligible, as the Stark shift of ion lines with effective charge Z_c scales with about Z_c^{-4} or Z_c^{-5}. In our experiment Z_c is always larger than 10, and we can safely assume that the reference lines are not shifted by the plasma.

Altogether, the lines of C VI and C V were measured reliably on five plates, the lines of O VIII and O VII on two plates, and the resonance lines of N VII on one plate. As each measured wavelength of the hydrogenlike or heliumlike lines did not deviate significantly (within ±0.015 Å) from the tabulated values of their wavelength, we combined together the results of the various plates and present the mean value of λ and estimates of the standard deviation in Table II. Also shown in Table II are the previously published wavelengths of the remeasured transitions. A relatively larger standard deviation is obtained whenever the wavelength of a weaker line is included in the average sum. The strongest satellite lines to the Lyman-α lines of C VI, O VII, and O VIII are also reported (in Table II), agreeing in wavelength with the measurement of Nicolosi and Tondello.[25]

The observation of the Lyman-α satellites is important for the estimation of the electron density and electron temperature, two essential input parameters for the theoretical estimation of the hydrogenic line shift.

A Doppler shift resulting from mass motion of the various components of the laser-produced plasma may affect greatly the determined wavelength. In the case of planar targets, blowoff velocities in the range $1-8\times10^7$ cm/sec were measured.[26] As in our experiment we use higher irradiation intensity, larger Doppler velocities may be expected to affect the spectral lines obtained from solid sphere targets. On the other hand, if all different ionic components of the plasma have approximately the same flow velocity, a proper measurement of the hydrogenic-ion lines will be obtained if the plate calibration is made under the assumption of no Doppler shift. Because ionization stages tend to be frozen into the flow toward lower-density regions while flow velocities change, there will in reality be a spread in flow velocities, say by ~ ±20% of the mean blowoff velocity of a given ion. Differences between mean velocities for different ions may also be of this order and could thus result in relative line shifts of about 0.02 Å.

The results of the present experiments, however, show that there is no measurable shift resulting from the possible combination of Doppler and plasma shifts. In the light of the varied experimental conditions, from spectrum to spectrum, it is difficult to assume that in each case the lack of measurable shift results from a cancellation effect, where an expected Doppler shift balances out a plasma shift. It is more reasonable to assume that in the present experiment the different ions may have very close expansion velocities, and that the possible plasma shifts are probably smaller than 0.015 Å.

TABLE I. List of spectrsocopic plates. Remark: The references herein contain more detailed lists of references which were actually used.

Plate No.	Spectra	References
1[a]	C V, C VI, Ni XVII–Ni XXII	16,17
2	C V, C VI, Al X, Al XI	18
3	C V, C VI, O VIII, Si X, Si XI, Si XII	19
4	O VII. O VIII, Si XI, Si XII	19
5[a]	C V, C VI, O VIII, Si X, Si XI, Si XII, Ti XV–Ti XX	19,20
6	C V, C VI, O VII, Si X, Si XI, Si XII	19
7[a]	C V, C VI, Ni XVIII–Ni XXII	16,17
8[a]	C V, C VI, Fe XVIII, Cu XIX, Cu XX, Cu XXI	21,22,19
9	C V, C VI, O VII, O VIII, Si XI, Si XII	19
10[a]	N VII, O VIII, Si X, Si XI, Si XII	19
11	O VII, O VIII, Si XI, Si XII	19
12[a]	N VI, N VII, O VII, O VIII, Si X, Si XI, Si XII	19
13[a]	C V, C VI, Mo XXX, Mo XXXI, Mo XXXII	23
14[a]	C V, C VI, O VIII, Si X, Si XI, Si XII, Ge XX–Ge XXIV	19,24

[a] Plates used in the study of hydrogenlike ions.

TABLE II. Measured wavelength of C V, C VI, N VI, N VII, O VII, and O VIII.

