Observation of H- and He-like X-Ray Line Emission in High-Density Tokamak Plasmas

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Characteristic x-ray spectra of plasma impurity ions have been measured in the region $\lambda = 4.3$–5.1 Å. The observation of strong principal $n=2$ to $n=1$ x-ray lines for H-like sulfur and for He-like sulfur and chlorine in the density range $(1-6)\times10^{14}$ cm^{-3} is reported. Dielectric recombination and inner-shell excitation satellite lines are weak. The results, which are of interest for both atomic physics and plasma diagnostic applications, are compared with atomic calculations of line spectra and transition rates.

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X-ray spectroscopy of highly ionized atoms, which started with the classical work on spark discharges in the 1940's,[1] has received renewed interest with the advent of the broad range of laboratory-produced hot plasmas as well as with improved observations of x rays from astrophysical plasmas. In magnetically confined plasmas, steady and controllable conditions of electron density N_e and temperature T_e can be sustained for extended periods of time (> 100 ms). With temperatures of a few kiloelectronvolts medium-Z impurity atoms, frequently found in plasmas from tokamaks, are stripped of all but the last few electrons. These plasmas produce characteristic x-ray emission from H-, He-, and Li-like ions. The resulting line spectra are relatively simple and can provide information on highly ionized atomic states and related transitions. They constitute a powerful diagnostic probe of plasma conditions. Here we report on the first measurements of the x-ray emission from sulfur and chlorine present as natural impurities in the high-density ($N_e < 8.5\times10^{14}$ cm^{-3}) tokamak Alcator C located at the Massachusetts Institute of Technology.

The intensities of the resonance ($w_{\rm H}$ and $w_{\rm He}$) transitions to the H- and He-like ground states ($1s\,^2S_{1/2}$-$2p\,^2P_{1/2,3/2}$ and $1s^2\,^1S_0$-$1s2p\,^1P_1$) reflect the abundance of these ions in the plasma. (Letters are used for transitions in the conventional way,[2] as summarized in Fig. 1). Since the abundance ratio is a predictable function of T_e (for a plasma in coronal equilibrium),[3] the intensity ratio $w_{\rm H}/w_{\rm He}$ is a temperature diagnostic or, if T_e is known, it provides a test of the assumption of equilibrium. The $w_{\rm H}$ and $w_{\rm He}$ transitions are accompanied by satellites of the type $1s(nl_j)$-$2p(nl_j)$ and $1s^2(nl_j)$-$1s2p(nl_j)$, respectively. The orbitals nl_j ($n>2$) are populated mainly through dielectronic recombination and so the satellite intensities depend strongly on T_e. Inner-shell excitation of the nl_j orbit is predicted to be strong for the q satellite and so its intensity relative to $w_{\rm He}$ can be used to detect departure from the coronal equilibrium abundance ratio of He- to Li-like ions in the plasma.[4] The intensities of the intercombination (x and y) and the forbidden (z) transitions relative to the resonance transition in the He-like charge state should be largely independent of N_e at low densities. At higher densities the rates of collisionally induced transitions between the long-lived $n=2$ states are comparable to those for decay by x-ray emission at some critical value of N_e [$N_e^* = (2-4)\times10^{13}$ cm^{-3} for S and Cl].[2] For densities exceeding N_e^*, the line ratio $z/(x+y)$ decreases, reflecting the collisional transfer of population from $2\,^3S_1$ to $2\,^3P_{2,1}$,[5] and, because of a preference for the $P_{1/2}$ state in the $2\,^2S_{1/2}$-$2\,^2P_{3/2,1/2}$ transitions due to proton impacts,[6] the $P_{3/2}$ and $P_{1/2}$ components of $w_{\rm H}$ are density dependent. Little experimental information exists, however, on the density dependence of the ratio $w_{\rm H}(P_{1/2})/w_{\rm H}(P_{3/2})$. Neither has the predicted density dependence of collisionally induced[5] redistribution (or excitation) of the He-like metastable $n=2$ states $2\,^1S_0$, $2\,^3S_1$, and $2\,^3P_{0,1,2}$ been confronted with much experimental information. In this Letter we report new measurements of the H- and He-like emission spectra of sulfur and chlorine under varying plasma conditions for densities near and above N_e^*.

