Observation of Charge-Transfer Population of High-n Levels in Ar^{+16} from Neutral Hydrogen in the Ground and Excited States in a Tokamak Plasma

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X-ray spectra of He-like argon (Ar^{+16}) have been obtained for the transitions $1snp \rightarrow 1s^2$, with $3 \leq n < \infty$, from Alcator-C tokamak plasmas. In the periphery of the plasma, the $n=9$ and 10 and $15 < n \leq 40$ levels are observed to be predominantly populated by charge transfer between Ar^{+17} and intrinsic neutral hydrogen in the ground and first few excited states. Neutral-hydrogen density profiles are deduced from these measurements. The first experimental observations of the reactions $Ar^{+17}(1s\,^2S) + H_0^*(n=2,3) \rightarrow Ar^{+16*}(1snp\,^1P) + H^+$ are presented and their cross sections are estimated.

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Charge transfer between neutral hydrogen and highly stripped ions has recently been the subject of intense theoretical and experimental investigation.[1-7] This process preferentially populates specific levels with high principal quantum number, n, in the recombined ion. The occurrence of charge transfer can be observed by detection of the subsequent radiative decay. In tokamak plasmas, charge transfer between injected beams of neutral hydrogen and naturally occurring low-Z impurities has been used widely for diagnostic purposes.[5,8,9] Charge transfer with intrinsic neutral hydrogen has also been observed.[10] It has been pointed out that this phenomenon could, in principle, be used to measure neutral-hydrogen densities.[11] In this Letter conclusive, quantitative observations of charge transfer between intrinsic hydrogen (H_0) and hydrogenlike argon (Ar^{+17}) in Alcator-C tokamak plasmas are presented. This transfer not only occurs with hydrogen in its ground state (which primarily populates the $n=9$ and $n=10$ levels in Ar^{+16}), but is also observed, for the first time, to occur with hydrogen in its first few excited states. Ground-state neutral density profiles are calculated from the $n=9$ and 10 data. Transfer from the excited levels in hydrogen populates very high-n Rydberg levels in Ar^{+16} (up to about $n=40$), and experimental cross sections for these reactions are estimated. These cross sections are large; this process may have important implications for the interpretation of ion-atom collision experiments, where a small contaminant of excited atoms could strongly influence the results.[1]

In this experiment radial profiles of ground-state transitions for the Rydberg series from $n=3$ to ∞ in Ar^{+16} were measured in Alcator-C tokamak discharges.[12] These transitions occur in the wavelength region from 3.0 to 3.4 Å and were detected with a high-resolution ($\lambda/\Delta\lambda = 3000$) crystal x-ray spectrometer.[13] The instrument was scanned vertically on a shot-to-shot basis, with a chordal resolution of ± 1.5 cm. Wavelengths taken from Seely and Feldman[14] were used to calibrate the spectrometer. The measure-

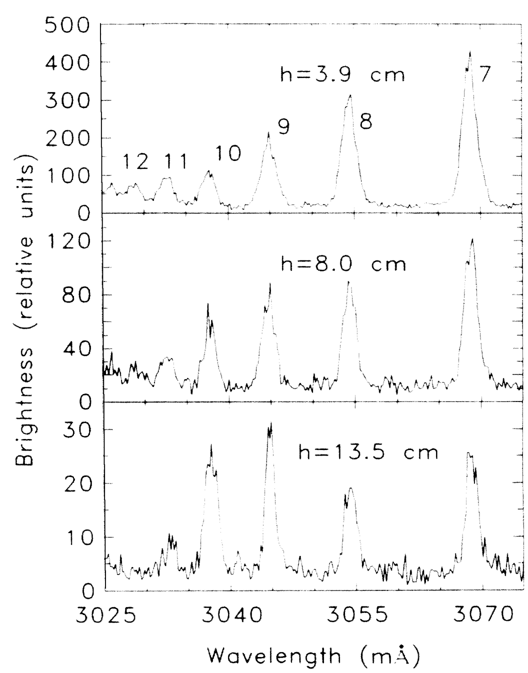

FIG. 1. Spectra from $1s7p \rightarrow 1s^2$ to $1s13p \rightarrow 1s^2$ transitions in Ar^{+16} through three radial chords. Molybdenum structures limit the discharge at a minor radius of 16.5 cm. The perpendicular distance from the plasma axis to the chordal view is designated by h.

ments were taken during a sequence of similar hydrogen discharges with toroidal field of 8 T, limiter radius (a_L) of 16.5 cm, plasma current of 500 kA, central electron temperature of 1800 eV, and central electron density of 2.2×10^{14} cm^{-3}. The argon was introduced into the discharges by gas puffing through a piezoelectric valve, and subsequently recycled, reaching a steady level in the discharge after about 100 msec.

