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Evidence for charge exchange of He-like argon with neutral hydrogen on TEXTOR-94

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Introduction

In the tokamak experiment TEXTOR-94, where the electron densities range from 5×10^{12} to 1×10^{14} cm^{-3} and electron temperatures range from 0.8 keV to 4.0 keV, conditions for coronal equilibrium are expected to be valid for high Z. Nonetheless, large deviations of the ArXVI/ArXVII from coronal equilibrium are routinely observed in the ArXVII spectra. It has been suggested that charge exchange of neutral hydrogen with ArXVII is primarily responsible for these variations[1]. Here the additional path for recombination shifts the charge state distribution to lower charge states. Direct measurement of charge exchange of neutral hydrogen with ArXVIII has been previously reported by Rice et. al. on Alcator-C [2]. In addition to charge exchange, the charge state distribution can also be altered by transport in the plasma[3]. Transport changes the charge state distribution by spreading out the charge states in the plasma. In this work we show that charge exchange makes a major contribution to the deviations of ArXVI/ArXVII from coronal equilibrium and that diffusion alone is not enough to explain the observed discrepancies.

Experiment

A series of experiments to investigate charge exchange of neutral hydrogen with ArXVII were carried out on the tokamak experiment TEXTOR-94 using hydrogen, helium and deuterium as working gases. Experiments in both ohmically heated plasmas and plasmas with the injection of neutral hydrogen beams were investigated. One neutral beam was injected across the line of sight of the spectrometer and the other was injected in a region of the plasma away from the spectrometer. In these experiments, the electron temperature was varied from 1.0 to 2.4 keV and the electron density from 1.0×10^{13} to 4.0×10^{13} cm^{-3}.

The spectra were measured using a crystal spectrometer in the Johann configuration. The crystal spectrometer consisted of a bent quartz 110 crystal and a multi-wire proportional counter. The quartz crystal, 10.0 mm in height, 70.0 mm in width, with a 2d spacing of 4.913 Å was bent to a radius of curvature of 3820 mm. The multi-wire proportional counter, which utilized Kr/CO_2 as a working gas, had an exposed area of 18 mm x180 mm and a working volume of 90 mm x 180 mm x 12 mm. The detector was optimized for count rate yielding a spatial resolution of 0.65 mm, which resulted in a spectral resolution $\lambda/d\lambda = 5300$ which corresponds to an ion temperature of 0.240 keV. A spatial resolution of 0.4 mm and a correspondingly higher spectral resolution can be obtained at lower count rates by increasing the HV on the detector. Further details of the instrument will be presented in a separate paper[4].

The central ArXVI/ArXVII was obtained by fitting a model of the spectra to the experimental spectra. The model included direct excitation with cascades, radiative recombination, dielectronic recombination, and inner shell ionization. For each radial position in the plasma the intensity of the lines were calculated from

$$I(r) = n_e(r) * n_{ion}(T_e(r)) * <\sigma v(T_e(r))>_{line}.$$

The spectra were then integrated over the line of sight using electron temperature profiles measured by ECE, density profiles produced from q-profiles[5], and coronal equilibrium charge state distributions. The atomic data used to fit the spectra was calculated for calcium by F. Bely-Dubau et. al. and scaled to argon according to Mewe and Schrijver [6-8].

Results

Figure 1. shows a comparison of the central ArXVI/ArXVII obtained from fitting the experimental spectra to the value predicted from coronal equilibrium as a function of the line integrated electron density. The two distinct curves correspond to the experiments with and without the injection of neutral beams. The higher experimental ArXVI/ArXVII compared to the predicted value by coronal equilibrium is expected since beam injection should directly increase charge exchange by supplying neutral hydrogen to the center. However, neutral-beam injection is also known to increase the diffusion. No difference, as expected, was seen between the beam directly observed by the spectrometer and the beam which was not directly observed, since the ArXVI lines must be produced by inner shell excitation and the addition of neutral hydrogen does not excite the inner shell electron. In addition, as the line averaged electron density was increased, the discrepancy between the calculated ArXVI/ArXVII and the measured value decreased according to the expectation that the penetration of neutrals to the center will be lower for higher electron densities. In the ohmic discharges, the expected variations with the different background gases were also observed. Here the discrepancies were largest for hydrogen and smallest for helium. This agrees with the expectation that the penetration of neutral hydrogen to the center of the plasma should be largest for hydrogen and smallest for helium.

