features of the dynamics of convective instabilities are fairly well described by a single-mode approach even for $\epsilon > 10$.

It should be noted that Eqs. (4)–(6) have the same structure as the equations derived in the so-called Lorenz model[14] of fluid instabilities. Discussions of the Lorenz model have been always concerned with the transition to turbulence, whereas the emphasis in this paper has been on the quantitative prediction of yet unexplained phenomena observed in the RBI and SDI transients in the region of regular roll convection. The analogy of the Lorenz-model equations with the Maxwell-Bloch laser equations has been considered by Haken.[15] A very interesting point open to investigation is the possibility of observing in convective instability experiments phenomena of the type already studied with the laser, such as the giant or superradiant pulses in the transient regime.

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Charge-Transfer Excitation of Impurity Ions in Tokamaks

R. C. Isler and E. C. Crume
Fusion Energy Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830
(Received 11 September 1978)

Detailed studies of spectra from the ISX-*A* (Impurity Study Experiment) tokamak at the Oak Ridge National Laboratory have shown that certain oxygen-ion lines appear too anomalously intense to have been excited solely by electron collisions. These results are interpreted as being due to charge transfer and suggest the necessity of incorporating this mechanism into analyses of tokamak plasmas.

Although electron collisions usually dominate atomic processes in tokamak-produced plasmas, charge transfer from hydrogen atoms should theoretically constitute an important recombination process for certain impurity ions. The charge transfer takes place into excited states; and, in, some circumstances, excitation *via* this mechanism should dominate excitation by electrons. Charge transfer has previously been observed through the sudden increase of radiation from the $n=3 \rightarrow n=2$ transition of O^{7+} when 10–30-keV hydrogen beams are injected into a tokamak[1]; but detection of this process has not been reported for the more typical, noninjected discharges where the temperature of hydrogen atoms is less than 1 keV and their ambient current densities, $n_H\langle v\rangle$, are one to two orders of magnitude smaller than the current densities of the beams. In this Letter we present data from the ISX-*A* (Impurity Study Experiment) tokamak[2] which show that certain spectral lines of O^{5+} and O^{6+} appear too anomalously intense for excitation to have been produced solely by electrons and demonstrate that these anomalies are consistent with excitation through charge transfer. The observations are similar to those made on carbon ions in laser-produced plasmas[3,4] where the electron temperatures are much lower, and the electron concentrations much larger, than in tokamaks. The present results demonstrate the necessity of including charge transfer as an effective recombination process when modeling the behavior of impurities in plasmas, and they also suggest that the reactions may be exploited for experimental studies of impurities.

A segment of a spectrum from the ISX-*A* tokamak is shown in Fig. 1. Most of the intense lines arise from oxygen and carbon; the quasicontinuous feature above 94 Å is a second-order tungsten radiation from metal injected into the plasma during the discharge. We concentrate primarily on the 2^2S-n^2P and 2^2P-n^2D transitions of O^{5+}, the 2^3S-n^3P and 2^3P-n^3D transitions of O^{6+}, and pairs of transitions in O^{4+} and C^{3+}. Other series of lines above 50 Å that are of interest have at least one member obscured by blends, and there are no relative intensity calibrations for the photographic plates below 50 Å.

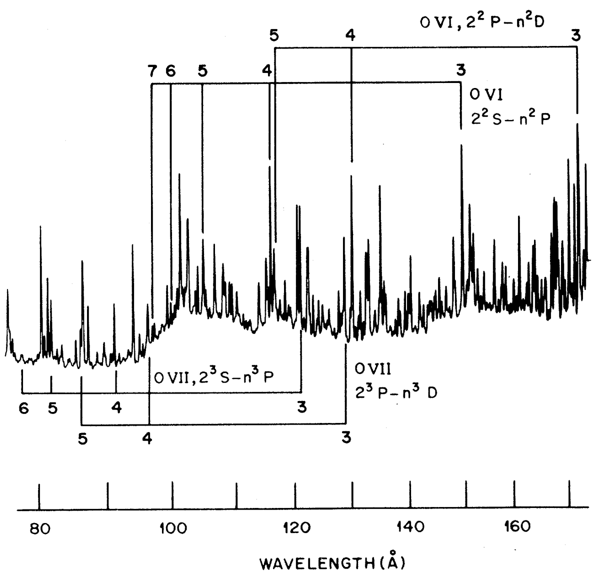

FIG. 1. Spectrum showing transitions from O VI and O VII.

