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Measurement of electron temperature and state of ionization in laser-produced plasmas by use of dielectronic satellite lines

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Alternative x-ray line-ratio techniques, using heliumlike and lithiumlike dielectronic satellite lines, are proposed for the measurement of electron temperature and state of ionization in dense plasmas, such as laser-produced and Z-pinch plasmas. These techniques are illustrated by application to the emission spectrum of the implosion core of a laser-imploded microballoon.

INTRODUCTION

In the experimental investigation of the plasmas produced by the laser ablation of solid surfaces and the laser implosion of microballoon targets, x-ray emission spectroscopy is widely used to measure the electron temperature, state of ionization, and density. These techniques have recently been reviewed by De Michelis and Mattioli.[1] The hydrogenlike (H-like) and heliumlike (He-like) resonance line spectra of medium-Z elements ($Z\sim 10-20$) are most widely used for these diagnostic purposes.[2,3]

Dielectronic satellite lines close to the H- and He-like resonance lines are due to the radiative decay of doubly excited, autoionizing states of He- and lithiumlike (Li-like) ions, respectively. The intensities of these dielectronic satellite lines relative to the parent resonance lines depend on the electron temperature.[4,5] Two problems arise when satellite-to-resonance line ratios are used to measure electron temperature in laser-produced, and other high-temperature, plasmas. Firstly, there are satellites due to transitions of the type $1snl$-$2l'nl''$ and $1s^2nl$-$1s2l'nl''$, with $n\geq 3$ which cannot be resolved from the Lyman-α (L_α) and $1s^2\,{}^1S_0-1s2p\,{}^1P_1$ (He_α) lines, respectively. The contribution of these high-n satellites to the apparent intensity of the resonance line is difficult to calculate.[6] Secondly, in the case of laser-produced plasmas, the L_α and He_α lines are often optically thick, which again complicates the interpretation of the satellite-to-resonance line ratio.

This paper describes new techniques of using the dielectronic satellite lines to measure the electron temperature and state of ionization in high-density plasmas while avoiding the problems referred to above. These techniques are illustrated by application to the x-ray emission spectrum from the implosion core of a laser-imploded microballoon.

THEORY

If, in a plasma, an autoionizing, doubly excited level j of a Li-like ion is populated mainly by dielectronic recombination and mainly depopulated by autoionization and radiative decay then the equilibrium population density, $N(\mathrm{Li},j)$, of that level is

$$N(\mathrm{Li},j)=\frac{D(\mathrm{Li},j)N_eN(\mathrm{He},g)}{\Gamma(\mathrm{Li},j)+\sum_k A(\mathrm{Li},k,j)}\ , \qquad (1)$$

where N_e is the electron density, $N(\mathrm{He},g)$ is the density of He-like ions in the ground state, and the summation is taken over all non-negligible radiative rates from the level j. The dielectronic recombination rate coefficient $D(\mathrm{Li},j)$ is related to the autoionization rate $\Gamma(\mathrm{Li},j)$ by detailed balancing, and is given by

$$D(\mathrm{Li},j)=\left[\frac{2\pi m_e kT_e}{h^2}\right]^{-3/2}\frac{g(\mathrm{Li},j)}{2g(\mathrm{He},g)}\Gamma(\mathrm{Li},j)\times\exp\left[\left[\frac{E(\mathrm{Li},j)}{kT}\right]\right]\ , \qquad (2)$$

where $g(\mathrm{Li},j)$ and $g(\mathrm{He},g)$ are the degeneracies of the doubly excited Li-like state and He-like ground state, respectively, and $E(\mathrm{Li},j)$ is the energy of the doubly excited state above the ionization limit of the Li-like ion. The doubly excited level can also be populated by inner-shell electron collisional excitation from the $1s^22s$ and $1s^22p$ Li-like states, but for the electron temperatures of interest here only a small fraction of the ions are Li-like. Thus, for doubly excited levels that are not metastable to autoionization, it can be shown that population by inner-shell excitation can be neglected.[5,7] For example, the Li-like $1s2p^2\,{}^2D_{3/2,5/2}$ level has a high autoionization rate, and so the satellite line multiplet $1s^22p\,{}^2P_{1/2,3/2}-1s2p^2\,{}^2P_{3/2,5/2}$ [denoted (j,k,l) in Gabriel's key letter notation] is mainly formed by dielectronic recombination.

