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

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Abstract

Characteristic X-ray spectra of plasma impurity ions have been measured in the region $\lambda = 4.3\text{-}5.1$ Å. We report the observation of the principal n=2 to n=1 X-ray lines for H-like sulphur, and for He-like sulphur and chlorine in the density range $N_e = (1\text{-}6) \times 10^{14}$ cm^{-3}. Dielectronic recombination and inner shell excitation satellites are only weakly seen. The results are compared with current atomic calculations of line spectra and transition rates, and are of interest for both atomic physics and plasma diagnostic applications.

X-ray spectroscopy of highly ionized atoms, which started with the classical work on spark discharges in the 40's (Edlén and Tyrén 1939), 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 stellar 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 keV 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 just as the application of such knowledge allows one to diagnose the plasma. Here we report on the first measurements on the X-ray emission from sulphur and chlorine present as natural impurities in the high density ($N_e \lesssim 8.5 \times 10^{14}$ cm^{-3}) tokamak Alcator C located at MIT.

The resonance (w) 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. (Transitions are related to with letter symbols as in Gabriel (1972)). Since the abundance ratio is a predictable function of T_e (for a plasma in coronal equilibrium) (Jacobs et al. 1979), the w_H/w_{He} ratio is a temperature diagnostic or, if T_e is known, it provides a test of this equilibrium. The w_H and w_{He} transitions are accompanied by satellites of the type $1s\ (nl_j) - 2p\ (nl_j)$ and

$1s^2 (nl_j) - 1s2p\ (nl_j)$. The orbitals nl_j ($n \geq 2$) are mainly populated through dielectronic recombination so these satellites have a strong dependence on T_e. Inner shell excitation of the nl_j-orbit is predicted to be strong for the q satellite so its intensity relative to w_{He} can be used to detect departure from the coronal equilibrium abundance ratio of He- to Li-like ions in the plasma (Bhalla et al. 1975). The intercombination transitions $1s^2\ {}^1S_0 - 1s2p\ {}^3P_{2,1}$ (x and y) and the forbidden transition $1s^2\ {}^1S_0 - 1s2s\ {}^3S_1$ (z) in the He-like charge state should appear with fixed intensities relative to w_{He} over a range of N_e and T_e. However, the rates of collisionally induced transitions between the long lived n=2 states increase with density and become comparable to those of the X-ray decays observed at some critical value of N_e ($N_e{}^* = (2-4) \times 10^{13}$ cm^3 for S and Cl) (Gabriel 1972). The most direct manifestation hereof is predicted to be a decrease in the line ratio z/x+y reflecting the collisional transfer of population from 2^3S_1 to $2^3P_{2,1}$ (Pradhan et al. 1981). The $P_{3/2}$ and $P_{1/2}$ components of w_H is also suggested to be density dependent in the region $N_e > 10^{13}$ cm^{-3} because of a preference for the $P_{1/2}$ state in the collisionally induced $2^2S_{1/2} \rightarrow 2^2P_{3/2,1/2}$ transitions (Vinogradov et al. 1977; Beigman et al. 1979). Little experimental information exists, however, on the density dependence of the $w_H(P_{1/2})/w_H(P_{3/2})$ ratio. Neither has the density dependence of collisionally induced (Pradhan et al. 1981) re-distribution (or excitation) of the He-like 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 sulphur 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 through-put, high resolution Bragg crystal spectrometer in the van Hamos geometry (Van Hamos 1933; Schnopper and Taylor 1977). The plasma is viewed through a re-entry tube located at a port which also accommodates two circular (r = 16 cm) Mo plasma limiters. 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 PET crystal (R = 58.5 cm and 2d = 8.742 Å) and detected with a position sensitive proportional counter. The dispersion (~0.3 mm/mÅ at λ ~4 Å) occurs along the horizontal cylinder axis and focussing takes place in the non-dispersive vertical direction. The overall resolution of the spectrometer is $\Delta\lambda/\lambda$ ~1/2000 corresponding to a spatial line width of 0.7 mm (FWHM), 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 readily available information on the macroscopic plasma parameters, the electron density and temperature of each plasma shot were obtained from independent diagnostics (Alcator group 1980). This allowed us to observe line spectra of X-ray emission under known plasma conditions of varying T_e and N_e. A typical example of an X-ray emission spectrum from a single plasma shot is shown in Fig. 1a. The results on selected spectral regions are shown in the lower three panels of Fig. 1, namely He- and Li-like emission in chlorine (Fig. 1b) and sulphur (Fig. 1c), and H-like emission in sulphur along with Ne-like emission in molybdenum (Fig. 1d). Several plasma shots of similar parameters were added in Fig. 1b-d. The plasma conditions [$N_e(10^{14}\ cm^{-3})$, T_e(keV)] for the cases a-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 (Vainshtein and Safronova 1978; Cowan 1981; Safronova 1981). It is thus found that the spectra of S and Cl are dominated by the w line along with x,y, and z (Figs. 1b,c). Besides these main lines of the He-like system, some of the predicted n=2 satellites of Li-like systems are present. Among the $1s^2\ 2s$ - 1s2s2p satellites from singly excited states, we see the q and r lines. Of the $1s^2\ 2p$ - $1s2p^2$ satellites from doubly excited states (populated by dielectronic recombination) the k line is observed, while the theoretically strongest one, the j line, is unseparable from z; j is estimated to be about 1.4 times the intensity of k (Bhalla et al. 1975). From the predicted intensities of the n=2 satellites, only j, k and q should give finite contributions to our S and Cl spectra given the observed intensity of k. Higher orbital ($n \geq 3$) satellites are probably the cause of the contributions appearing on the long wavelength side of w_{He}.

