Observation of the Reaction $H^0 + O^{8+} \rightarrow H^+(O^{7+})^*$ during Neutral-Beam Injection into ORMAK*

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Several lines of O VIII have been investigated during the injection of hydrogen atoms at energies of 10, 15, and 30 keV into the Oak Ridge tokamak (ORMAK). The Lyman-α, -β, and -γ lines and the Balmer-β line exhibit slowly increasing signals, but the intensity of the Balmer-α line increases sharply as soon as injection begins. This prompt signal is interpreted to be the direct result of charge transfer from hydrogen to O^{7+} ions in excited states.

Injection of high-energy hydrogen atoms into tokamak-produced plasmas is one of the most promising means of providing the supplementary heating necessary to approach temperatures at which ignition can take place. However, the presence of impurities may severely inhibit the effectiveness of this technique by attenuation of the neutral beam through charge exchange or through direct ionization in regions outside the central core.

Oxygen is the dominant impurity in most tokamaks; theoretical considerations[1] indicate that the charge-transfer cross section for 30-keV hydrogen atoms incident on O^{8+} may be as large as 3×10^{-15} cm^2. A multistate Landau-Zener model predicts that this transfer takes place primarily into excited states of O^{7+} which have $n=4$ or 5. A comparison of the rates at which these states should be excited by electronic collisions[2,3] and by charge-exchange interactions shows that the latter process may well dominate and, therefore, be distinguished by preferential enhancement of lines which originate from the levels with $n=4$ or 5. In principle, then, details of the interaction of the beam with impurity ions can be investigated by radiation from the impurities themselves.

In this Letter, I present the results of recent experiments on ORMAK-produced plasmas in which excitation of O^{7+} via charge exchange with neutral beams appears to have been observed for the first time. However, this process has been detected through the selective excitation of the Balmer-α line ($n=3\rightarrow n=2$) rather than through transitions which originate from higher levels. Some possible reasons for the apparent discrepancies with theory will be discussed. These observations anticipate the possibility of refining spectroscopic techniques to explore the details of the deposition of neutral beams within plasmas.

In the present experiments both normal- and grazing-incidence monochromators are used to monitor radiation from the plasma. The acceptance cones of these instruments include sections of the plasma along the axis of one of the two beams. A typical value for the neutral-beam current delivered to the plasma is 20 A for the sum of the two sources, divided among 10-, 15-, and 30-keV atoms in ratios close to 1:2:1.

The Ohmic-heating current is maintained at 70 kA during the initial steady-state period of the discharge, and injection begins at 38 ms after breakdown. The sequence of shots analyzed here has been obtained subsequent to discharge cleaning overnight with oxygen.

Temporal dependences of various spectral lines are illustrated in Fig. 1. The upper two traces in all of the pictures result from the 1032-Å line of O VI which is detected at two different sensitivities, whereas the lower traces represent the behavior of various features in the soft–x-ray region. Figures 1(a) and 1(b) are illustrative of the differences observed between shots that are taken with and without injection. Breakdown occurs at 4 ms after the oscilloscope is triggered. After 15 ms, the intensities of the lines remain constant or decrease slowly when there is no injection. However, when the injectors are activated, the trace due to the O VI line exhibits a sudden change in slope as the intensity begins to increase. Similarly, the intensity of the Lyman-α line of O VIII increases, but the initial rate is slower than the rate observed for the O VI line. These results are indicative of oxygen being ejected from the liner as a result of bombardment by energetic hydrogen atoms.