Shown in Fig. 1 are the line-of-sight-integrated spectra from $1snp \rightarrow 1s^2$ transitions, with $7\leq n\leq 13$, obtained for three different chordal views. For the outer chords, the $1s9p\rightarrow 1s^2$ and the $1s10p\rightarrow 1s^2$ lines are greatly enhanced relative to the $1s7p\rightarrow 1s^2$ and $1s11p\rightarrow 1s^2$ lines. This is definite evidence of population by charge transfer, since the cross section for transfer between ground-state hydrogen and Ar^{+17} is predicted[4] to have a strong dependence upon the n level of the recombined argon ion, with a maximum around $n=9$. This process is most important in the cooler regions of the plasma, where there is a relatively large neutral density, and where direct population by electron-impact excitation from the ground state becomes negligible ($T_e\leq 300$ eV).

Shown in Fig. 2 is the sum of spectra in the 3.005- to 3.040-Å region obtained from the plasma periphery ($0.5 < h/a_L < 0.8$). The recombination continuum[15] is evident in the data, with the edge being located at 3.0088 Å. Even more prominent is the broad feature between 3.01 and 3.02 Å, which is more intense than the $1s10p\rightarrow 1s^2$ line. The maximum of this feature corresponds to the wavelength for the $\sim 1s27p\rightarrow 1s^2$ transition in Ar^{+16} and the shoulder at ~ 3.018 Å is near the $1s18p\rightarrow 1s^2$ wavelength. As the results of classical-trajectory Monte Carlo calculations have shown,[1] charge transfer between neutral hydrogen in level n_i and Ar^{+17} should occur into levels n_f which are n_i times the dominant level for charge exchange between neutral hydrogen in the ground state and Ar^{+17}. This means that transfer from hydrogen in excited states with $n_i=2$, 3, and 4 would populate Ar^{+16} in levels n_f near 18, 27, and 36, respectively. Thus, the shoulder on the feature in Fig. 2 near 3.018 Å is attributed to charge transfer from hydrogen in the $n_i=2$ state, and the peak at 3.013 Å is due to transfer from hydrogen in the $n_i=3$ level. This requires the presence in the plasma of excited neutral hydrogen in the $n_i=2$ and $n_i=3$ levels; for conditions near the edge of Alcator-C plasmas, a collisional-radiative model[16] yields density ratios with the ground state of 0.6% and 0.25%, respectively, for these excited levels. These features at very high n_f are quite strong since the classical radius of the hydrogen atom increases as n_i^2; theoretical considerations[1] lead to the expectation that the total cross section should scale as n_i^4.

Abel-inverted radial emissivity profiles for the $1snp\rightarrow 1s^2$ series are shown in Fig. 3, obtained from a

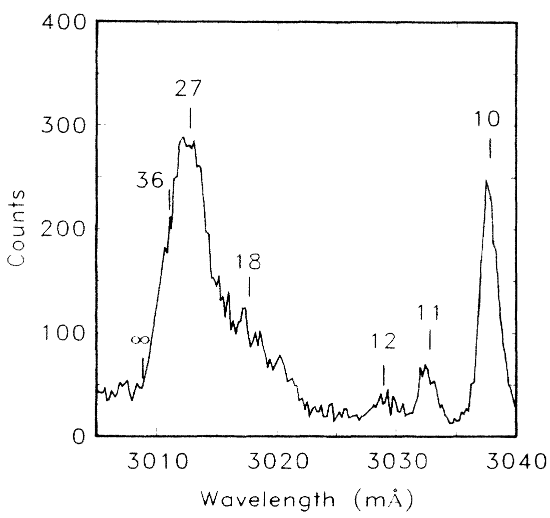

FIG. 2. Spectrum of $1snp\rightarrow 1s^2$ transitions in Ar^{+16} with $10\leq n<\infty$. The locations of specific transitions are indicated. The broad feature observed for $n>15$ is due to charge transfer between Ar^{+17} and H_0 in the first few excited states. The recombination edge (series limit) is located at 3008.8 mÅ.

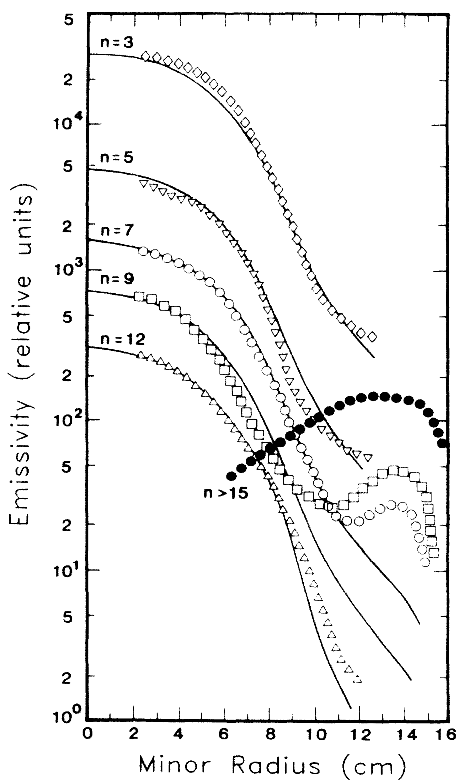

FIG. 3. Radial emissivity profiles for $1snp\rightarrow 1s^2$ transitions in Ar^{+16}. The solid curves are emissivity profiles calculated under the assumption that the upper level of each transition is populated only by electron-impact excitation and radiative recombination.