The experiment was performed at the Alcator C tokamak with a newly installed high-throughput, high-resolution Bragg crystal spectrometer in the van Hamos geometry.[7] The plasma may be viewed through a reentry tube located at a port which also accommodates two circular Mo plasma limiters of radius 16 cm. The vertical entrance slit of the spectrometer was placed about 70 cm from the plasma center. The photons are diffracted off a cylindrically curved, highly reflective pentaerythritol crystal ($R = 58.5$ cm and $2d = 8.742$ Å) and detected with a position-sensitive proportional counter.[8] The dispersion (~0.3 mm/mÅ at ~4 Å) occurs along the horizontal cylinder axis and focusing takes place in the nondispersive vertical direction. The overall resolution of the spectrometer is $\Delta\lambda/\lambda \sim \frac{1}{2000}$ corresponding to a spatial line width of 0.7 mm full width at half maximum, partially limited by the detector.

Plasmas of deuterium or hydrogen were produced at toroidal magnetic fields of 60 to 80 kG and at plasma currents of 350 to 500 kA. The discharges were typically 300 ms long with a steady current condition prevailing for 100–150 ms, which was selected for our measurements. Besides the information on macroscopic plasma parameters (such as plasma current, position, and voltage), the electron density and temperature were obtained from independent diagnostics.[9] A typical example of an x-ray emission spectrum from a single plasma shot is shown in Fig. 1(a). The results on selected spectral regions are presented in the lower three panels of Fig. 1. They show He- and Li-like emission in chlorine [Fig. 1(b)] and sulfur [Fig. 1(c)], and H-like emission in sulfur along with Ne-like emission in molybdenum [Fig. 1(d)]. Several plasma shots for similar parameters were added in Figs. 1(b)–1(d). The plasma conditions [N_e (10^{14} cm^{-3}), T_e (keV)] for the cases 1(a)–1(d) were [3,1.1], [2.3,1.2], [3.2,1.2], and [3.5,1.3].

Line identification was made with spectroscopic information from atomic calculations.[10-12] The spectra of S and Cl for our plasma conditions are dominated by the principal lines, w, x, y, and z of He-like spectra [Figs. 1(b) and 1(c)]. Other weaker features can be identified with some of the predicted $n = 2$ satellites from Li-like charge states. Among the satellites from singly excited states the q and r lines are apparent. Of the satellites from doubly excited states, populated by dielectronic recombination, the k line is observed, but the strongest one, expected on theoretical grounds, the j line, cannot be separated from z. The j line is estimated to be about 1.4 times the intensity of the k line.[4] Given the observed intensity of k and assuming the predicted relative intensities of the $n = 2$ satellites, only j, k, and q should give measurable contributions to