But in Fig. 1(c), which illustrates the temporal behavior of the radiation from the Balmer-α line, one sees an evolution which differs markedly from that of the Lyman-α line. There is a

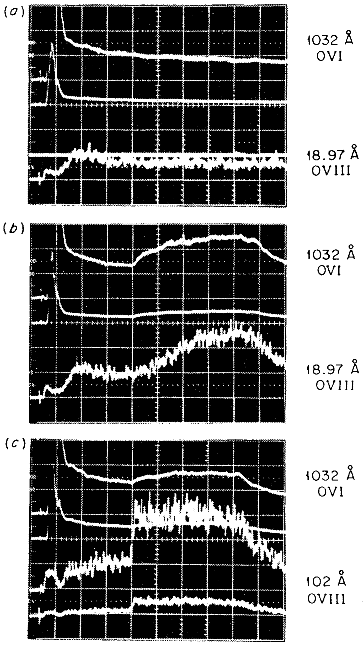

FIG. 1. Temporal dependences of the radiation from several spectral lines. The intensity of the 1032-Å line of O VI is recorded at two different sensitivities as shown in the upper two traces of all three figures. Signals from the Lyman-α (18.97-Å) and Balmer-α (102-Å) lines of O VIII are recorded on the lower traces. Curves in (a) are characteristic of shots without injections; those in (b) and (c) are representative of behavior when injection is employed. Sweeps are at 10 msec/cm.

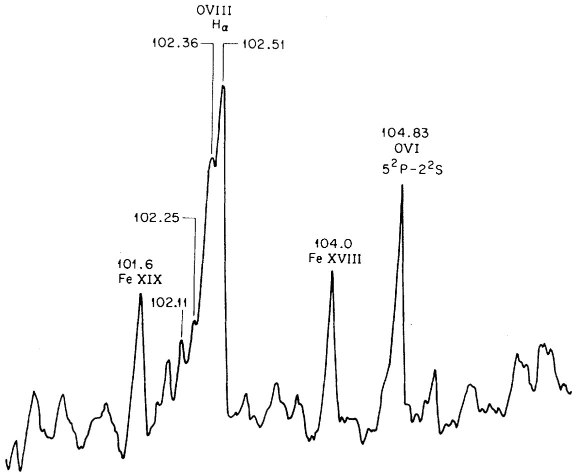

FIG. 2. The spectrum in the vicinity of the Balmer-α (102-Å) line of O VIII.

sudden, sharp increase in the intensity as soon as the injector is turned on. This prompt signal in the Balmer-α line is reproducible, although it does not appear as dramatically in all of the shots as it does in Fig. 1(c). Nevertheless, after the contribution due to continuum radiation is subtracted, the data from six different shots all show that the intensity of the Balmer-α line increases by a factor of 4 within 4 ms after injection begins, whereas the intensities of the Lyman-α, $-\beta$, and $-\gamma$ lines and of the Balmer-β line all show increases of less than 20% in this interval.

It appears certain that the behavior observed in Fig. 1(c) is the result of direct interaction between the particles of the beam and the plasma, but because the theory indicates that charge transfer on O^{8+} should proceed primarily through the $n = 4$ and 5 levels rather than through the $n = 3$ level, it is necessary to be sure that the spectroscopic observations really have been made on the Balmer-α line of O VIII rather than on some other nearby impurity line. It is also necessary to reconcile the fact that similar sudden increases of intensity are not observed in the Lyman-β line, which also originates on the $n = 3$ state, or in the Lyman-α line as a result of cascading. As a starting point, examine the spectral region around 102 Å as shown in Fig. 2. This figure is the result of a densitometer tracing of a plate taken during a series of shots in which the Ohmic-heating current averaged 125 kA rather than the 70 kA employed when the observations of Fig. 1 were made; approximately one-half of the shots included injection. The spectral bandwidth is 0.075 Å, and the measured values of the two most prominent peaks are 102.51 and 102.36 Å with an absolute uncertainty of ± 0.05 Å. The components of the Balmer-α line of O VIII span the range[4] from 102.35 to 102.55 Å so that these brightest features do indeed appear to arise mainly from the $n = 3$ to $n = 2$ transition of hydrogenlike oxygen. The two lines at 102.25 and 102.11 Å are considered to be unidentified, although it is possible to assign them to iron or nickel. Iron is the most prominent metallic impurity, and it exists in concentrations of 10^{-3} times the concentration of oxygen at currents of 125 kA. We do not have similar estimates at 70 kA, but the relative concentration of iron is undoubtedly much smaller than 10^{-3} since the usually intense line of Fe XVI at 360.8 Å could not be detected during the shots at lower currents. Only by invoking an unreasonably large cross section could our observations be attributed to a minor impurity.