Normalized experimental emission rates of several series of lines are listed in Table I together with calculated rates for coronal conditions. For optically allowed transitions, we use the following expression for electron-excitation rate coefficients[5]:

$$R = 3.14\times 10^{-7}\frac{I_H}{\Delta E}\left(\frac{I_H}{kT}\right)^{1/2} \times \langle \bar{g}\rangle f e^{-\Delta E/kT} \text{ cm}^3/\text{sec}. \quad (1)$$

TABLE I. Normalized emission rates, *I*, for several series of spectral lines. Calculated reates pertain to excitation by electron collisions. Approximate internuclear distances for charge transfer to occur are shown in the last column.

Ion	Transition	λ (Å)	I_{exp}	I_{calc}	R_c (a.u.)
O^{4+}	2^1S-3^1P	172.2	1.00	1.00	3.8
	-4^1P	135.5	0.10	0.08	12.3
O^{5+}	2^2S-3^2P	150.1	1.00	1.00	3.2
	-4^2P	115.8	0.45	0.15	7.8
	-5^2P	104.8	0.066	0.052	> 20.0
	-6^2P	99.7	0.032	0.027	>> 20.0
	-7^2P	96.8	0.012	0.016	-
	2^2P-3^2D	173.0	1.00	1.00	3.3
	-4^2D	129.8	0.11	0.12	8.0
	-5^2D	116.4	0.016		> 20.0
	-6^2D	110.2	0.007		>> 20.0
O^{6+}	2^3S-3^3P	120.3	1.00	1.00	2.6
	-4^3P	91.0	0.22	0.15	5.7
	-5^3P	81.9	0.22	0.05	12.3
	-6^3P	77.7	0.031		> 20.0
	2^3P-3^3D	128.5	1.00		2.7
	-4^3D	96.1	0.30		5.8
	-5^3D	86.1	0.19		12.5
	-6^3D	81.5			> 20.0
C^{3+}	2^2S-3^2P	312.4	1.00	1.00	7.3
	-4^2P	244.9	0.25	0.23	> 20.0

It is reasonable to consider $\langle \bar{g} \rangle$ as a constant[6] approximately equal to 0.2 for transitions in which $\Delta n \neq 0$; the oscillator strengths f are well known.[7,8] Although there are pitfalls in employing this expression indiscriminately, our use of it for comparing line intensities from light ions appears justified by laboratory measurements since *relative* experimental excitation rates of $2s$-$3p$ and $2s$-$4p$ transitions of Li- and Be-like ions are within 15% of the calculated ratios.[9] The lines of O^{6+} are assumed to be excited primarily from the 2^3S metastable state, and corrections are made for branching and cascading. Rate coefficients for exciting the ^2D states of O^{5+} are computed from the work of Kunze and Johnson.[9]

The temperature range at which a given ion species exists in the plasma is determined by a model calculation that assumes impurities continually recycle between the edge and the interior of the plasma. Analytic profiles of the electron temperature and density which approximate the average plasma conditions under which Fig. 1 was obtained are shown in Fig. 2(a). The calculated profiles for the temperature and the concentration of neutral hydrogen are shown in Fig. 2(a), and the concentrations of inward-flowing oxygen ions are shown in Fig. 2(b). Where experimental and calculated rates are compared, they agree within 50% except for the 2^2S-4^2P transition of O^{5+} and the 2^3S-5^3P transition of O^{6+}. For these two multiplets the discrepencies are a factor of 3–5. It is these anomalies which we believe can be reasonably ascribed to charge exchange.

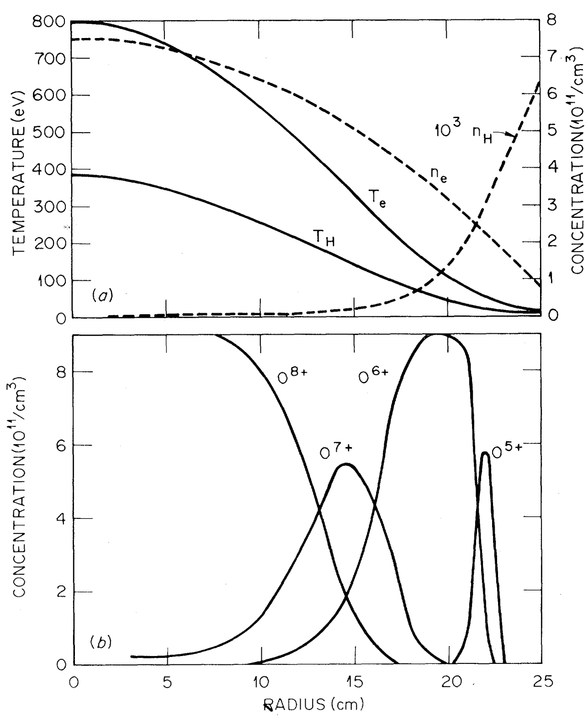

FIG. 2. Radial profiles employed for calculations of oxygen excitation rates: (a) Electron and hydrogen-atom temperatures and concentrations; (b) concentrations of inward-moving oxygen ions.