At high electron density, electron collisions can redistribute the populations of the doubly excited states leading to an increase in the intensity of satellites from upper levels that are metastable to autoionization.[7-9] Doubly excited levels that are strongly autoionizing give rise to satellites that are not significantly affected by this collisional redistribution until much higher values of electron density are reached. For example,[7] in a silicon plasma at 500 eV, the intensities of the (j,k,l) Li-like satellites are only affected by collisional redistribution for electron densities above 10^{24} cm^{-3}. Similarly,[8] for He-like dielectronic satellites from strongly autoionizing levels (e.g., $1s2p\ ^1P_1-2p^2\ ^1D_2$) inner-shell excitation makes only a small contribution and collisional redistribution is important only for electron densities above 10^{24} cm^{-3}. Thus, when dielectronic recombination, autoionization, and radiative decay predominate the power emitted per unit volume in a He-like satellite line is

$$I(\mathrm{He},i,j)=\frac{N_e N(\mathrm{H},g)h\nu(\mathrm{He},i,j)\left[\frac{2\pi m_e kT_e}{h^2}\right]^{-3/2}q(\mathrm{He},i,j)}{2g(\mathrm{H},g)}\exp\left[-\left[\frac{E(\mathrm{He},j)}{kT_e}\right]\right], \tag{3}$$

where

$$q(\mathrm{He},i,j)=\frac{g(\mathrm{He},j)A(\mathrm{He},i,j)\Gamma(\mathrm{He},j)}{\Gamma(\mathrm{He},j)+\sum_k A(\mathrm{He},k,j)}. \tag{4}$$

For a H-like ion in a plasma, an energy level of principal quantum number n will be in local thermodynamic equilibrium (LTE) with respect to higher levels and the continuum of free electrons if[10]

$$N_e>\frac{2\times10^{18}Z^6(kT_e)^{1/2}}{N^{17/2}}\mathrm{cm}^{-3}. \tag{5}$$

Thus for this partial LTE to apply to the $n=3$ level of H-like silicon the electron density must be greater than 3×10^{22} cm^{-3}. A similar criterion applies for partial LTE of the He-like levels. The population of these He-like levels is proportional to the population of the H-like ground state, and the power emitted in a He-like resonance line from a level 1 is

$$I(\mathrm{He},g,l)=N_e N(\mathrm{H},g)h\nu(\mathrm{He},g,l)A(\mathrm{He},g,l)\times\left[\frac{2\pi m_e kT_e}{h^2}\right]^{-3/2}\frac{g(\mathrm{He},l)}{2g(\mathrm{H},g)}\times\exp\left[\frac{\chi(\mathrm{He},l,\infty)}{kT_e}\right], \tag{6}$$

where $\chi(\mathrm{He},l,\infty)$ is the ionization potential from the level 1. Thus the relative intensity of a He-like satellite from an autoionizing level and a He-like resonance line from a level that is in LTE with the next ion is given by

$$\frac{I(\mathrm{He},i,j)}{I(\mathrm{He},g,l)}=\frac{h\nu(\mathrm{He},g,l)q(\mathrm{He},i,j)}{h\nu(\mathrm{He},g,l)g(\mathrm{He},l)A(\mathrm{He},g,l)}\times\exp\left[-\left[\frac{E(\mathrm{He},j)+\chi(\mathrm{He},l,\infty)}{kT_e}\right]\right]. \tag{7}$$

For example, the relative intensity of the Si XIII $1s2p\ ^1P_1-2p^2\ ^1D_2$ and Si XIII $1s^2\ ^1S_0-1s4p\ ^1P_1$ lines is given by

$$\frac{I(\mathrm{Si\,XIII}\ 1s2p\ ^1P_1-2p^2\ ^1D_2)}{I(\mathrm{Si\,XIII}\ 1s^2\ ^1S_0-1s4p\ ^1P_1)}=12.6\exp\left[-\left[\frac{1550}{kT_e}\right]\right], \tag{8}$$

where kT_e is in eV. The autoionization and radiative transition rates are taken from the tabulation of Vainshtein and Safronova.[11] It is clear that this line ratio is strongly dependent on the electron temperature. The temperature sensitivity of this line ratio can be understood by noting that the satellite line samples the electron distribution well above the He-like ionization limit, while the resonance line is derived from an energy level somewhat below that ionization limit.