A four-point scan over this spectral range at intervals of 0.33 Å has indicated that the sharp rise in intensity displayed in Fig. 1(c) appears only in the region of the prominent lines and not in the underlying continuum. Furthermore, if discharge cleaning has been performed with hydrogen, essentially no O^{8+} ions are present before injection when the machine current is at 70 kA, and, indeed, in this case the prompt signal is not observed when injection begins. In summation, all of the available spectroscopic data support the contention that the injection results in a directly observable increase in population of the $n = 3$ level of O^{7+}.

The failure to observe the prompt signal in the Lyman-α line due to cascading can be explained by the fact that excitation of the $n = 2$ level by electronic collisions is much more probable than excitation by cascading, and the sudden increase of intensity expected from the charge-transfer reaction has about the same amplitude as the fluctuations of Fig. 1(b). This conclusion is reached by utilizing a coronal equilibrium model[5] for the concentrations of O^{7+} and O^{8+} in conjunction with the rate coefficients calculated by Jacobs[2,3]; the ratio of the emission rates of the Balmer-α and Lyman-α lines should be 0.05 if only electronic excitation is operative. By assuming that this ratio of emission rates holds before injection and calculating the expected increase of intensity in the Lyman-α line from the measured signals after injection, one finds that the contribution due to cascades should correspond to only one small division of the graticule in Fig. 1(b).

The observation of the charge-transfer reaction through lines which originate from the $n = 3$ level apparently contradicts the theoretical expectations that the transfer proceeds through higher levels, but this conclusion cannot be drawn justifiably without a more extensive examination of the hydrogenic lines of O^{7+}. Many lines of possible interest lie outside the region accessible with the 2400-lines/mm grating which has been used in the grazing incidence instrument, and those which we have investigated are somewhat obscured by a continuous background. The possibility that our present observation results from cascades cannot be ruled out.

The objection can be raised to the present analysis that the signal from the charge exchange should appear strongly in the Lyman-β line if it appears in the Balmer-α line. Salop and Olson[1] indicate that only the $|n,0,n-1,0\rangle$ parabolic states are populated significantly by the primary curve crossings and that the angular momentum states, $|n, l, 0\rangle$, of the separated hydrogenic ion are populated in the ratios determined by the vector-coupling coefficients which relate these two basis sets. This latter conclusion is not justified because the parabolic states are not eigenstates of hydrogenic ions because of the presence of the electron spin and the radiative interactions between states having the same total angular momentum. The $|n,0,n-1,0\rangle$ states correlate adiabatically to the $P_{1/2}$ states of O^{7+} because the interaction which produces the Lamb shift causes the $S_{1/2}$ states to lie at higher energies than the $P_{1/2}$ states.[6] However, because of the small value of the Lamb shift and the relatively high velocity at which the particles separate, it appears most probable that the system would pass through this interaction region diabatically so that the $S_{1/2}$ states are preferentially populated.[7] This conclusion might be altered by refinements of the theory to incorporate rotational coupling and by the possibility that the nuclear motion could couple σ states which even the adiabatic approximation can cross in one-electron systems. Nevertheless, it appears highly plausible that the charge exchange can result in very different populations of the angular momentum states which have the same total quantum number n. In such circumstances the emission rate of the Lyman and Balmer lines that originate from the same level may be very different.

It is hoped that further experimental and theoretical work may resolve some of the questions posed by the present investigations and that optical spectroscopy may prove to be a satisfactory diagnostic technique for examining the role played by impurities in neutral-beam heating or for studying the details of the deposition.

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Position and Dynamics of Ag Ions in Superionic AgI Using Extended X-Ray Absorption Fine Structure*

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By use of extended x-ray absorption fine structure, the Ag ions in superionic AgI are shown to occupy the distorted tetrahedral sites in the iodine bcc lattice, being slightly displaced from the center toward the faces along the most probable diffusion path. The residence time of the Ag ions in these sites is determined to be longer than their flight time, implying that the jump-diffusion model is more appropriate than a free-diffusion model.

