

Observations of Recombination Population of $n = 2$ Excited States of Ar^{16+} in Tokamak Plasmas

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(Received 17 October 1983)

Results from the first radial measurements of the $n = 2$ to $n = 1$ x-ray transitions of high- Z elements in deuterium tokamak plasmas are presented. The observed line intensity ratios cannot be explained by electron-impact excitation and dielectronic recombination processes. Radiative and charge-transfer recombination are proposed as additional population mechanisms. The emission lines emitted in the cascade following capture constitute a unique diagnostic probe of the neutral component of plasmas.

PACS numbers: 52.70. - m, 32.30.Rj, 34.70.+e

High-resolution spectroscopy of the He-like $n = 2$ to $n = 1$ x-ray emission of high- Z elements in high-temperature plasmas, particularly in tokamaks, has developed into a powerful technique for determining the main plasma parameters such as electron temperature T_e and density N_e as well as the ion temperature and ionic charge state distribution. Detailed rate calculations¹ predict the observed relative intensities of the principal transitions, the resonance (w), intercombination (x and y), and forbidden (z) lines from respectively the 2^1P_1 , $2^3P_{2,1}$, and 2^3S_1 states, and satellite lines.^{2,3} The agreement between measured and calculated line ratios confirms that excitation of the Ar^{16+} ground state, by electron impact and dielectronic recombination, is the principal population mechanism. Most measurements, however, have been limited to the plasma core region, where the x-ray emission is brightest and most easily measured, and studies are needed to test this model throughout the plasma.

We report here a systematic study of the He-like spectrum for a high- Z element (argon) in a deuterium plasma as a function of distance from the plasma center along the minor radius. An earlier study of oxygen has been carried out by Peacock and Summers.⁴ The relative intensity of lines of Ar^{16+} originating in triplet and singlet $n = 2$ states is found to increase strongly along the more peripheral lines of sight. The variation cannot be explained by electron impact and dielectronic recombination and we suggest that the increase arises in part from radiative recombination and in part from

charge-transfer recombination, $\text{D} + \text{Ar}^{17+} \rightarrow \text{D}^+ + \text{Ar}^{16+}$. A fraction of the plasma working gas exists as neutral atoms with the highest concentration found towards the plasma edge because of recycling from the wall of the vacuum vessel and the plasma limiters. In plasmas heated by neutral-beam injection, charge transfer of highly ionized atoms can significantly affect the overall power balance. Excitation by charge transfer in the visible and ultraviolet has been seen in line emission during active H and D beam injection.⁵⁻⁸ Here we demonstrate the effects of charge-transfer recombination on line intensities of the x-ray spectrum of a high- Z element in quiescent, Ohmically heated plasma.

The experiment was performed at the Massachusetts Institute of Technology tokamak, Alcator C, with a Bragg crystal spectrometer. The instrument is a new, small spectrometer of von Hamos geometry, previously described.⁹ It was mounted with a pivot at the spectrometer entrance slit which allowed scanning of the radial dependence of the x-ray line emission with a spatial resolution of about 30 mm. The quartz crystal had a two-dimensional lattice spacing of 6.687 \AA using the $10\bar{1}1$ plane. The wavelength band width was about 2.1% so either of the entire H- or He-like spectra of argon could be recorded. For the photon detection we used the active delay-line proportional counter¹⁰ together with commercially available 1-MHz electronics for the time-to-digital conversion and storage of the resulting position histograms. The system was operated up to a data rate of about

0.5 MHz and a counting rate of up to 200 kHz for the strongest emission line alone; a detailed account of the detection system will be given elsewhere. To achieve the desired counting rate, the plasma was seeded with Ar but the concentration was always small ($< 0.1\%$); it had no significant effect on Z_{eff} nor did it perturb the plasma. The plasma conditions were kept constant during the radial scan with $T_e = 1.45$ keV and $N_e = 2.9 \times 10^{14} \text{ cm}^{-3}$ at the center for a plasma current of 450 kA and a toroidal field of 8 T. The limiter had a radius of 16.5 cm.