I_{on}	Transition	λ_{lit} (Å)[a]	$\lambda_{\text{expt.}}$ (Å)[b]	σ (Å)[c]
C V	$1s^{2\,1}S_0$–$1s2p\,^1P_1$	40.268	40.268	0.005
C V	$1s^{2\,1}S_0$–$1s3p\,^1P_1$	34.973	34.963	0.011
C V	$1s^{2\,1}S_0$–$1s4p\,^1P_1$	33.426	33.435	· · ·
C V	$1s2p\,^3P$–$2p^{2\,3}P$	34.586[d]	34.591	0.009
C VI	L_α	33.736	33.738	0.004
C VI	L_β	28.466	28.459	0.010
C VI	L_γ	26.970	26.982	0.017
C VI	L_δ	26.357	26.360	· · ·
N VI	$1s^{2\,1}S_0$–$1s2p\,^1P_1$	28.787	28.784	· · ·
N VII	L_α	24.781	24.782	· · ·
N VII	L_β	20.910	20.905	· · ·
N VII	L_γ	19.826	19.820	· · ·
N VII	L_δ	19.361	19.360	· · ·
O VII	$1s^{2\,1}S_0$–$1s2p\,^1P_1$	21.602	21.601	· · ·
O VI	$1s^23s\,^2S$–$1s2p3s\,^2P$	21.676[d]	21.676	· · ·
O VI	$1s^22p\,^2P$–$1s2p^{2\,2}P$	22.044[d]	22.055	· · ·
O VI	$1s^22p\,^2P$–$1s2p^{2\,2}D$	22.120[d]	22.162	· · ·
O VII	$1s2p\,^3P$–$2p^{2\,3}P$	19.330[d]	19.339	0.004
O VII	$1s2p\,^1P$–$2p^{2\,1}D$	19.385[d]	19.398	· · ·
O VIII	L_α	18.969	18.973	· · ·
O VIII	L_β	16.006	16.005	· · ·
O VIII	L_γ	15.176	15.153	· · ·

[a] Published wavelength, Ref. 19; however, see footnote d.

[b] Experimental wavelength determination.

[c] Calculated standard deviation whenever more than two measurements of different plates were made. No extrapolated values are included.

[d] Measured by Nicolosi and Tondello, Ref. 25.

There are several theoretical estimates for the expected plasma shift of the hydrogenlike ion resonance lines, but they differ considerably among themselves in magnitude and even in direction.[1,2,11–13,27–30] In order to compare the experimental results with the various theories, the electron temperature and density (T_e and N_e) were estimated from the observed intensity ratio of the C V and O VII transitions $1s2p\,^3P-2p^{2\,3}P$ and $1s2s\,^3S-2s^{2\,3}P$ and the intensity ratio of the Lyman-α line and the first resonance line in the heliumlike ion. Using the model of Seely and co-workers,[31,32] an estimate of N_e is obtained which depends weakly on T_e. The ratio of the resonance lines in the hydrogenlike ion determines then T_e. Only lower and upper limits could be obtained, giving the values $70 \leq T_e \leq 100$ eV and $10^{21} \leq N_e \leq 10^{22}$ cm^{-3}.

The shifts predicted by all the plasma-shift models mentioned above with $N_e = 5\times10^{21}$ cm^{-3} and $T_e = 70$ eV are larger than 0.05 Å for at least one of the observed Lyman series lines. However, the experimental results indicate there are no significant shifts greater than $2\sigma = 0.02$ Å. Our observations, therefore, indicate a disagreement between some of the theoretical models (Refs. 2, 6, 8, 10, 13, and 27) and experiment.

SUMMARY AND CONCLUSIONS

In this paper possible plasma shifts have been investigated for the resonance lines of the ions C VI, N VII, and O VIII, excited in high density laser-produced plasmas. The wavelengths of these lines were determined relative to the lines of high-Z (>10) ions. Within the estimated experimental accuracy of ±0.015 Å, no measurable shifts have been observed. When estimates of N_e and T_e, as derived from observed intensity ratios between two satellite lines (to the Lyman-α transition) and between the Lyman-α line and the heliumlike ion first resonance line, are used for theoretical shift estimates, a discrepancy with the theoretical models is obtained.

In view of the existing experimental uncertainties, e.g., need for better defined T_e, N_e, and plasma uniformity, further experimental work is needed to provide a more significant test for the various theoretical models. Yet, the present observations indicate that the disagreement[11] between experiment and theory suggested for $N_e \leq 10^{18}$ cm^{-3} also persists to a much higher electron density, $N_e = 5\times10^{21}$ cm^{-3}. Hence, the use of line shifts as a diagnostic tool for denser laser-produced plasmas depends strongly on the future experimental confirmation of some new shift models.[28,29] We finally note that recent theoretical research[33,34] indicates substantial cancellations of various contributions to the shifts. Such reduced shifts may well be consistent with previous[11] and present experiments.

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