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ON X-RAY SPECTRAL LINES OF HIGH n RYDBERG TRANSITIONS IN Ar$^{16+}$
OBSERVED FROM A TOKAMAK PLASMA

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Abstract

The He-like spectrum of $1s^2 - 1snp$ transitions and satellites in Ar$^{16+}$ have been measured from the plasma of the Alcator C tokamak. In the wavelength region of $\lambda = 3.0$ to $3.4$ Å, three groups of satellite lines $1s^22s - 1s2s n\ell$ are observed which accompany each of the resonance lines emanating from the upper orbitals from $n = 4$ to $n = 10$. Results of new calculations are presented and used for identification of the observed spectra and for discussion of line intensities and wavelengths. All satellite lines belonging to the high $n$ states observed ($n = 4$ to $n = 10$) have been identified in the calculations.

1. INTRODUCTION

In high temperature plasmas the dominant excitation mechanism is electron impact excitation from the ground state of the various ion species. The radiative transitions mostly observed in the X-ray region are the $\Delta n = 1$ ($n = 2$ to $n = 1$) and in the VUV region the $\Delta n = 0$ ($n = 3$ to $n = 3$ and $n = 2$ to $n = 2$) transitions. However, present day research of hot laboratory plasmas involve many operation schemes which can enhance other population mechanisms. So, for example, with neutral beam injection the charge exchange process becomes important and other $n$ states are populated than those populated by electron impact excitation. Furthermore, the ions are moving in the plasma, diffusing to hotter or colder regions than where they were produced and fast ionization, maybe double ionization, as well as radiative recombination processes must be taken into account. In the present paper we describe results of an experiment undertaken to study high $n$ states of Ar$^{16+}$, states which normally are not studied but which become important in the cases when charge exchange recombination has to be considered. In order to identify the spectra and the accompanying satellite lines we have also performed calculations for the satellite lines accompanying the $n=4$ and 5 states. A detailed description of the calculations and comparison with experimental data will be given elsewhere; this paper gives the first identification of the spectral features.
2. THE PLASMA SOURCE

X-ray spectra were recorded by observing the X-ray emission from the plasma of the Alcator C tokamak. The central electron density and temperature were $2.1 \times 10^{19}$ cm$^{-3}$ and 1.4 keV as measured with a far infrared interferometer and with an X-ray pulse-height system, respectively. Argon was introduced into the plasma by gas puffing, the amount of argon was adjusted to allow observation of the weakest line in the X-ray spectra and still keeping the argon density low enough so as not to disrupt the plasma. The X-ray spectrometer viewed the plasma along a central chord and all spectra were recorded during the quiescent phase of the plasma discharge (see Fig.1).

![Graph showing plasma current, electron density, and soft X-ray emission](image1)

**FIG.1** Time evolution of plasma current ($I_p$), electron density ($n_e$), central soft X-ray emission and the Ar$^{14+}$ resonance line intensity during the plasma discharge.

3. THE X-RAY SPECTROMETER SYSTEM

Fig.2 shows a schematic of the X-ray spectrometer set-up with a central line-of-sight through the plasma. The X-ray spectra to be recorded, the full Rydberg series from He-like argon, has a relative amplitude range of three orders of magnitude. Thus, the spectrometer system must have a large dynamic range in order to be able to record the high intensity part of the spectrum together with the weak lines accompanying the high n states. A small instrument built in van Hamos geometry was used together with a specially designed high count rate, high resolution multiwire proportional counter. The crystal (quartz 1011, 25x25 cm) was curved in the van Hamos geometry to a radius of 50 cm by gluing the thin crystal (-0.2 mm) to a machine polished curved crystal holder. The details of the X-ray detector has been described elsewhere; the spatial resolution is 80 μm and it has a count rate capability of 1 MHz limited by the electronic read-out modules.

4. EXPERIMENTAL RESULTS

Fig.3 shows the complete X-ray spectra of the $n=10$ to $n=3$ to ground state $n=1$ transitions both on a linear and on a logarithmic intensity scale (the latter in order to more clearly show the satellite structure in the spectra). The spectra were recorded with two different settings of the spectrometer; the two parts are separated in the figure with a solid vertical line. Identification of the three groups of satellite lines belonging to each diagram transition $np-1s$ ($n=4$ to $10$) are marked with vertical lines in the figure.
FIG. 3 The measured He-like spectrum of Ar. The 1snp $^{1}P_{1} - 1s^{2}1S_{1}$ resonance lines ($W_n$) and accompanying satellites ($S_1$, $S_2$, and $S_3$) are indicated as well as the $1s3p ~^{3}P_{2} - 1s^{2}1S_{1}$ intercombination line ($X_0$), and the 1s $- 3p$ resonance line of H-like Ar($W_1$).

