DIRECT SPECTROSCOPIC OBSERVATION OF CHARGE-EXCHANGE
RECOMBINATION OF MEDIUM-Z ELEMENTS IN THE PLT TOKAMAK

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ABSTRACT

We report the first observation of line emission resulting directly from charge-exchange recombination of medium-Z elements (Al, Sc) injected into a PLT discharge. Transitions due to the radiative cascade immediately following charge-exchange of He-like Al and Sc were observed by a VUV spectrograph and two air monochromators. In two cases, AlXI 3209 Å and ScXIX 112.1 Å, the observed transition had not previously been experimentally identified. Spatial scans provided information on the profile of the neutral beam in the plasma.

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INTRODUCTION

Charge-exchange recombination has been recognized as having an important role in impurity radiation losses in fusion plasmas heated by neutral hydrogen beams.¹ The increase in radiation losses due to charge-exchange recombination of medium and high-Z elements puts stringent constraints on the maximum acceptable level of these impurities if the high temperatures necessary for ignition are to be achieved. From a diagnostic point of view, important advances in measurements of totally ionized oxygen and carbon densities, plasma rotation, and diffusion coefficients have been based on spectroscopic observations of charge-exchange recombination.²⁻⁸

In the present paper we report the first direct observations of charge-exchange recombination of medium-Z elements in the Princeton Large Torus (PLT). Effects of charge-exchange recombination on line emission of medium-Z elements have been observed previously in PLT (Fe, Ti)⁹ and DITE (Ti)¹⁰ where changes in emission of transitions excited in the ground state were reported. By contrast, in the present work we report direct observation of the radiative cascade immediately following charge-exchange recombination of He-like Al and Sc. This radiation is only observable in the region of the plasma intersected by the neutral beam, and its intensity is proportional to the product of the neutral beam and He-like ion densities.

EXPERIMENTAL ARRANGEMENT

In these experiments the PLT tokamak was operated with deuterium with a line average electron density $\bar{n}_e$ in the range $1.2 - 1.8 \times 10^{13} \text{ cm}^{-3}$ and central electron temperature, $T_e(0)$: 1.5 - 2.5 keV. Three neutral heating beams North (N), East (E), and West (W) were operated with hydrogen at 28-37 kV, 300-600 kW. Aluminum or scandium was injected into the plasma by the laser blow-off technique.¹¹

Three spectrometers were used to observe the plasma radiation (Fig. 1). One, a time resolving grazing incidence VUV spectrograph,¹² based on an image intensified photodiode array detector, is labelled J.H. GIMS in Fig. 1. The spectrograph has been radiometrically calibrated over the 60-360 Å range at the NBS SURF II electron storage ring. A wavelength range of 40 Å with the detector centered at 40 Å, to 80 Å with the detector centered at 200 Å was observed during a plasma discharge, with an integration time of 5.4 ms. The instrument could be moved in a vertical plane providing a spatial scan of the plasma emission from minor radius, $r = +10$ cm (above the midplane) to $r = -22$ cm. The line of sight of the instrument was close to the point where the W neutral beam entered the plasma. With the instrument observing the (horizontal) midplane, the center of the W neutral beam intersected the line of sight of the instrument at $r = +30$ cm (outside the minor axis). The second spectrometer FARM¹³ (labelled Monochromator with fast spectral and spatial scanning in Fig. 1) is an *at* monochromator with a fast rotating mirror capable of repetitive spatial scans. It views the plasma in the region where the E neutral beam intersects the minor axis. The third instrument, labelled 1M Monochromator (Doppler T_1) has a vibrating LiF plate for fast spectral scans and is located between the N and W neutral beams.

EXPERIMENTAL RESULTS

Aluminum

The E, N, and W neutral beams were operated during a series of PLT discharges. Approximately 10^{18} Al atoms were injected into the plasma during the neutral beam pulse. The VUV spectrograph was first set to view the 50 Å region, and the AlXI 48.3 Å (2s-3p) and AlXI 52.4 Å (2p-3d) transitions were observed following Al injection. With the neutral beams the signals were a

factor of two higher, but they were clearly observed in discharges without the neutral beams. The AlXI 154.7 Å (3d-4f) transition was also observed after Al injection; however, this transition was only clearly observable for discharges with the W neutral beam present (Fig. 2). A very weak signal was observed with the N beam (but no W beam) and no emission could be detected with only the E beam or no beams present. This is completely consistent with the experimental geometry (Fig. 1), thus we identify the 154.7 Å emission as being part of the radiative cascade immediately following charge-exchange recombination of AlXII. The VUV instrument was scanned in a vertical plane and the spatial distribution of the AlXI 48.3 Å brightness without beams and the AlXI 154.7 Å brightness with beams is shown in Fig. 6. This data will be discussed with the Sc results.

These observations stimulated our search in the UV region with air monochromators for high n transitions following charge-exchange recombination. Figure 3 shows repeated vertical scans of the AlXI 3209 Å (10-9) transition with the E neutral beam (near the FARM monochromator location) operating. The volume emission rate of the AlXI 3209 Å line was calculated by Abel inversion and is seen to be centrally peaked (Fig. 3; this will be discussed with the Sc data). The same transition was also observed by the IM monochromator with fast spectral scanning when the N neutral beam was operating. Averaging over four scans yielded a gaussian line profile with an excellent signal to noise ratio (Fig. 4), and an ion temperature of 1.3 keV measured similarly to the case of OVIII.⁸

The wavelength of the AlXI 3209.8 Å transition was calculated from the semi-empirical formula of Edlen.¹⁴ To our knowledge this is the first time it has been observed experimentally. Its long wavelength is especially significant as it permits measurements of medium-Z elements in the convenient air region of the spectrum without the difficulties of VUV instrumentation.