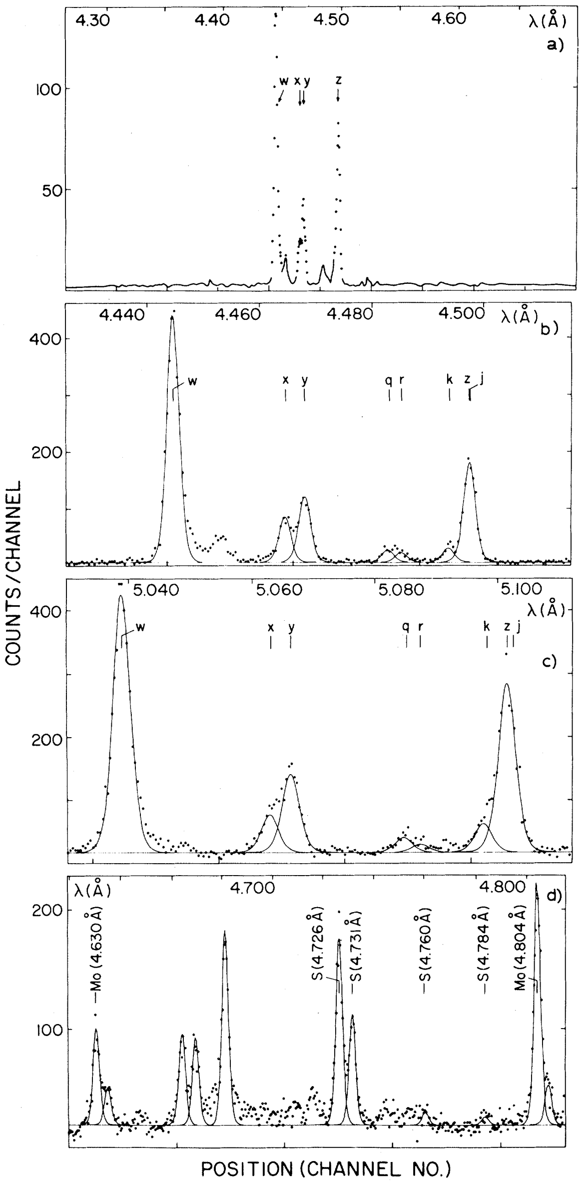

FIG. 1. (a) Example of x-ray spectrum recorded for a single plasma discharge showing the full λ range covered by the detector. (b)–(d) Partial spectra showing the x-ray emission of (b) He-like Cl and (c) S, and (d) H-like S along with emission from Mo. Wavelengths of predicted (Refs. 2, 10, and 12) S and Cl lines are indicated relative to the resonance line (w). Key to the letter symbols (Ref. 2): w, $1s^2\,{}^1S_0$-$1s2p\,{}^1P_1$; q, $1s^22s\,{}^2S_{1/2}$-$1s(2s2p\,{}^1P)\,{}^2P_{3/2}$; x, $1s^2\,{}^1S_0$-$1s2p\,{}^3P_2$; r, $1s^22s\,{}^2S_{1/2}$-$1s(2s2p\,{}^1P)\,{}^2P_{1/2}$; y, $1s^2\,{}^1S_0$-$1s2p\,{}^3P_1$; k, $1s^22p\,{}^2P_{1/2}$-$1s2p^2\,{}^2D_{3/2}$; z, $1s^2\,{}^1S_0$-$1s2s\,{}^3S_1$; j, $1s^22p\,{}^2P_{3/2}$-$1s2p^2\,{}^2D_{5/2}$.

our S and Cl spectra. Higher orbital ($n > 3$) satellites are probably the cause of the contributions appearing on the long-wavelength side of w.[13]

Sulfur in the H-like charge state is manifested [Fig. 1(d)] by the resonance doublet seen at 4.726/4.731 Å (separation 5.3 mÅ) which agrees with prediction.[12] Peaks were fitted to the measured spectrum at $\lambda = 4.760$ and 4.784 Å which are the predicted locations of the w_{H} satellites.[10] They amount to less than $\frac{1}{20}$ of the w_{H} intensity which is an upper limit since the line identification is obscured by the presence of molybdenum emission. The Mo spectrum is dominated by principal Ne-, Na-, and Hg-like $2p$-$3d$ transitions [indicated in Fig. 1(d)] along with dielectronic recombination satellites.[11] The most significant difference between our He-like spectra of S and Cl and those of Fe measured at the Princeton PLT tokamak at $T_e \sim 2$ keV[14] is the increase by an order of magnitude of the relative intensity of $n = 2$ satellites in the Fe spectra, which occurs mainly because of differences in atomic numbers and wavelengths (λ is 1.8 Å for Fe).

Typical values of relative satellite intensities are 0.09 and 0.07 as observed for the k and q transitions in Cl. Comparison with calculated k and q intensities and their dependence on electron (T_e) and ionization (T_z) temperature implies plasma conditions of $T_e \approx 1.0$ keV and $T_z \approx 0.7$ keV.[4] The T_e value is quite close to the accepted T_e value of 1.2 keV for our plasma conditions. The parameter T_z is the temperature at which the abundance ratio of Li- to He-like ions equals that in coronal equilibrium. If $T_e > T_z$, a plasma must be in a state of transient ionization. No other diagnostic measurement of T_z is available. For comparison we can use our measurement of the intensity ratio $w_{\mathrm{H}}/w_{\mathrm{He}}$. Our results on $w_{\mathrm{H}}/w_{\mathrm{He}}$ as a function of T_e are presented in Fig. 2 and compared with the predicted T_e dependence based on coronal equilibrium.[3] The prediction follows the trend of the data though there is some scatter among the individual data points. The scatter may indicate deviations from coronal equilibrium although the experimental uncertainties are quite large and there may occur differences in the radial charge-state distributions. Dual diagnostics of T_z based on simultaneous measurements of the ratios $w_{\mathrm{H}}/w_{\mathrm{He}}$ and $q_{\mathrm{Li}}/w_{\mathrm{He}}$ would help distinguish effects of departure from coronal equilibrium.