The spatial scan measurement, spanning three decades in count rate, was made possible only by the combination of high plasma density, high throughput in the spectrometer, and the argon seeding. Typical examples of spectra taken for three lines of sight at $d = -0.7, 8.3,$ and 11.3 cm off the plasma axis are shown in Figs. 1(a), 1(b), and 1(c), respectively; d is the distance along the plasma minor radius to the chord of observation. Spectra were recorded for each 20 ms of the discharge but those shown were integrated over 200 ms to increase the statistics; the plasma conditions were constant during this time period with no obvious change in the He-like spectrum. In all, the He-like spectrum was recorded for ten lines of sight in the range $d = -7.8$ to 12.8 cm and the H-like spectrum in the range $d = -4.5$ to 7.1 cm. Line fits were made to eight readily distinguishable transitions for the He-like spectrum (shown in Fig. 1) from which we determined the following line intensity ratios: $G = (x + y + z)/w$, $K = k/w$, and $Q = q/w$. The dependence of these ratios on T_e and the abundance ratio $N(\text{Ar}^{15+})/N(\text{Ar}^{16+})$ are the standard diagnostic probes. To this list we added $S = (x + y)/w$ which is the triplet-to-singlet ratio for the $2P$ state. To obtain the intensity of the z line we included a correction of -1.3 times the intensity of the line k to account for the estimated admixture of the unresolved line j .² The measured line ratios are given in Fig. 2 as a function of d .

The most conspicuous feature of the data in Fig. 2 is the behavior in the region $d \geq 8$ cm. Thus, S and G increase rapidly with d followed by a tendency to level off at large d , and K and Q increase towards large d followed by a decrease at $d \approx 8$ cm. From electron-impact excitation and dielectronic recombination we expect a monotonic increase in the line ratios G , K , and Q with decreasing T_e . In the range $T_e = 1.4$ to 0.2 keV, corresponding to the temperatures¹¹ at $d = 0$ and 12.8 cm, G is indeed predicted¹² to increase but only by 25%. The ratio K shows initially the expected increase with decreasing $T_e(d)$, which trend is interrupted at $d \approx 10$