SCANDIUM

In a separate series of experiments, $\sim 4 \times 10^{17}$ scandium atoms were injected into the plasma during the neutral beam pulse. The ScXIX 112.1 Å (5g-4f) transition was observed by the VUV spectrograph in discharges when the W neutral beam was present (Fig. 5). Without the W beam no signal was detected. In contrast the ScXIX $2s\ 2s_{1/2}-2p\ 2p_{3/2}$ 279.8 Å transition was observed in discharges both with and without the W neutral beam, indicating the ScXIX 112.1 Å emission was part of a radiative cascade following charge-exchange of ScXX. This transition was weaker than the AlXI 154.7 Å line due to a combination of a lower number of atoms injected and a smaller fraction of ions expected to be in the He-like state at $r = 30$ cm. The wavelengths of the ScXIX 5-4 transitions were calculated from the semi-empirical formula of Edlen,¹⁴ and are 112.19 Å for the 5g-4f transition and 112.09 Å for the 5f-4d transition. Theoretical calculations^{15,16} for medium-Z ions with 25-50 keV H⁺ predict charge-exchange recombination predominately to levels with high angular momentum quantum number (l). Thus, due to cascading, we expect the ScXIX 5g-4f transition to be the most intense 5-4 transition following charge-exchange recombination. The observed line at 112.1 (± 0.2) Å was sometimes blended with weaker lines at 111.9 Å and 112.4 Å, probably due to transitions in ScXIV and ScXV, respectively¹⁷; however, the 112.1 Å line was the only feature consistently correlated with the W neutral beam. The identification of the ScXIX 112.19 Å 5g-4f transition provides experimental confirmation that the semi-empirical formula of Ref. 14, previously checked against observations for $6 < Z < 14$, are also correct for $Z = 21$. A spatial scan of the ScXIX 112.1 Å line is shown in Fig. 6.

SPATIAL PROFILES

Figure 3 shows the radial distribution of the AlXI 3209 Å emission after Abel inversion. The emission is centrally peaked with a full width at half intensity of 11 cm. In general, the width of this feature was always within the range 12 ± 4 cm. The spatial profiles of the brightness of the AlXI 154.7 Å and ScXIX 112.1 Å transitions are shown in Fig. 6 together with the AlXI 48.3 Å profile; the latter data being obtained without the neutral beams. The spatial profile of the AlXI 154.7 Å and ScXIX 112.1 Å transitions are the same and contrast completely with the AlXI 48.3 Å data.

The horizontal scale in Fig. 6 corresponds to the shortest distance from the viewing chord of the VUV spectrograph to the center of the plasma ($r=0$). However, the W neutral beam crosses in front of the VUV spectrograph significantly closer than the $r=0$ point. Thus for the 154.7 Å and 112.1 Å data, the distance scale in Fig. 6 multiplied by a factor of 0.75 represents the distance above the midplane of the line of sight of the VUV spectrograph at the neutral beam. Because of the lack of (horizontal) symmetry about $r=0$, these data have not been Abel inverted, but it is clear that the width of the profile is similar to the Al 3209 Å data. These profiles are also similar to the HeII 4686 Å, CVI 3434 Å, CVI 5291 Å, and OVIII 2976 Å data obtained on PLT.⁸ They imply a neutral beam cross section of 12 ± 4 cm. This is surprisingly small, much smaller than that measured on the neutral beam test stand with a scanning calorimeter,^{18,19} or measured via neutral particle detection in PLT without plasma.²⁰ More experiments are planned to resolve this discrepancy.

CONCLUSIONS

The radiative cascade following charge-exchange recombination has been observed for the first time in medium-Z elements on the Al_KI 3209 Å (10-9), 154.7 Å (4-3), and Sc_KIX 112.1 Å (5-4) transitions. The Al_KI 3209 Å result is particularly significant for spectroscopic diagnostics because of the convenient (air) wavelength. The spatial profile of these transitions imply a surprisingly narrow neutral beam width.

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FIGURE CAPTIONS

- FIG. 1 Arrangement of diagnostic instrument in relation to the Neutral Beams used in the present experiments.
- FIG. 2 Brightness of the AlXI 154.7 Å 4f-3d transition with the E and W beam operating (solid line) and without the (W) beam (dashed line).
- FIG. 3 (a) Repeated vertical scans of the AlXI 3209 Å 10-9 transition with the E beam operating.
- (b) Emission of AlXI 3209 Å transition vs. minor radius after Abel inversion.
- FIG. 4 (a) Repetitive spectral scan of the AlXI 3209 Å line as a function of time (time of one scan is 5 ms).
- (b) Spectral line profile as a result of averaging over four individual profiles from 400-420 ms in the above scan.
- FIG. 5 Brightness of the ScXIX 112.1 Å 5g-4f transition with the (W) and (N) beam (solid line) and without the (W) beam (dashed line).
- FIG. 6 Brightness of the AlXI 154.7 and ScXIX 112.1 Å transition vs. minor radius during the (W) and (E) neutral beam pulse. The ScXIX 112.1 Å brightness has been multiplied by a factor of 10. Also shown is the brightness of the AlXI 48.3 Å transition vs. minor radius in arbitrary units (the spectrograph absolute intensity calibration does not extend to 48 Å). The line is intended as a visual aid.

Fig. 1

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Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

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