Sulphur in the H-like charge state is manifested (Fig. 1d) by the resonance doublet seen at 4.726/4.731 Å (separation 5.3 mÅ) which agrees with the prediction (Safronova 1981). Peaks were fitted to the measured spectrum at λ = 4.760 and 4.784 Å which are the predicted locations of the w_H satellites (Vainshtein and Safronova 1978). They amount to less than 1/20 of the w_H intensity which is an upper limit since the line identification is impeded by the presence of molybdenum emission. The Mo spectrum is dominated by principal Ne-, Na-, and Mg-like 2p-3d transitions (indicated in Fig. 1d) along with dielectronic recombination satellites (Cowan 1981). The satellite intensities in our S or Cl and Mo spectra from the same plasma exhibit the expected trend of a $\sim Z^4$ dependence (Gabriel 1972). We also note that the single most significant difference between our He-like spectra of S and Cl and those of Fe previously measured at the Princeton PLT tokamak (at $T_e \approx 2$ keV) (Bitter et al. 1979) is the order of magnitude larger relative intensity of n=2 satellites in the Fe spectra; this is largely a manifestation of the Z^4 dependence and the difference in wavelengths (4.4 resp 1.8 Å).

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, would imply plasma conditions of $T_e \approx 1.0$ keV and $T_z \approx 0.7$ keV (Bhalla et al. 1975). This T_e-value is somewhat lower than the 1.2 keV set by other diagnostics. The parameter T_z represents the temperature at which the abundance ratio of Li- to He-like ions represents coronal equilibrium; i.e., our result $T_e > T_z$ would indicate a plasma in a state of transient ionization. There is no other diagnostic measurement on T_z available. We can, however, make use of our own measurement of the ratio w_H/w_{He} in this context.

The result on w_H/w_{He} as a function of T_e is presented in Fig. 2 and compared with the predicted T_e dependence based on coronal equilibrium (Jacobs et al. 1979). Although the prediction follows the trend of the data there is some scatter among the individual data points. It is not clear whether this indicates true deviation from equilibrium or could be accounted for within experimental uncertainties. We envisage the value of dual diagnostics of T_z and plan experiments for simultaneous measurements of the ratios w_H/w_{He} and q_{Li}/w_{He}.

The principal He-like transitions always dominate our spectra and we give 0.13(0.19), 0.25(0.28), and 0.50(0.47) as typical relative intensities for the x, y, and z transitions in S (Cl). The calculations of Gabriel (1972) predict quite similar ratios, namely, 0.13 (0.17), 0.25(0.25), and 0.64(0.60) but for densities below its critical value. Data from solar flare measurements have already confirmed these predictions for the low density regime $N_e << N_e^*$ (Doschek et al. 1981). 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) x 10^{14} cm^{-3}. These results are suggestive of a higher value for the critical density than predicted in the framework of standard theories.

