SPECTRAL EXCITATION DUE TO CHARGE TRANSFER*

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INTRODUCTION

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Charge transfer processes have been studied extensively in basic research on atomic collisions. They have also become of practical interest recently in controlled fusion research. In tokamaks, atomic hydrogen at the local ion temperature coexists with highly ionized impurities, and neutral hydrogen beams with energies of several keV are employed to heat the plasmas. Both the ambient atoms and the beam atoms may undergo charge exchange with the impurities and, in some cases, produce undesirable consequences. The efficiency of the neutral beam to heat the plasma may be inhibited, and the effective recombination mechanism could prevent impurities from "burning out" to weakly radiating stages.

Many charge exchange processes take place principally into excited states of the products and can be studied through the subsequent spectral line radiation. In particular, the most important collisions of this type between hydrogen and highly ionized impurities always proceed through excited channels and direct observations of these have been made in tokamak-produced plasmas. In this paper we describe briefly the physical picture of the charge exchange mechanism at low collision energies where $v_{rel} \ll 2 \times 10^8$ cm/sec and discuss modifications to this picture for intermediate collision energies. Examples of spectroscopic studies are presented from both atomic beam research and from plasma studies in tokamaks.

THEORETICAL DESCRIPTIONS

At low energies, where the relative velocity of the colliding particles is much less than the velocity of the charge exchanged electron ($\sim 2 \times 10^8$ cm/sec), it is most useful to view the system as a quasi-molecule. The particles approach each other along a potential curve, and the electron transfer takes place at an internuclear distance, R_c, where the incoming channel crosses a channel that dissociates into charge exchanged products. In the simplest two-state model [ref. 1] the cross section is given by

$$\sigma = 4\pi R_c^2 \ [E_3(\eta) - E_3(2\eta)], \tag{1}$$

where E_3 is a third order exponential integral and the argument, η, is given by

$$\eta = [2\pi H_{01}^2/h \ (\Delta V_{01}')] \cdot [M/2 \ E_0(1 - V_c/E_0)]^{\frac{1}{2}}. \tag{2}$$

Here, H_{01} is the matrix element which couples the channels and $\Delta V_{01}'$ is the difference in their slopes at the crossing point. In real cases, there are many channels involved rather than two, and it is necessary to perform extensive close-coupling calculations to obtain the best theoretical

results. Still, the reactions may selectively populate only a few states at a given impact energy.

At energies comparable to those of neutral beam particles (10-40 keV) the quasi-molecular theoretical approach begins to fail. However, the velocities are far below those that could be considered for sudden approximations. It is still useful, therefore, to think in terms of a quasi-molecular formulation but to realize that the charge transfer process will excite states with less selectivity.

EXPERIMENTAL RESULTS

An example of spectra produced by charge transfer in atomic beam experiments is shown in Fig. 1 for three collision energies of helium ions incident on argon [ref. 2]. The collision channels which lead to neutral helium in the ground state predominantly result in excited argon ions. At the lowest impact energies, excitation of the $3s3p^6$ configuration of Ar^+ is most probable, but as the energy increases lines from other stages become increasingly prominent. It is interesting to note that although the $4s\,^2P$ states have the lowest threshold, outside of the $3s3p^6$ configuration, they are not populated as strongly as higher levels at a collision energy of 65 eV. Also, it is found that when the collision energy reaches 10 keV, the excitation of the $3s3p^6$ configuration again becomes by far the dominant channel for charge transfer. This highly selective behavior as a function of energy reflects the very complicated nature of the network of quasi-molecular potential curves.

The observation of charge transfer excitation in plasmas is complicated by the fact that other mechanisms contribute to the excitation of spectral lines. In tokamaks, electron collisions with ions in the ground state or metastable state are usually the dominant mechanism. However, certain highly excited states should be populated significantly by charge exchange. In the ISX tokamak certain spectral lines appeared too anomalously intense for excitation to have been produced solely by electrons [ref. 3]: namely, the $4\,^2P-2\,^2S$ transition of OVI and the $5\,^3P-2\,^3S$ transition of OVII. Calculations based on theoretical plasma models indeed show that the rates of excitation of these lines by charge transfer from hydrogen atoms should be greater than the rates of excitation by electrons. Similar, but even more striking, results have been observed in laser-produced carbon plasmas [ref. 4].