The relative intensity of a He- and a Li-like dielectronic satellite is given by

$$\frac{I(\mathrm{He},i,j)}{I(\mathrm{Li},i,j)}=\frac{h\nu(\mathrm{He},g,l)N(\mathrm{H},g)g(\mathrm{He},g)q(\mathrm{He},i,j)}{h\nu(\mathrm{Li},g,l)N(\mathrm{He},g)g(\mathrm{H},g)q(\mathrm{Li},i,j)}\times\exp\left[-\left[\frac{E(\mathrm{He},j)-E(\mathrm{Li},j)}{kT_e}\right]\right]. \tag{9}$$

Thus the relative intensity of the Si XIII $1s2p\ ^1P_1-2p^2\ ^1D_2$ and Si XII (j,k,l) satellites is

$$\frac{I(\mathrm{Si\,XIII}\ 1s2p\ ^1P_1-2p^2\ ^1D_2)}{I[\mathrm{Si\,XIII}(j,k,l)]}=0.65\frac{N(\mathrm{H},g)}{N(\mathrm{He},g)}\exp\left[-\left[\frac{67}{kT_e}\right]\right]. \tag{10}$$

For an electron temperature greater than 300 eV this line ratio is weakly dependent on the temperature, but depends mainly on the ratio of H- and He-like ions.

For H- and He-like resonance lines, where the upper levels are in LTE with the next ion stage, the relative intensity is given by

$$\frac{I(\mathrm{H},g,k)}{I(\mathrm{He},g,l)}=\frac{h\nu(\mathrm{H},g,k)A(\mathrm{H},g,k)g(\mathrm{H},k)g(\mathrm{H},g)N(B)}{h\nu(\mathrm{He},g,l)A(\mathrm{He},g,l)g(\mathrm{He},l)g(B)N(\mathrm{H},g)}\times\exp\left[\frac{\chi(\mathrm{H},k)-\chi(\mathrm{He},l)}{kT_e}\right], \tag{11}$$

where B indicates the fully stripped ion. For example, the intensity ratio of Si XIV L_β and Si XIII $1s^2\ ^1S_0-1s4p\ ^1P_1$ lines is given by

$$\frac{I(\mathrm{Si\,XIV}\ L_\beta)}{I(\mathrm{Si\,XIII}\ 1s^2\ ^1S_0-1s4p\ ^1P_1)}=5.8\frac{N(B)}{N(\mathrm{H},g)}\exp\left[\frac{146}{kT_e}\right]. \tag{12}$$

This line ratio depends mainly on the ratio of fully stripped and H-like ions.

EXPERIMENTAL SPECTRA

The silicon x-ray emission spectrum from the implosion core of a laser-imploded glass microballoon is shown in Fig. 1. The implosion is of the exploding pusher type, and is similar to those described earlier.[3] The spectrum was recorded using a miniature, space-resolving, x-ray crystal spectrograph.[3] The diameter of the x-ray emitting core was about 25 μm. The methods described in Ref. 3 were used to analyze the spectrum; the slope of the Si XIII and Si XIV recombination continuum gave an electron temperature of 490±50 eV, and Stark broadening showed that the electron density was $(6\pm2)\times10^{22}$ cm^{-3}

Figure 2 shows the Si XIV L_α line with its associated satellites. The intensity ratio

$$\frac{I(\text{Si XIII } 1s2p\ ^1P_1-2p^2\ ^1D_2)}{I(\text{Si XIII } 1s^2\ ^1S_0-1s4p\ ^1P_1)}=0.28\pm0.03\ ,$$

which, from Eq. (8), gives an electron temperature of 410±10 eV.

Figure 3 shows the Si XIII $1s^2\ ^1S_0-1s2p\ ^1P_1$ line and its associated satellites. The intensity ratio

$$\frac{I(\text{Si XIII } 1s2p\ ^1P_1-2p^2\ ^1D_2)}{I[\text{Si XIII } (j,k,l)]}=0.47\pm0.05\ ,$$

which, from Eq. (10), implies that the population density ratio of H and He-like ground-state ions is $N(\text{H},g)/N(\text{He},g)=0.82\pm0.08$. The optically thin, collisional-radiative equilibrium model of Lee *et al.*[12] predicts that this ion ratio will be obtained at 560±20 eV for an electron density of 6×10^{22} cm^{-3}.