shot-to-shot brightness scan. For clarity, $n=4$, 6, 8, 10, and 11 have been omitted from the figure; all relevant trends are nevertheless represented. The line intensities have been modeled as a balance among radiative decay of the excited $1snp$ levels, electron-impact excitation[17] out of the ground state of Ar^{+16}, and radiative recombination[18] of ground-state Ar^{+17}. Collisional deexcitation and excitation from any other levels, radiative transitions to any levels except the ground state, and cascades from upper levels have all been ignored. Density profiles for Ar^{+16} and Ar^{+17} in the ground state have been obtained from an impurity transport simulation which includes the effects of self-diffusion and convection derived from trace-impurity transport studies on plasmas with similar discharge conditions.[19] In this case, a diffusion coefficient of $D=2000$ cm^2/sec and a convection velocity of $v=-v_0r/a_L$, with $v_0=120$ cm/sec, were used. The argon was assumed to be in steady state, with 100% recycling at the edge. Profiles of electron density and temperature were obtained from laser interferometer, visible continuum, Thomson scattering, and soft x-ray measurements. The calculated emissivity profiles obtained from this model are shown as the solid curves in Fig. 3. There is only one normalization used, for $n=7$ at $r=3$ cm. The agreement with the data is excellent inside of $r\approx 9$ cm. For $r\gtrsim 9$ cm, the main departures occur for the $1s9p\rightarrow 1s^2$ and $1s10p\rightarrow 1s^2$ (not shown) transitions. These departures are due to direct population of the upper levels by charge transfer from H^0 in the ground state.

The enhancement of the $n=9$ and $n=10$ transitions over the calculated values can be combined with available charge-transfer cross sections to determine the neutral density profile $[n_0(r)]$. The cross sections for capture into the various n levels of Cl^{+17} (interpolated from Ref. 4) have been used to model Ar^{+17}, which is the relevant species for this experiment. The values used were $\sigma_9=6\times 10^{-15}$ cm^2 and $\sigma_{10}=3\times 10^{-15}$ cm^2 at 0.5-keV interaction energy. At the low interaction velocities here, about 25% of the charge transfer can be expected to occur into the $l=1$ levels[20] of $n=9$ and $n=10$ (the only l levels that are observed directly). It is assumed that only population of the $1snp\ ^1P$ system leads to observed photons and that the triplet-to-singlet population ratio is 3:1. Shown in Fig. 4 is the neutral-hydrogen density profile obtained in this way from the enhancement of the $1s9p\rightarrow 1s^2$ and $1s10p\rightarrow 1s^2$ transitions. In addition, the $n>15$ emission is attributed entirely to charge exchange. Since the density ratios of excited- to ground-state hydrogen can be calculated by use of the collisional-radiative model,[16] the shape of $n_0(r)$ can also be obtained from the profile of the high-n spectral feature. The density ratios increase by about 50% as one goes from $r=14$ cm to $r=9$ cm. These results are also shown in Fig. 4, with the neutral density normalized to the average of those obtained at $r=12$ cm from $n=9$ and 10. The results are in good agreement with simulations from the FRANTIC neutral transport code[21] also shown in the figure. In this case, the edge neutral density has been fixed at 5×10^{10} cm^{-3}. While the calculated $n_0(r)$ is sensitive to this assumption, the shape of the $n_0(r)$ profile is not strongly affected in the region $r>9$ cm. The calculated energy spectrum for the fast neutral outflux, derived from the FRANTIC profile of Fig. 4, is in excellent agreement with that observed by the fast-neutral-particle energy analyzer under these plasma conditions; the shape of this spectrum is very sensitive to the assumed $n_0(a_L)$. While it is likely that toroidal asymmetries exist in the neutral density,[22] both the charge-exchange and x-ray measurements were done at the same toroidal location, which in this case was also a limiter port.