A very obvious example of charge transfer excitation by neutral beam injection is seen in Fig. 2 [ref. 5]. Fig. 2a shows typical signals from oxygen lines without injection, and Fig. 2b indicates that when injection is begun (at 40 msec) that additional oxygen impurities are transported into the plasma on time scales of tens of milliseconds. However, the $n = 3 \rightarrow n = 2$ transition of OVIII (Fig. 2c) shows an almost instantaneous enhancement as soon as the beam is turned on. This result seems to be explicable by no other mechanism except a charge exchange of H° with O^{8+}.

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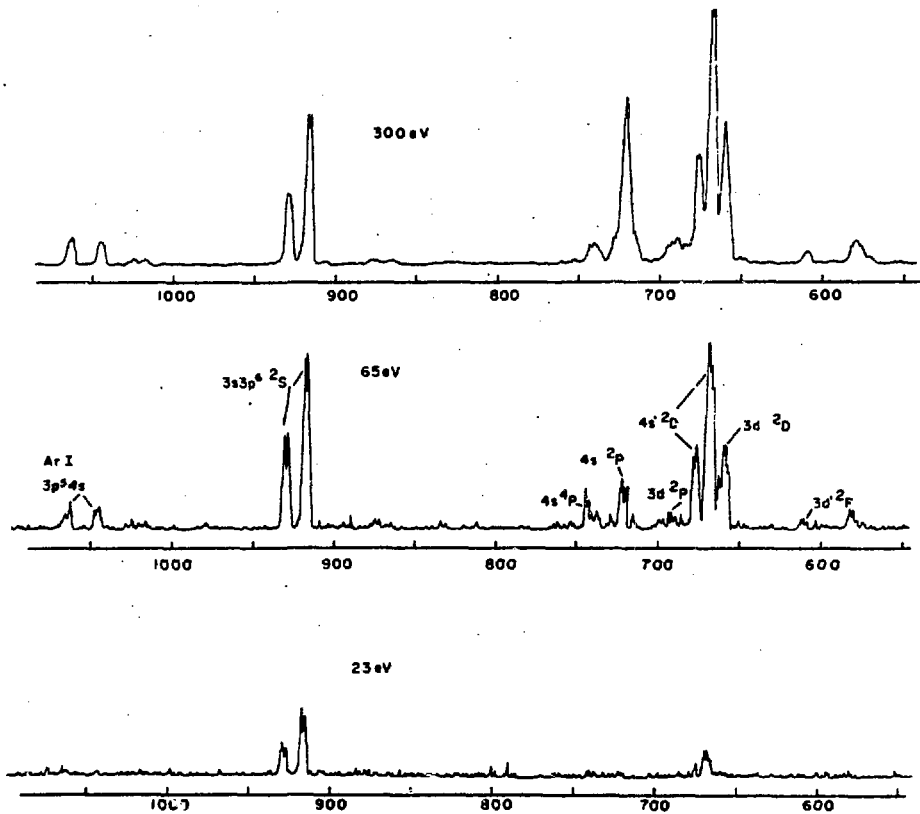
Fig. 1. Spectra produced by collisions of He$^+$ incident on Ar at energies of 23, 65, and 300 eV.
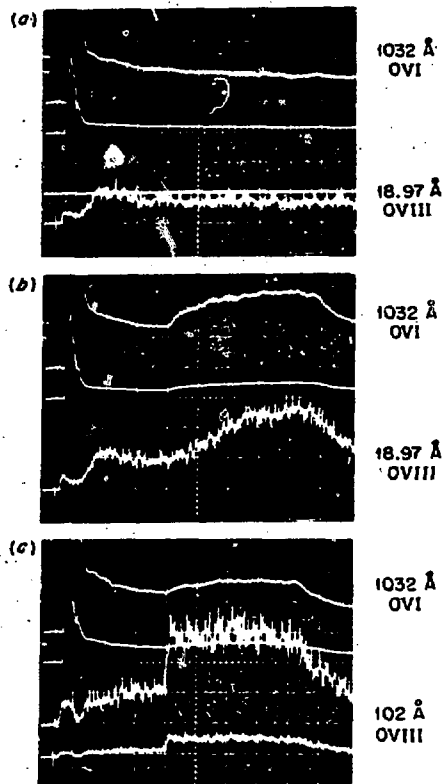
Fig. 2. Temporal dependences of the radiation from several spectral lines.
The intensity of the 1032-Å line of O VI is recorded at two different
sensitivities as shown in the upper two traces of all three figures.
Signals from the Lyman-α (18.97-Å) and Balmer-α (102-Å) lines of O VIII
are recorded on 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.