A conspicuous feature of our results is the degree of fluctuations observed in the X/y and z/x+y line ratios for seemingly similar plasma discharges even though the average line ratios fall close to atomic predictions. In particular, the intensities of x,y and z can vary a factor of two from the averages even for nearly constant w emission. These variations sometimes occur in connection with unusual time histories of the X-ray emission. Therefore, one might seek the cause in the transient features of the plasma such as the 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 (Pradhan et al. 1981) from 2 $^3S_1$ to 2 $^3P_{1,2}$. Of note here is the predicted (Vinogradov et al. 1977; Beigman et al. 1979) collisional mixing of the n=2 states for H-like ions affecting even the $P_{1/2,3/2}$ states and resulting in line ratios $w_H(P_{1/2})/w_H(P_{3/2}) > 0.5$. We have measured this line ratio for H-like S and find values that indeed are larger than 0.5. The observed range of variation is 0.5 to 0.8 for densities in the range (1-4) x 10^{14} cm^{-3} but with no apparent correlation in the variation of $w_H(P_{1/2})/w_H(P_{3/2})$ and N_e. A common cause of these line ratio variations and those of the principal He-like transitions might be suspected which calls for simultaneous measurements of both the H-like and He-like parts of the spectra.

In conclusion, we have measured H-, He- and Li-like line spectra for S and Cl and identified the principal $2n \rightarrow 1n$ 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 sulphur. Collisional mixing of the 2n states should be important in our density regime ($N_e \gtrsim 10^{14}$ cm^{-3}) but the predicted manifestation of such effects, the depletion of the forbidden line, is not observed. 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 or that transient plasma effects such as departure from ionization equilibrium are important.

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References

Alcator Group, 1980, J.Vac.Sci.Technol. 17, 258.

Beigman, I.L., Bureeva, L.A., and Yu Skobelev, I., 1979, Sov.Astron. 23, 725.

Bhalla, C.P., Gabriel, A.H., and Presnyakov, L.P., 1975, MNRAS, 172, 359.

Bitter, M., et al., 1979, Phys.Rev.Lett. 43, 129.

Cowan, R.D., 1981, unpublished, private communication.

Doschek, G.A., et al., 1981, Astroph. J.. 249, 372.

Edlén, B. and Tyrén, F., 1939, Nature 143, 940.

Gabriel, A.H., 1972, MNRAS 160, 99.

Jacobs, V.L., et al., 1979, Astroph.J. 230, 627.

Pradhan, A.K., Norcross, D.W., and Hummer, D.G., 1981, Astroph. J. 246, 1031, ibid 249, 821.

Safronova, U.I., 1981, Physica Scripta, 23, 241.

Schnopper, H.W. and Taylor, P.O., 1977, DOE Report E4-76-S-02-4021.

Vainshtein, L.A. and Safronova, U.I., 1978, Atomic Data and Nuclear Data Tables 21, 49.

