Direct Spectroscopic Observation of Charge-Exchange Recombination of Medium-Z Elements in the PLT Tokamak

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We report the first observation of line emission resulting directly from charge-exchange recombination of *medium-Z elements* injected into a PLT discharge. Transitions due to the radiative cascade immediately following charge-exchange of He-like Al and Sc were observed. One of the newly observed lines, Al XI 3209 Å, offers a convenient spectroscopic and medium-Z charge-exchange diagnostic due to its long (air) wavelength. Spatial scans provided information on the profile of the neutral beam in the plasma.

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Charge-exchange recombination has been recognized as having an important role in magnetic fusion plasmas heated by neutral beams.[1] 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 of low-Z ($Z < 10$) elements.[2-8] In addition, the increase in radiation losses due to charge-exchange recombination of medium and high-Z elements[9,10] puts stringent constraints on the maximum acceptable level of these impurities if the high temperatures necessary for ignition are to be achieved. This limit is more severe than that on low-Z elements which radiate mainly on the plasma edge.

In the present paper we report the first direct observations of the radiative cascade following charge-exchange recombination of *medium-Z elements* in the Princeton Large Torus (PLT). This radiation is only observable in the region of the plasma intersected by the neutral beam, and its intensity maps the product of the neutral beam and He-like ion densities. The observed transitions offer the first direct diagnostic in the medium-Z region of neutral-beam–induced charge exchange, the Al XI 3209 Å observation being particularly significant because of its long (air) wavelength.

In these experiments the PLT tokamak was operated with deuterium with a line-average electron density in the range $1.2–1.8\times10^{13}$ cm^{-3} and central electron temperature 1.5–2.5 keV. Three tangential 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. One, a time-resolving grazing-incidence vacuum ultraviolet (vuv) spectrograph,[12] has been radiometrically calibrated over the 60–360 Å range at the U.S. National Bureau of Standards Synchrotron Ultraviolet Radiation Facility II electron storage ring. The instrument could be moved in a vertical plane providing a spatial scan of the plasma emission. The line of sight of the instrument was close to the point where the W 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, fast rotating mirror system (FARM), is an air monochromator with a fast rotating mirror capable of repetitive spatial scans. It views the plasma in the region where the E beam intersects the minor axis. The third instrument, a 1-m monochromator, has a vibrating LiF plate for fast spectral scans and observes the region where the co-injected W beam and counter-injected N beam intersect the minor axis.

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 Al XI 48.3 Å ($3p \rightarrow 2s$) and Al XI 52.4 Å ($3d \rightarrow 2p$) transitions were observed by the vuv spectrograph following Al injection. With the neutral beams, the signals were a factor of 2 higher, but they were clearly observed in discharges without the beams. The Al XI 154.7 Å ($4f \rightarrow 3d$) transition was also observed after Al injection; however, this transition was only clearly observable for discharges with the W neutral beam

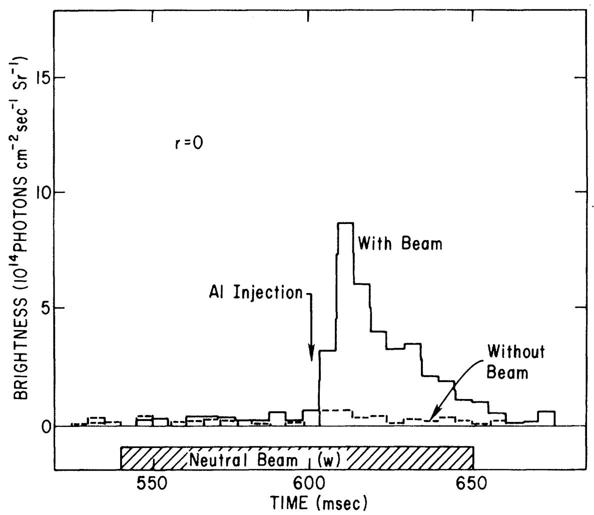

FIG. 1. Brightness of the Al XI 154.7 Å $4f$-$3d$ transition with the E and W beam operating (solid line) and without the W beam (dashed line). The spectrograph integration line was 5.4 ms.

present (Fig. 1). A very weak signal was observed with the N beam (but no W beam) present. (The N beam is attenuated by 2.4 m of plasma before it reaches the line of sight of the vuv spectrograph.) No emission could be detected with only the E beam or no beams present. The data are completely consistent with the experimental geometry; thus we identify the 154.7 Å emission as being part of the radiative cascade immediately following charge-exchange recombination of Al XII.