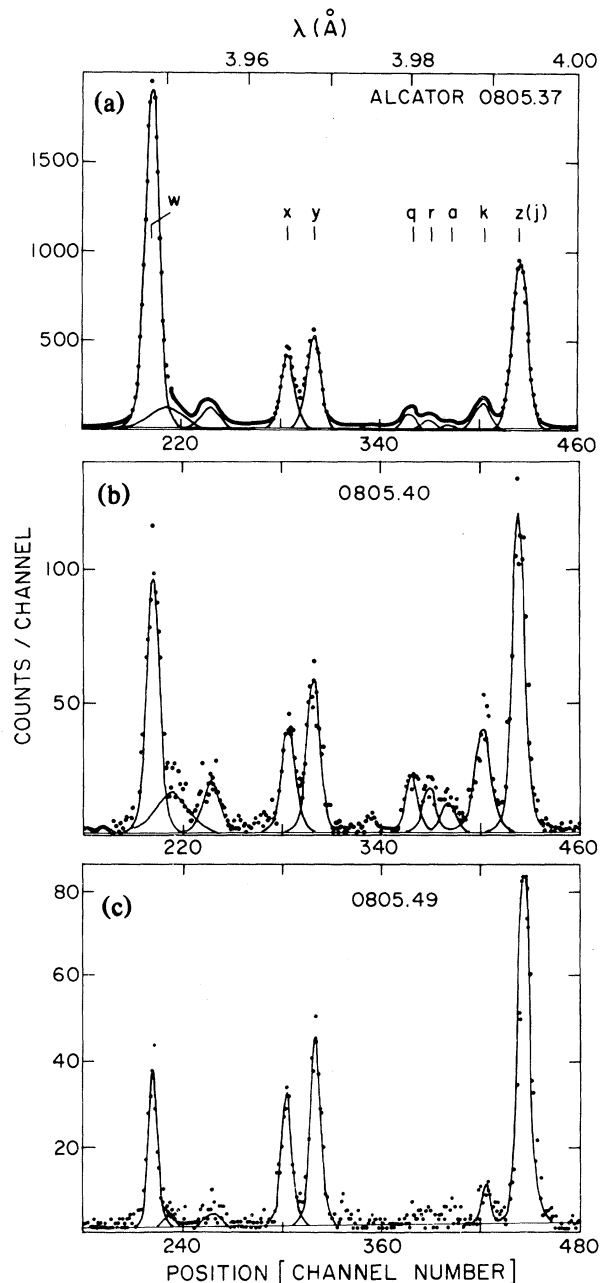


FIG. 1. The He-like spectrum of argon recorded during 200 ms of single plasma discharges for three different lines of sight through (a) the plasma center, and points at (b) $d = 8.3$ and (c) 11.3 cm from the center. The low data points in (a) are shown as a thick line. The abscissas give the actual counts recorded without correction for variations in the Ar concentration. Predicted wavelengths (Ref. 2) are indicated relative to the resonance line (w). Key to the letter symbols (Ref. 3): w , $1s^2 1S_0 - 1s 2p^1 P_1$; x , $1s^2 1S_0 - 1s 2p^3 P_2$; y , $1s^2 1S_0 - 1s 2p^3 P_1$; q , $1s^2 2s^2 S_{1/2} - 1s(2s 2p^1 P)^2 P_{3/2}$; r , $1s^2 2s^2 S_{1/2} - 1s(2s 2p^1 P)^2 P_{1/2}$; a , $1s^2 2p^2 P_{3/2} - 1s 2p^2 P_{3/2}$; k , $1s^2 2p^2 P_{1/2} - 1s 2p^2 D_{3/2}$; z , $1s^2 1S_0 - 1s 2s^3 S_1$; j , $1s^2 2p^2 P_{3/2} - 1s 2p^2 D_{5/2}$.

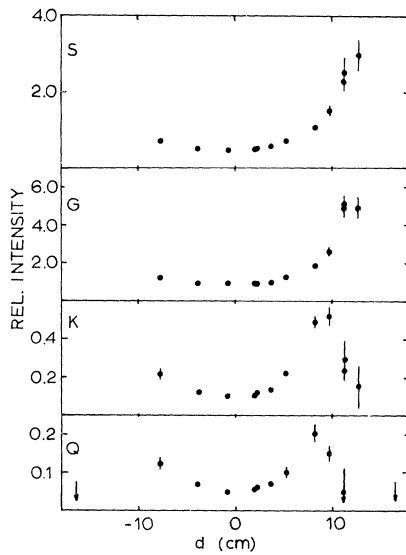


FIG. 2. Results on the line intensity ratios, $S = (x + y)/w$, $G = (x + y + z)/w$, $K = k/w$, and $Q = q/w$, for different lines of sight given by the distance d from the plasma center. The errors shown are statistical and the arrows show the extension of the plasma limiters.

cm. Such effects suggest underlying changes in population mechanisms.

At the diminished temperatures, the impact excitation processes proceed more slowly while the recombination rates increase. For instance, at $T_e = 350$ eV which is reached at $d = 11.3$ cm, the rate coefficient for excitation of Ar^{16+} is $5 \times 10^{-15} \text{ cm}^3 \text{ s}^{-1}$ whereas that for recombination of Ar^{17+} is $3 \times 10^{-12} \text{ cm}^3 \text{ s}^{-1}$. Accordingly, the latter process is the more effective one when the Ar^{17+} -to- Ar^{16+} abundance ratio exceeds 3×10^{-3} which indeed seems to be the case as discussed later. Some of the variations in line intensity ratios are thus qualitatively consistent with radiative recombination and also with charge transfer, which must be considered. It has a rate coefficient of about $10^{-7} \text{ cm}^3 \text{ s}^{-1}$, depending weakly on T_e so that at 350 eV it is comparable to radiative recombination when the fractional neutral content N_0/N_e is 3×10^{-5} . Models of the neutral deuterium distribution¹³ in the Alcator machine indicate that $N_0/N_e \approx 10^{-4}$ at a radius of 12 cm close to a limiter. In contrast to the principal lines (w , x , y , and z), the satellites are not affected by radiative or charge-transfer recombination. The observed decrease in the line ratios K and Q is thus consistent with the suggested change in population mechanism at $d \approx 8$ cm.

We suggest that the measured intensity variations

can be explained by a combination of contributions from excitation processes and from radiative and charge-transfer recombination. There is a narrow spatial region between 8 and 12 cm from the plasma axis in which the dominant contribution switches from excitation to recombination. The charge-transfer process varies slowly with T_e and its effectiveness grows rapidly at large distances because of the increase in neutral-particle density towards the plasma edge and should become the major population mechanism beyond some critical distance from the plasma axis. Indeed there may occur three regions dominated in turn by the three types of processes.