AgI is typical of a class of superionic conductors that achieve their high-conducting state through a structural phase transition. Below 147°C, AgI has the hexagonal wurtzite structure (β phase). At 147°C, it transforms to the α phase in which the iodine ions form a body-centered cubic lattice with the Ag sublattice disordered,[1,2] and the ionic conductivity increases by 4 orders of magnitude to 1 $(\Omega\ \mathrm{cm})^{-1}$.[3] We have used the extended x-ray absorption fine structure (EXAFS) on the Ag K-shell absorption to obtain information on both the position and the dynamics of the Ag ions in the superionic α phase of AgI. First, we show that the Ag-ion position distribution function is peaked ~0.1 Å from the center of the distorted tetrahedron formed by the bcc iodine lattice, displaced toward a tetrahedral face. Secondly, we determine that the residence time of the Ag ions in the displaced tetrahedral site is roughly 3 times the flight time between different tetrahedra. Finally, we show that previous conclusions on the position and dynamics of the Ag ions in superionic AgI which were drawn from x-ray[1,2] and neutron[4,5] scattering studies are inconsistent with the EXAFS data.

The EXAFS on the Ag K-shell absorption in AgI was measured in the ionic insulating β phase at 20°C and 98°C and in the superionic α phase at 198°C and 302°C using the facilities of the Stanford Linear Accelerator Center Synchrotron Radiation Project. The EXAFS is observed as an oscillation in the absorption cross section above the Ag K edge.[6] Using procedures which have been described in detail elsewhere,[7] we extracted the EXAFS as a function of final-state electron momentum, k, from the measured absorption and made a Fourier transformation into real space. The resultant complex transform, $\varphi(r)$, is shown in Fig. 1 for the 20°C and the 198°C data. Note that the vertical scales differ by a factor of 2. All the data were collected on the same sample and were reduced in an identical manner.

The Fourier transform, $\varphi(r)$, of the EXAFS on K-shell absorption can be expressed[7] as a sum of contributions, ξ, from each shell of atoms surrounding the excited atom:

$$\varphi(r)=\sum_\alpha\int_0^\infty (dr'/r'^2)\,p_\alpha(r')\,\xi_\alpha(r-r'), \qquad (1)$$

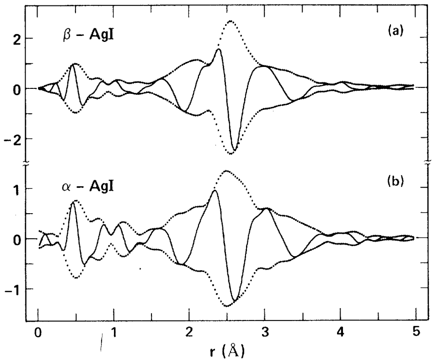
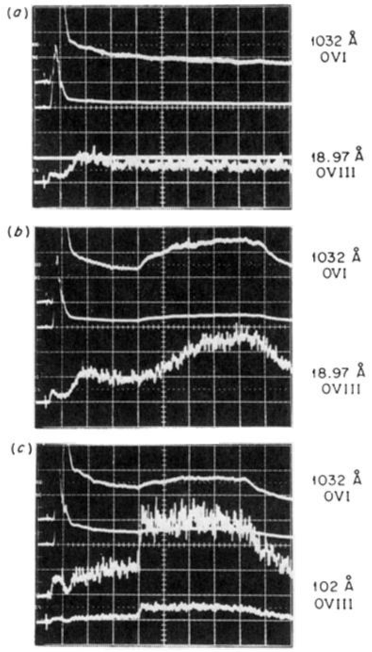


FIG. 1. The real part (solid line) and the magnitude of the Fourier transform $\varphi(r)$ of the EXAFS on the Ag K-shell absorption in AgI: (a) at 20°C (well below the normal-superionic transition) and (b) at 198°C (well above the transition). Note that the vertical scales differ by a factor of 2. The data were collected on the same sample and transformed over the same interval in k space.



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