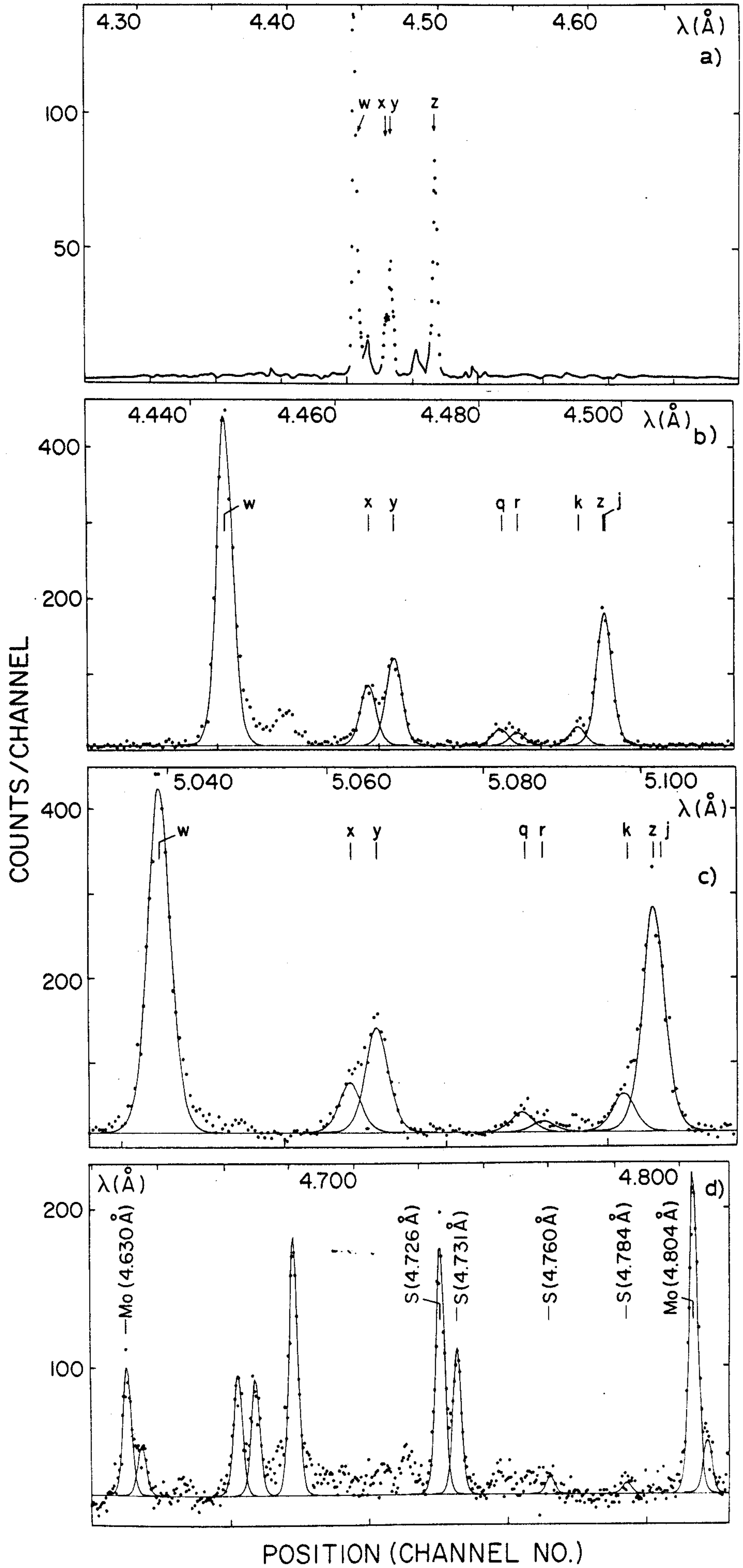
Van Hamos, L., 1933, Ann.der Physik 17, 716.

Vinogradov, A.V., Yu Skobel, I., and Yukov, E.A., 1977, Sov.J.Plasma Physics 3, 389.