A number of uncertainties influence the neutral-density measurements. There are poloidal[23] asymmetries in the neutral density which could affect the Abel inversion, although these will be largest at the extreme edge of the plasma ($r>16$ cm). Other uncertainties include the following: The cross sections used were for Cl^{+17} rather than the Ar^{+17} in the experiment, although previous measurements with lower Z (≤ 8) ions show that this has little effect on total

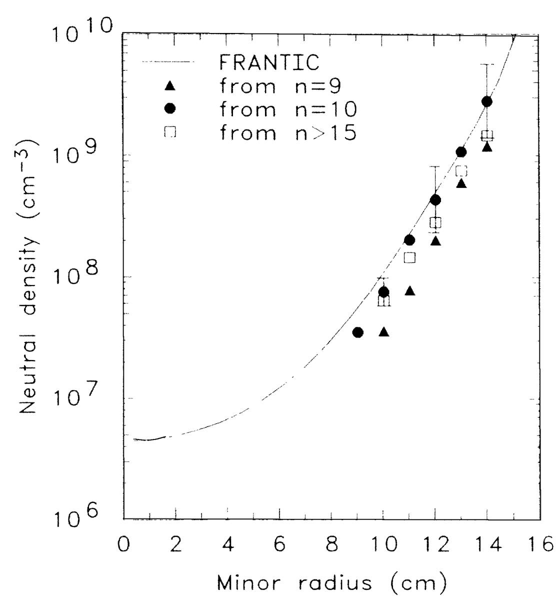

FIG. 4. Neutral-hydrogen density profiles deduced from charge-transfer–enhanced $1snp\rightarrow 1s^2$ emissivity profiles for $n=9$, $n=10$, and $n>15$. The solid line is calculated from a neutral-transport code (Ref. 21) on the assumption that $n_0(a_L)=5\times 10^{10}$ cm^{-3}. The results from $n=9$ and 10 are absolute, while the $n>15$ result is relative, and has been normalized at $r=12$ cm.

cross sections[7]; any possible l mixing[24], of the upper levels before radiative decay has been ignored; the decay from the $1snp\,^3P_1$ level to the ground state is not strictly forbidden[25]; cascades have been ignored (the factor of ~ 2 disagreement in Fig. 3 for $n=7$ at $r \gtrsim 13$ cm may be due to cascades). Over all, an absolute uncertainty of about a factor of 5 must be ascribed to the n_0 measurements. However, the shape of the n_0 profile is much less uncertain, since the errors introduced by incorrect atomic physics assumptions will influence the absolute n_0 inferred, but will not be strong functions of position in the plasma. The main uncertainty in the profile shape comes from the use of the transport model to obtain the density of Ar^{+17} at the large radii. The error bars in Fig. 4 are indicative of this relative uncertainty. The charge-transfer process has not been included in a self-consistent manner in the calculation of the Ar^{+17} density. However, it only becomes important when $n_0\langle\sigma v\rangle_{C-T} \approx n_e\langle\sigma v\rangle_{R-R}$. At $T_e=300$ eV, $n_e=1\times10^{14}$ cm^{-3}, the two terms are equal when $n_0 \simeq 5\times10^9$ cm^{-3}, and so including the charge-transfer term self-consistently would not significantly alter the results of Fig. 4.

By our combining theoretical calculations of the population distributions in the various n levels of H_0 in the plasma[16] with the average $n_0(r)$ deduced from $n=9$ and $n=10$, the cross sections for the reactions $Ar^{+17}(1s\,^2S)+H_0^*(n=2,3) \rightarrow Ar^{+16*}(1snp\,^1P)+H^+$ can now be calculated. The $n>15$ feature is fitted by three Gaussians, peaked near $n=18$, 27, and 36, respectively. The results are $\langle\sigma_{n=2}v\rangle/v_{\rm th} \approx 1.0\times10^{-13}$ cm^2 and $\langle\sigma_{n=3}v\rangle/v_{\rm th} \approx 2.5\times10^{-13}$ cm^2, where the $\langle\sigma v\rangle$'s are the rate coefficients averaged over a Maxwellian neutral thermal distribution, and include transfer into a distribution of n_f's. It is assumed that the neutrals are in thermal equilibrium with the local ions ($T_i=300$ eV at $r=13$ cm, $v_{\rm th}=3\times10^7$ cm/sec) and that population of the ^3P levels does not lead to observed photons. Given the large uncertainties in the derivation, these absolute cross sections must be considered as order-of-magnitude estimates. The relative cross sections have a smaller uncertainty (about a factor of 2) and appear to increase somewhat less rapidly than the n^4 scaling predicted theoretically.[1]

In summary, charge transfer from the ground state of intrinsic neutral hydrogen has been shown to be an important mechanism populating the Ar^{+16} $1s9p$ and $1s10p$ levels in the cooler regions of the Alcator-C plasma, where the neutral density is large. Intrinsic neutral-density profiles have been inferred from the data, and are in good agreement with neutral-transport simulations. Charge transfer from excited states in neutral hydrogen has been identified experimentally for the first time, and was found to be the dominant population mechanism for levels above $n=15$ in heliumlike argon.

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