These observations stimulated our search in the uv region with air monochromators for high n transitions $n \gtrsim 7$ following charge-exchange recombination. Figure 2 shows repeated vertical scans of the Al XI 3209 Å ($10 \rightarrow 9$) transition with the E neutral beam (near the FARM monochromator location) operating. The same transition was also observed by the 1-m monochromator when the N neutral beam was operating. Averaging over four spectral scans yielded a Gaussian line profile with an excellent signal-to-noise ratio and an ion temperature of 1.3 keV, measured similarly to the case of O VIII.[8] The wavelength of the Al XI 3209.8 Å transition was calculated from the semiempirical formula of Edlen.[13] To our knowledge this is the first time it has been observed experimentally.

Figure 2 shows the radial distribution of the Al XI 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

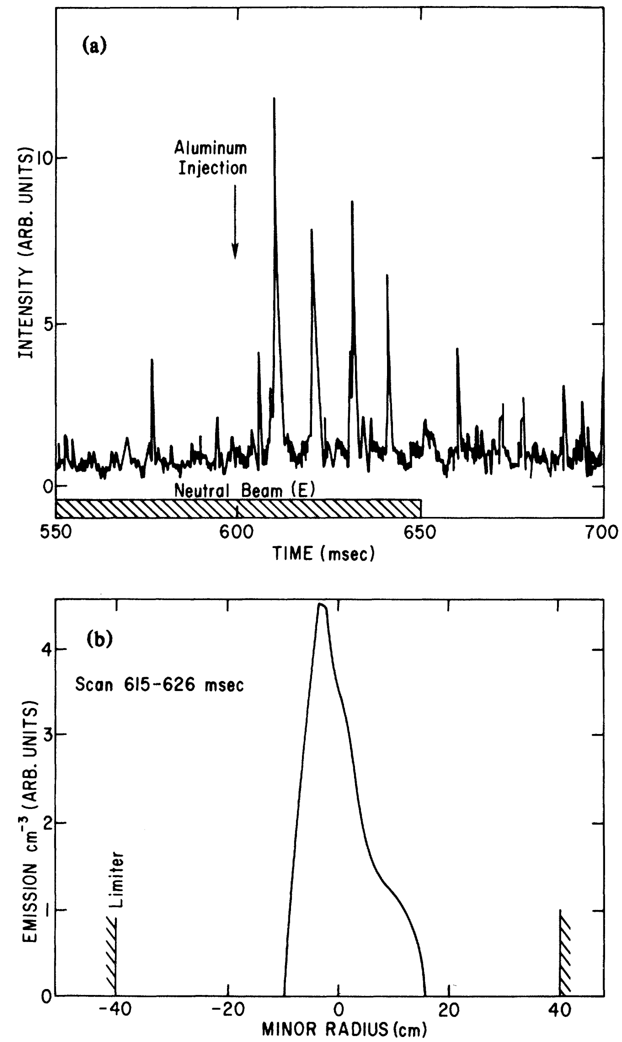

FIG. 2. (a) Repeated vertical scans of the Al XI 3209 Å 10-9 transition by the FARM monochromator with the E beam operating. (b) Emission of Al XI 3209 Å transition vs minor radius after Abel inversion.

spatial profile of the brightness of the Al XI 154.7 Å transition is shown in Fig. 3 together with the Al XI 48.3 Å profile, the latter data being obtained without the neutral beams. The spatial profile of the Al XI 154.7 Å and Sc XIX 112.1 Å (see later) transitions are the same and contrast completely with the Al XI 48.3 Å data.

The horizontal scale in Fig. 3 corresponds to the vertical distance from the viewing chord of the vuv spectrograph to the center of the W neutral beam. Here, the center of the beam is not at the center of the plasma ($r = 0$) and these data have not been Abel inverted, but it is clear that the width of the profile is similar to the Al XI 3209 Å data (Fig. 2). These profiles are also similar to the He II 4686 Å,