The intensity ratio

$$\frac{I(\text{Si XIV } L_\beta)}{I(\text{Si XIII } 1s^2\ ^1S_0-1s4p\ ^1P_1)}=0.92\pm0.09\ ,$$

which, from Eq. (12), implies that $N(B)/N(\text{H},g)=0.19\pm0.02$. This ion density is predicted to occur at 490±30 eV.

The optical opacities of the various lines used above have been estimated; the (j,k,l) satellite, the L_β and the $1s^2\ ^1S_0-1s4p\ ^1P_1$ lines have opacities of about 1, while the L_α satellite is optically thin. Taking this reabsorption into account will slightly decrease the temperature measured by the L_α satellite to $1s^2\ ^1S_0-1s4p\ ^1P_1$ ratio, and the degree of ionization measured by L_α satellite to (j,k,l) ratio.

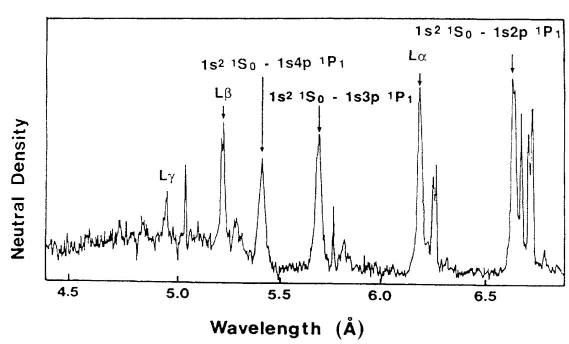

FIG. 1. Microdensitometer trace of the x-ray emission spectrum from the implosion core of a laser-imploded glass microballoon showing the H-like and He-like silicon resonance lines.

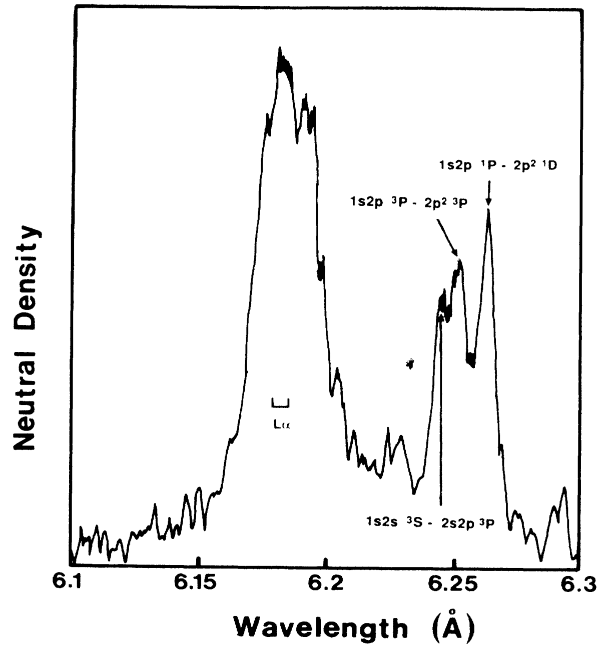

FIG. 2. Si XIV L_α line and its associated satellites from the implosion core.

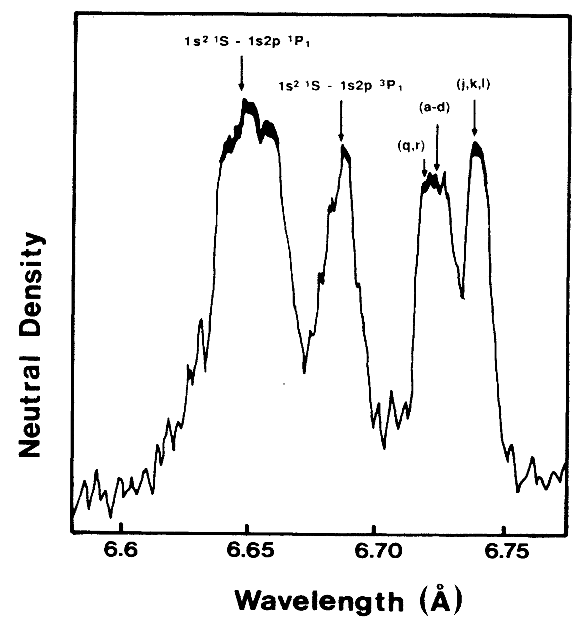

FIG. 3. Si XIII $1s^2\ ^1S_0-1s2p\ ^1P_1$ line and its associated satellites from the implosion core.