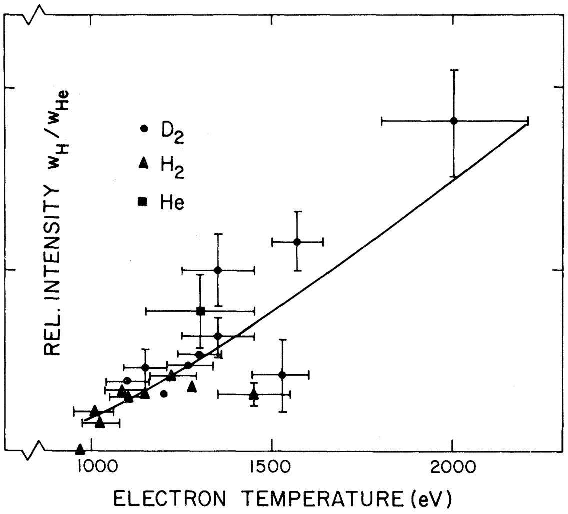

FIG. 2. Measured intensity ratios of the resonance transitions w_{H} ($1s\,^2S_{1/2}$-$2p\,^2P_{3/2,1/2}$) and w_{He} ($1s^2\,^1S_0$-$1s2p\,^1P_1$) in H- and He-like sulfur plotted vs electron temperature. Comparison is made with coronal equilibrium prediction.

The principal He-like transitions always dominate our spectra and they are seen with enough intensity to allow determination of x, y, and z intensities relative to w to within an uncertainty of 5%–15% for individual plasma discharges. The results show unexpected variations in the line ratios which seem not to correlate with changes in the plasma parameters N_e and T_e. Variations by a factor of 2 have been observed for the ratio x/y. At the present we are unable to explain the variations. Because they sometimes occur in connection with unusual time histories of the x-ray emission, their origin may be in transient features of the plasma such as a departure from ionization equilibrium. Under such conditions, collisional excitations could contribute significantly to the population of the $2\,^3P_{2,1}$ and $2\,^3S_1$ states and affect the line ratios in a more complex way than just a population transfer[5] from $2\,^3S_1$ to $2\,^3P_{1,2}$. Collisional mixing of the $n = 2$ states for H-like ions affecting the $P_{1/2,3/2}$ states and resulting in line ratios $w_{\mathrm{H}}(P_{1/2})/w_{\mathrm{H}}(P_{3/2}) > 0.5$ has been predicted.[6] We have measured the line ratio for H-like S and find values which indeed are larger than 0.5. The observed range of variation is 0.5 to 0.8 for densities in the range $(1-4) \times 10^{14}$ cm^{-3} but with no apparent correlation in the variation of $w_{\mathrm{H}}(P_{1/2})/w_{\mathrm{H}}(P_{3/2})$ and N_e. Simultaneous measurements of both the H-like and He-like parts of the spectra will be needed to ascertain whether or not the line-ratio variations and the variations of the principal He-like transitions have a common origin.

Our measurements of the intensities of the He-like transitions of x, y, and z relative to w have been averaged for a number of discharges representing plasmas with the mean conditions $T_e = 1.2$ keV and $N_e = 3 \times 10^{14}$ cm^{-3}. The intensities are found to be 0.13 (0.19), 0.25 (0.28), and 0.50 (0.47) for S (Cl). The calculations of Gabriel[2] predict similar ratios, 0.13 (0.17), 0.25 (0.25), and 0.64 (0.60) but for densities below the critical value. Data from solar flare measurements have confirmed these predictions for the low-density regime $N_e \ll N_e{}^*$.[15] From our results it now appears that the x, y, and z lines remain strong at densities an order of magnitude above $N_e{}^*$. In particular, the lack of a significant decrease in the ratio $z/(x+y)$ at our typical densities of $N_e \sim 3 \times 10^{14}$ cm^{-3} is noteworthy. There is also no clear indication of a simple N_e dependence in the observed x, y, and z intensities for our plasmas of varying density in the range $(1-6) \times 10^{14}$ cm^{-3}. Any N_e-dependent variations are masked by variations due to other causes.

In conclusion, we have measured H-, He- and Li-like line spectra for S and Cl and identified the principal $1s$-$2p$ and $1s$-$2s$ transitions and the satellites. The satellite intensities are weak which can qualitatively be explained within existing theories as can the relative intensities of the resonance transitions of H- and He-like sulfur. Collisional mixing of the $2n$ states should be important in our density regime ($N_e > 10^{14}$ cm^{-3}) but the predicted manifestation of such effects, the depletion of the forbidden line, is not apparent in our data. Instead, the fine-structure components of both the H-like resonance and He-like intercombination transitions show quite large variations, which might suggest that density-dependent collisional effects are of a complex nature and that transient plasma effects such as departure from ionization equilibrium are important.

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