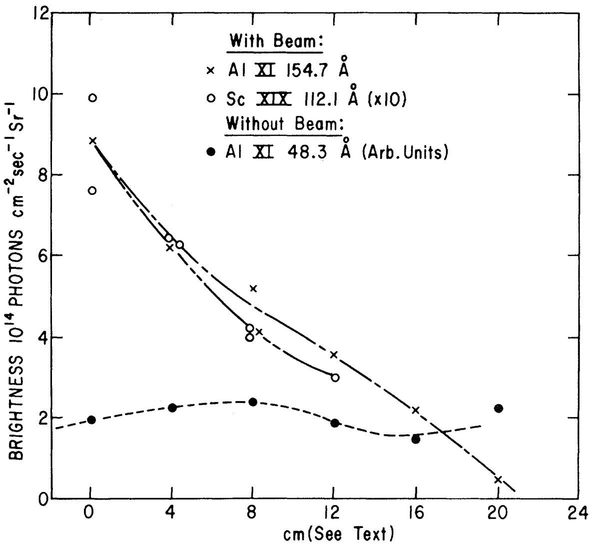

FIG. 3. Brightness of the Al XI 154.7 and Sc XIX 112.1 Å transition vs minor radius during the W and E neutral beam pulse. The Sc XIX 112.1 Å brightness has been multiplied by a factor of 10. Also shown is the brightness of the Al XI 48.3 Å transition vs minor radius in arbitrary units (the spectrograph absolute intensity calibration does not extend to 48 Å). The line is intended as a visual aid.

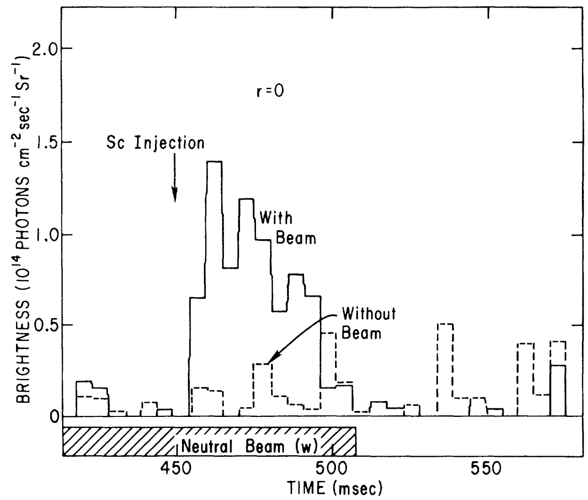

FIG. 4. Brightness of the Sc XIX 112.1 Å $5g \rightarrow 4f$ transition with the W and N beam (solid line) and without the W beam (dashed line). The spectrograph integration time was 5.4 ms.

C VI 3434 Å, C VI 5291 Å, and O VIII 2976 Å data obtained on PLT.[8] They imply a neutral-beam full width at half intensity of 12 ± 4 cm. This is surprisingly small, much smaller than that measured on the neutral-beam test stand with a scanning calorimeter,[14,15] or measured via neutral particle detection in PLT without plasma.[16] More experiments are planned to resolve this discrepancy.

In a separate series of experiments, $\sim 4 \times 10^{17}$ scandium atoms were injected into the plasma during the neutral-beam pulse. The Sc XIX 112.1 Å ($5g \rightarrow 4f$) transition was observed by the vuv spectrograph in discharges only when the W neutral beam was present (Fig. 4). In contrast the Sc XIX $2p\ ^2P_{3/2} \rightarrow 2s\ ^2S_{1/2}$ 279.8 Å transition was observed in discharges both with and without the W beam, indicating the Sc XIX 112.1 Å emission was part of a radiative cascade following charge exchange of Sc XX. The wavelengths of the Sc XIX $5 \rightarrow 4$ transitions were calculated from the semiempirical formula of Edlen,[13] and are 112.19 Å for the $5g \rightarrow 4f$ transition and 112.09 Å for the $5f \rightarrow 4d$ transition. Theoretical calculations[17,18] for medium-Z ions with 25–50 keV H^0 predict charge-exchange recombination predominately to levels with high angular-momentum quantum number (l). Thus, due to cascading, we expect the Sc XIX $5g \rightarrow 4f$ transition to be the most intense $5 \rightarrow 4$ transition following charge-exchange recombination. The identification of the Sc XIX 112.19 Å $5g \rightarrow 4f$ transition provides experimental confirmation that the semiempirical formula of Ref. 13, previously checked against observations for $6 < Z < 14$, is also correct for $Z = 21$. A spatial scan of the Sc XIX 112.1 Å line is shown in Fig. 3 and provides further evidence for a narrow neutral-beam cross section.

In conclusion we report the first direct observation of charge exchange of *medium-Z* elements (Al, Sc) in a tokamak. In particular the Al XI 3209 Å observation permits measurements of medium-Z elements in the convenient air region of the spectrum without the difficulties of vuv instrumentation. This will be especially significant as tokamaks progress to a D-T burning mode as emission at air wavelengths can be transferred using optical fibers to a remotely located spectrometer without activation and neutron damage problems with the detector. These results open the way to directly monitoring the impact of radiation losses, due to charge exchange of medium-Z elements, on plasma temperatures as tokamaks approach the $Q = 1$ and ignition regimes.

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