DISCUSSION

The various emission line-ratio methods described above give a measure of the electron temperature and ion distribution in a high-density plasma. The temperature of 410±10 eV obtained from the ratio of the L_α satellite and the $1s^2\,{}^1S_0-1s4p\,{}^1P_1$ lines is somewhat lower than the temperature indicated by the state of ionization derived from the ratio of L_α and $1s^2\,{}^1S_0-1s2p\,{}^1P_1$ satellites (560 eV), or the ratio of He- and H-like resonance lines (490 eV). This discrepancy could be due to spatial and temporal variation of the electron temperature since the L_α satellite will mainly be emitted in the high-temperature region and phase of the plasma, while the $1s^2\,{}^1S_0-1s4p\,{}^1P_1$ line can also be emitted from cooler, or recombining, plasma. This has the effect of decreasing the measured line ratio in a time- and space-integrated measurement, with a consequent reduction in the measured temperature. This problem can be avoided by time and space resolving the emitted spectrum. In addition, opacity on the He- and H-like resonance lines will enhance the degree of ionization above the level predicted by the optically thin collisional-radiative model.

The collisional-radiative[12] calculation of the various line ratios considered above includes small contributions, due to inner-shell excitation, collisional transfer between doubly excited states and deviation from LTE in bound levels, that are not accounted for in the analytic expressions derived in this paper, giving line ratios that show a weak dependence on electron density. For example, in a silicon plasma at 500 eV, the ratio of the L_α satellite to $1s^2\,{}^1S_0-1s4p\,{}^1P_1$ varies by only a factor of 2 over the electron density range 10^{21} to 10^{23} cm^{-3}, which corresponds to a 20% change in measured electron temperature.

In conclusion, some new line-ratio techniques, using dielectronic satellite lines, have been derived for the measurement of electron temperature and state of ionization in a dense plasma, and these have been shown to agree with earlier methods. The development of comprehensive collisional-radiative equilibrium models makes it possible to calculate a complete emission spectrum and vary the plasma parameters to obtain a fit to the measured spectrum. When such models are available the line-ratio techniques described here can draw attention to the aspects of the spectrum that yield a sensitive measure of the plasma conditions.

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[1]C. De Michelis and M. Mattioli, Nucl. Fusion **21**, 677 (1981).

[2]B. Yaakobi *et al.*, Phys. Rev. A **19**, 1247 (1979).

[3]J. D. Kilkenny, R. W. Lee, M. H. Key, and J. G. Lunney, Phys. Rev. A **22**, 2746 (1980).

[4]A. H. Gabriel, Mon. Not. R. Astron. Soc. **160**, 99 (1972).

[5]C. P. Bhalla, A. H. Gabriel, and L. P. Presnyakov, Mon. Not. R. Astron. Soc. **172**, 359 (1975).

[6]F. Bely-Dubau, A. H. Gabriel, and S. Volonté, Mon. Not. R. Astron. Soc. **189**, 801 (1979).

[7]V. L. Jacobs, and M. Blaha, Phys. Rev. A **21**, 342 (1980).

[8]J. G. Lunney and J. F. Seely, Phys. Rev. Lett. **46**, 342 (1981).

[9]J. G. Lunney, J. Phys. B **16**, L83 (1983).

[10]H. R. Griem, *Plasma Spectroscopy* (McGraw-Hill, New York, 1964).

[11]L. A. Vainshtein and U. I. Safronova, At. Data Nucl. Data Tables **21**, 49 (1978).

[12]R. W. Lee, B. L. Whitten, and R. E. Stout, J. Quant. Spectrosc. Radiat. Transfer **32**, 91 (1984).