Although the data supports charge exchange as an explanation for the discrepancies in ArXVI/ArXVII, transport can also lead to observations in the same direction. To study the effects of diffusion on the charge state distribution for both the measured and predicted ArXVI/ArXVII, STRAHL code calculations for the radial charge state distributions of ArXVI, ArXVII, ArXVIII were made assuming different diffusion coefficients in the plasma[9]. A few spectra from ohmic plasmas were then fit again with these radial charge state distributions to determine the deduced central ArXVI/ArXVII under these conditions. Figure 2. shows the assumed radial distribution of the diffusion coefficients used in the analysis. The calculations were made for $n_e = 1.03 \times 10^{13}$, 1.77×10^{13}, and 3.23×10^{13} cm^{-3} for deuterium to observe the scaling with density. In addition, the calculations were made for hydrogen at $n_e = 1.74 \times 10^{13}$ cm^{-3} and for helium at $n_e = 1.5 \times 10^{13}$ cm^{-3} to compare different working gases under similar conditions. Figure 3. shows the ratio of central ArXVI/ArXVII obtained from the fit to that obtained from the STRAHL calculations as a function of density and diffusion coefficient. For the same diffusion coefficient, the discrepancy between the measured and predicted central ArXVI/ArXVII was found to be higher for hydrogen than for deuterium and helium giving strong evidence of charge exchange with neutral hydrogen. To check if it was reasonable to assume the same diffusion coefficient for the three working gases, the energy confinement time τ_e was checked for the three shots around $1.5 - 1.75 \times 10^{13}$ cm^{-3}. The confinement times were found to be 62, 68, and 79 ms for hydrogen, helium and deuterium respectively. Since particle diffusion is linked to the energy confinement time, it is reasonable to assume that the hydrogen and helium plasmas had similar diffusion coefficients. Even if the diffusion coefficients were a factor two higher for hydrogen, it can not explain the remaining discrepancy of a factor of two between the theoretical and experimental ArXVI/ArXVII observed in the hydrogen and helium discharges. The results further suggest that diffusion alone may be able to explain the observed discrepancies of ArXVI/ArXVII for the helium discharges. To verify this, measurements of the diffusion are necessary for these plasma conditions. In the current analysis, the diffusion in the beam heated plasmas was not considered in detail. More detailed results will presented in a future publication.

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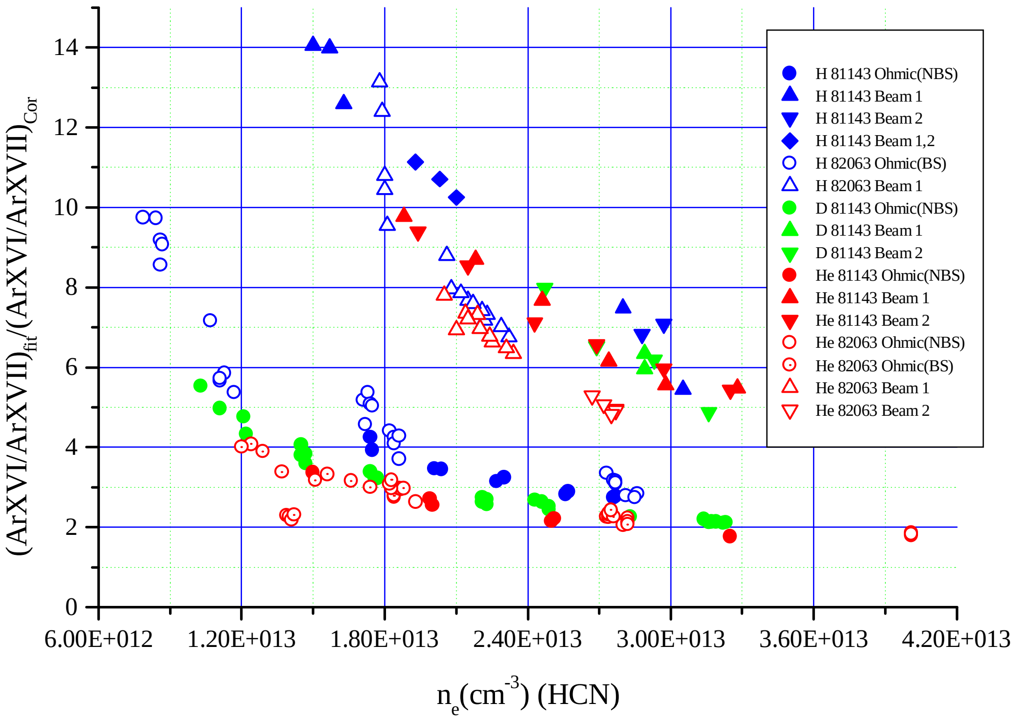

Figure 1. Comparison of the central ArXVI/ArXVII obtained from a fit of the experimental spectra to the value predicted by coronal equilibrium. The blue points corresponds to hydrogen, the green to deuterium, and the red to helium for the working gas. Circles are ohmic, up triangles have beam 1 hydrogen injection, down triangles have beam 2 hydrogen injection, and diamonds have both beam 1 and beam 2 hydrogen injection. The closed symbols are from shots 81143-81182 and the open symbols are from shots 82063-82110.