5. IDENTIFICATION OF SATELLITE STRUCTURE

The dielectronic satellite spectrum of transitions from $n = 4$ and $n = 5$ in Ar$^{16+}$ were calculated using the numerical methods previously applied to $n = 3$ satellite structures. A set of three groups consisting of altogether twelve lines ($S_1$, $S_2$ and $S_3$) are identified as satellites to the main diagram line for $n = 4$ (with separation of 44, 62 and 72 mA, respectively). The same general satellite structure of relative wavelengths and intensities is produced for the $n = 5$ orbital which is also in agreement with the measurement. For interpreting the $n > 5$ transition spectrum, we relied on small systematic changes in relative satellite intensities and wavelength separations as a function of $n$.

6. DISCUSSION

The intensity of the diagram lines falls off as $1/n^3$ as shown in Fig.4a inferring that the lines are all produced by electron impact excitation from the ground state of Ar$^{16+}$. It must be emphasized, however, that all observations described in this paper are through a central line-of-sight, i.e., observing emission from the central part of the plasma. In cases of observations off the central line the high $n$ states have been observed populated to a much larger degree than predicted by the $1/n^3$ dependence.$^{1,5}$

FIG. 5 Comparison of $n = 4$ to $n = 1$ with $n = 2$ to $n = 1$ transitions of the He-like Ar spectrum.

FIG.4 The measured relative intensity variation (a) of the 1snp $- 1s^{2}$ resonance lines $W_n$ and (b) of the intensity ratios $I(S_3)/I(W_n)$ of satellite to resonance line as a function of orbital number $n$. 

FIG.3 The measured He-like spectrum of Ar. The 1snp $^{1}P_{1} - 1s^{2}1S_{1}$ resonance lines ($W_n$) and accompanying satellites ($S_1$, $S_2$, and $S_3$) are indicated as well as the $1s3p ~^{3}P_{2} - 1s^{2}1S_{1}$ intercombination line ($X_0$), and the 1s $- 3p$ resonance line of H-like Ar($W_1$).
Three groups of satellite lines have been identified and can fully explain the satellite spectrum belonging to these high $n$ states. The three groups originate from the transitions $1s2s(^1S_0)np - 1s^22s 2S_{1/2}(S_1)$, $1s2s(^3S_1)np - 1s^22s 2S_{1/2}(S_2)$, and $1s2p(^3P)np - 1s^22p 2P_{1/2,3/2}(S_3)$, respectively. Thus, $S_1$ and $S_2$ are ground state transitions while $S_3$ belongs to the $2p$ excited state. It is instructive to compare the spectra from $n = 2$ to $n = 1$ with one from $n = 4$ to $n = 1$ (Fig. 5) to identify the three groups of satellite lines belonging to a diagram line. The lines are clearly separated from the main diagram line in the higher $n$ spectrum and ambiguity can only arise when satellite lines from a higher $n$ orbital overlap with a lower $n$ diagram line. The satellite intensity relative to the diagram line as a function of $n$ stays constant as shown by Fig. 4b implying that the production mechanism of the satellite lines are dielectronic recombination and inner-shell excitation and not electron impact excitation as for the diagram lines. This $n$ dependence also aid in the identification of the satellite lines.

The wavelength separations of the satellite lines to the diagram line are predicted from the theoretical calculations and a formula has been applied to predict the wavelength separations for $S_3$. Similar dependencies can also be derived for the $S_2$ and $S_1$ satellite lines.

**FIG. 6** The measured separation in wavelength $\lambda(S_3) - \lambda(W_n)$ between the satellite groups $S_3$ and the resonance lines $W_n$ as function of $n$.

7. CONCLUSIONS.

We have presented new measurements of $n>2$ satellites for Ar$^{16+}$ $1snp - 1s^2 n24$ from a tokamak plasma with central electron temperature of about 1.5 keV. We found three distinctive groups of satellite lines ($S_1$, $S_2$, and $S_3$) of each resonance line $1snp - 1s^2$ for $n$ between 4 and 10. These were identified with the help of atomic calculations as belonging to transitions of the type $1s2s(^1S_0)np - 1s^22s$ and $1s2s(^3S_1)np - 1s^22s$ and $1s2p(^3P)np - 1s^22p$, respectively. The $n$ dependences of intensities and wavelengths are discussed and comparisons were made with the commonly studied He-like spectra of $1s2p - 1s^2$ transition.

REFERENCES