The recombination on Ar^{17+} relative to excitation of Ar^{16+} depends on the abundance ratio $N(\text{Ar}^{17+})/N(\text{Ar}^{16+})$. If this ratio were given by the ionization and recombination of ions in corona equilibrium, it should decrease rapidly with T_e and hence radius, to become less than 10^{-4} for $d > 8$ cm. Our measurements of the H- and He-like Ar spectra in the range $d = 0$ to 8 cm suggest a rather moderate decrease with radius so that $N(\text{Ar}^{17+})/N(\text{Ar}^{16+})$ remains above 10^{-2} at 8 cm. We take this to mean that in regions of large radial N_e and T_e gradients, ion transport becomes a factor in the charge-state balance which would, in effect, reduce the rate at which the ratio $N(\text{Ar}^{17+})/N(\text{Ar}^{16+})$ would otherwise decrease with radius. The finding that radiative or charge-transfer recombination is needed to explain the data for $d > 8$ cm is thus consistent with the large ratios $N(\text{Ar}^{17+})/N(\text{Ar}^{16+})$ deduced from the relative intensities of H- and He-like spectra measured separately in this experiment. It can be noted that more direct information on the charge-state balance will be provided by planned experiments with spectrometers of extended bandwidth ($\Delta\lambda/\lambda = 10\%$) for simultaneous measurements of the H- and He-like spectra.

In the region where either radiative or charge-transfer recombination is dominant, the triplet-to-singlet ratio S should statistically be about 3 as is observed at large distances. Differences, however, can occur in the 2^3S_1 and $2^3P_{1,2}$ level populations resulting from differences in the capture distributions of the two processes. In $\text{Ar}^{17+} + \text{D} \rightarrow \text{Ar}^{16+} + \text{D}^+$, captures occur preferentially into states of principal quantum numbers lying in the range $n = 7-11$ and, at the low ion velocities involved, into states of low angular momentum l .¹⁴ The high-lying states cascade down with the emission of dipole radiation, sometimes directly to the ground $1s^2 1S_0$ state, but most decays pass through

the excited $n=2$ states. Detailed cascade calculations have been carried out¹⁵ to determine the line ratios G and R . It is found that in the regions of the plasma dominated by radiative and charge-transfer recombinations into states with $n=2$ to 10, the ratio G is greatly enhanced because of preferential cascades to the triplet states, 2^3S and 2^3P , over the singlet state, 2^1P . The ratio R is relatively constant. At about 350 eV, the calculated values of G and R are approximately 7.0 and 1.0, respectively. The observed values from Fig. 1(c) are ≥ 5.0 and 0.9 ± 0.2 , respectively. It would require more detailed modeling in order to resolve the remaining qualitative discrepancies between theory and experiment; however, the qualitative interpretation is supported by the calculations. It is worth noting that the $n=2$ to $n=1$ transitions studied are part of the Lyman α series of Δn transitions. The most direct manifestation of charge transfer would therefore be the spectrum of Δn transitions spanning the range $\Delta n=1$ to 10 corresponding to $\lambda=4.0$ to 3.0 Å. The signature of charge-transfer population would be found in the Δn intensity distribution which would also reflect its capture rates to certain atomic states and the neutral density in the plasma. Such an experiment, therefore, might be done by developing a spectrometer with extra-large Bragg-angle span, i.e., $\Delta\theta$ of about 11° in our case.

In conclusion, we have presented new measurements of the x-ray line emission of He-like Ar from both central and peripheral regions of a tokamak plasma. We find that the principal lines of the spectrum for peripheral plasma regions ($d > 8$ cm) are dominated by population through radiative and charge-transfer recombination because of two factors: The temperature in this region is low so as to disfavor population by electron-impact excitation of $n=2$ Ar¹⁶⁺ states; the abundance ratio $N(\text{Ar}^{17+})/N(\text{Ar}^{16+})$ is found to be enhanced which is believed to result from radial ion transport. We argue that charge transfer will become the supreme population mode for the principal lines of the He-like spectrum beyond some critical radius because of the rapid increase of the neutral concentration N_0/N_e towards the plasma edge. Our spectra for $d > 10$ cm are consistent with dominant charge-transfer population. The results illustrate that the technique is sufficiently efficient to record neutral concentra-

tions of 10^{-4} to 10^{-5} at $T_e=200$ –500 eV and we suggest that dedicated studies of higher Δn transitions should offer even greater sensitivity. The spectroscopy of He-like ions can thus be used for diagnostic of neutrals in tokamak plasma (from both passive and active sources) and it can also be of interest for atomic rate studies.

We gratefully acknowledge the continuous support we have enjoyed from Dr. R. R. Parker and the Alcator staff and the enthusiastic work by Scott Magoon on computer programming.

This experiment was supported by U. S. Department of Energy Contracts No. DE-AS02-76ET-53052 and No. EA77AO1-6010 (with the National Bureau of Standards) and Division of Chemical Sciences Contract No. DE-AC02-76ER02887.

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