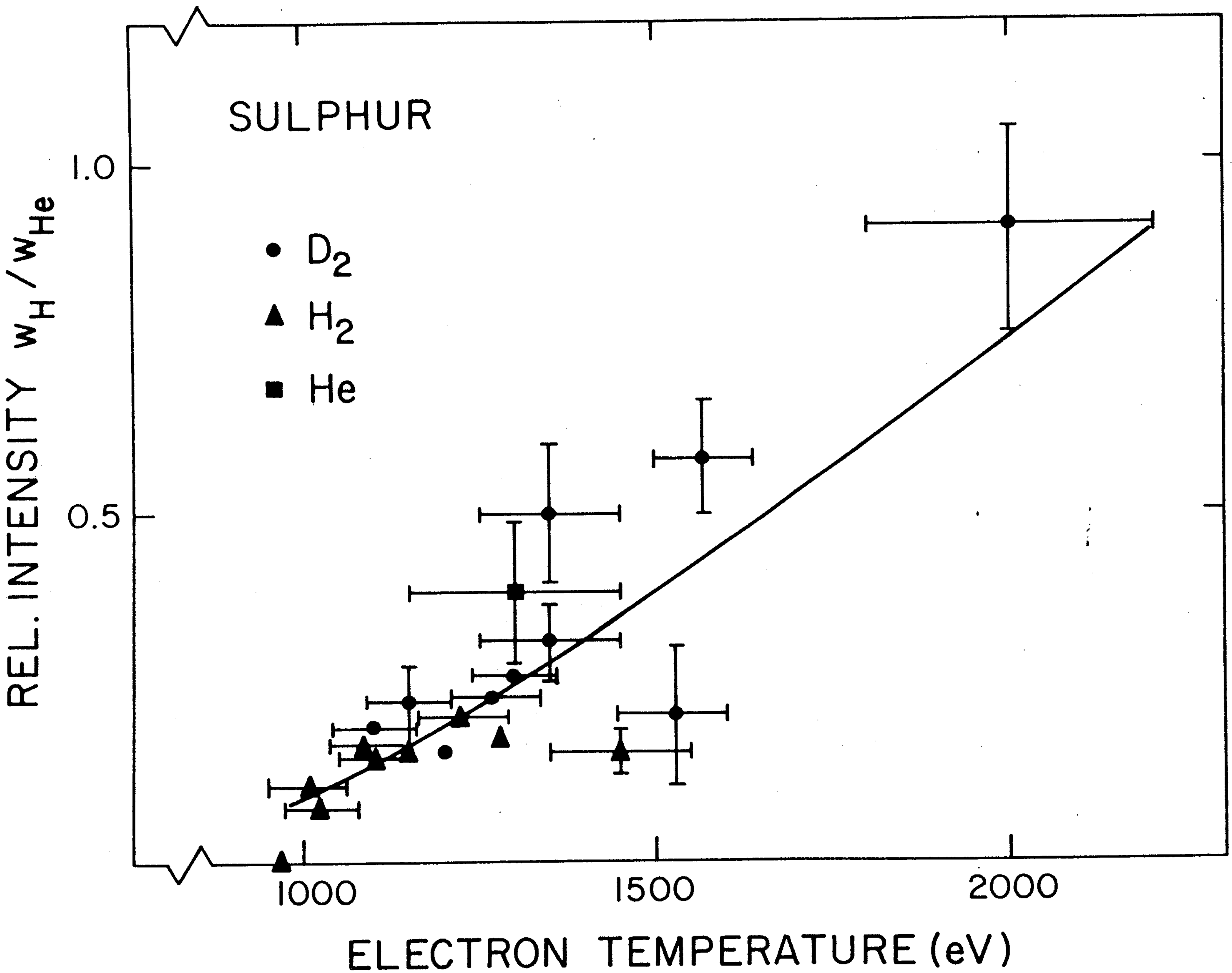
Figure Captions

Fig. 1 Example of X-ray spectrum recorded for a single plasma discharge showing the full λ-range covered by the detector [a]. Partial spectra showing the X-ray emission of He-like Cl [b] and S [c], and H-like S along with emission from Mo [d]. Wavelengths of predicted (Gabriel 1972; Vainshtein and Safronova 1978; Safronova 1981) S and Cl lines are indicated relative to the resonance line (w); for the letter symbols used, see the text.

Fig. 2 Measured intensity ratios of the resonance transitions in H- and He-like sulphur plotted vs. electron temperature. Comparison is made with coronal equilibrium prediction.



4.30
4.40
4.50
4.60
λ(Å)
a)
w x y
z
100
50
4.440
4.460
4.480
4.500
λ(Å)
b)
400
200
w
x y
q r
k z j
5.040
5.060
5.080
5.100
λ(Å)
400
200
w
x y
q r
k z j
c)
COUNTS/CHANNEL
λ(Å)
4.700
4.800
d)
200
100
Mo (4.630 Å)
S(4.726 Å)
S(4.731 Å)
S(4.760 Å)
S(4.784 Å)
Mo(4.804 Å)
POSITION (CHANNEL NO.)


SULPHUR
● D_2
▲ H_2
■ He
REL. INTENSITY w_H / w_{He}
1.0
0.5
1000
1500
2000
ELECTRON TEMPERATURE (eV)