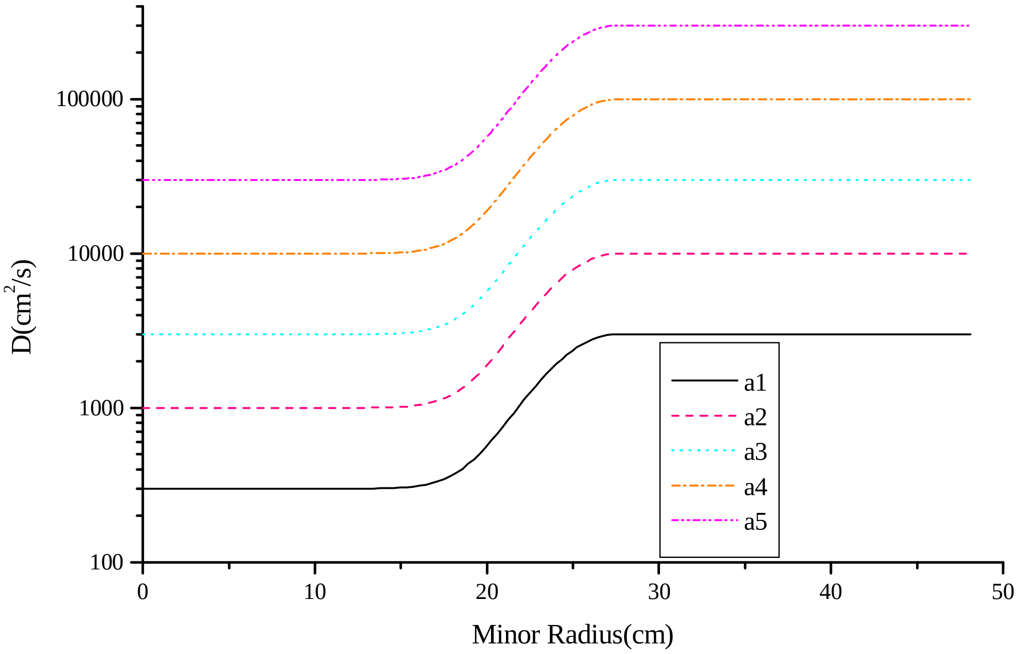

Figure 2. To check the effect of the diffusion on both the calculated and measured ArXVI/ArXVII, five different radial profiles for diffusion were assumed.

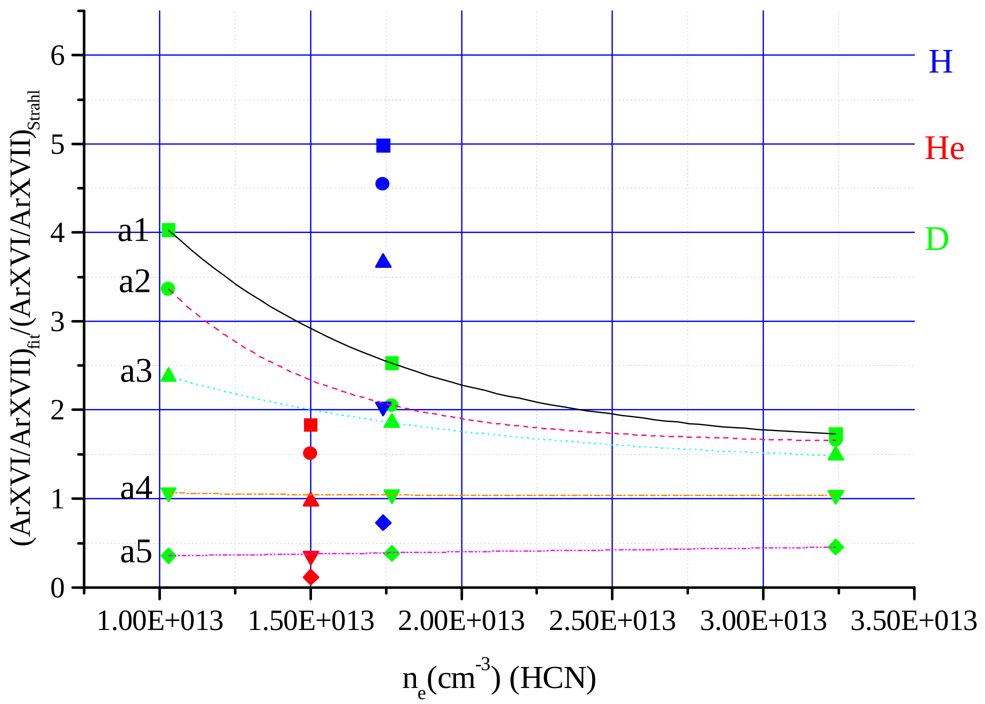

Figure 3. The ratio of the central ArXVI/ArXVII from a fit of selected spectra to that calculated with the STRAHL code for the radial diffusion coefficients given in figure 2 vs. the line integrated electron density measured by the HCN interferometer.