Neither theoretical nor experimental charge-exchange cross sections at low energies are known for the transitions we consider here except for the reaction[10] $C^{4+} + H^0 \to C^{3+} + H^+$. We will return to a discussion of this system, but for the present consider some general aspects of a simple two-state Landau-Zener description of the charge-transfer process which permits us to make semiquantitative plausibility arguments. In this theory the charge-transfer cross section is written as

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

where R_c is the internuclear distance at which quasimolecular potentials of the initial and final systems cross. The potential of the initial system varies little at internuclear distances beyond $4a_0$, and the potential of the final (exoergic) system is determined by the Coulomb repulsion between the separating ions. In this case we express the parameter η as[11]

$$\eta = 7.46\times10^6(U_{01}^2R_c^2/qv_0), \tag{3}$$

where U_{01} (in eV) is the matrix element which couples the initial and final channels, q is the charge (in terms of proton charge) of the final-state ion, v_0 is the relative velocity (cm/sec) of the colliding particles, and R_c is expressed in atomic units. Values of U_{01} tend to decrease from a few eV to about 10^{-2} eV as R_c varies from 4 to 14 a.u.[11] The term in square brackets in Eq. (2) has a maximum value of 0.113 when η is equal to 0.424. Because the energies of atomic hydrogen atoms in the plasma range from 10 to 400 eV, only those channels which have crossings between about 8 and 12 a.u. are expected to undergo strong charge transfer.

The values of R_c from our simplified picture are listed in Table I. It of course must be realized that the actual crossing points may easily vary by ±1 a.u. from the values listed. For example, the crossing points for three Σ and two Π channels which lead to populating the $n=3$ levels of C^{3+} are actually spread between 6 and

8 a.u.[10] Furthermore, the localized-interaction curve-crossing picture must be replaced by a close-coupling calculation including all these channels (and some additional ones) to generate an accurate theoretical cross section. Nevertheless, we can see from Table I that ehancement of spectral lines might be expected for the $n=4$ states of O^{4+} and O^{5+}, the $n=5$ (and possibly the $n=4$) states of O^{6+}, and the $n=3$ states of C^{3+}. The two oxygen lines which definitely appear to be anomalous (115 Å for O^{5+} and 81.9 Å for O^{6+}) do, indeed, originate from levels into which charge transfer could take place, and although the excitation rates are not available for the ^3D states of O^{6+}, it would appear from the rates at which the other series decrease in intensity as a function of n that the 2^3D-5^3D transition might also be enhanced.

In contrast to the intensities of the 115.8- and the 81.9-Å lines, several other lines that could be populated by charge transfer do not show anomalies. In this connection, we first note that it is unlikely that the various angular momentum states that correlate to a given level, n, are populated equally (or statistically) by charge exchange at low collision energies; but our highly simplified picture of the charge-transfer process does not permit us to estimate the relative probabilities. Secondly, although we have shown that conditions are favorable for charge transfer into certain states, it is necessary to assess the magnitude of this process relative to electron excitation. This comparison has been accomplished by using the profiles shown in Fig. 2.[12] For O^{6+} and O^{4+} the potential curve crossing has been assumed at 12 a.u., and ηv has been taken as 1.9×10^5 cm/sec. Charge-transfer cross sections are calculated from Eq. (2) for energies corresponding to the temperature of atomic hydrogen. The electron excitation rates are computed from the impurity-recycling model, and in the calculations for O^{6+} the spectrum of Fig. 1 is also employed to obtain the concentration of the triplet metastable state. The results shown in Table II indicate that charge transfer may dominate the excitation of the $n=5$ level of O^{6+}, but that it may contribute only 25% to the intensity from the $n=4$ level of O^{4+}. Hence, it is quite plausible that a large enhancement of the O^{4+} line is not seen even though a curve crossing exists at a favorable internuclear distance.

Similar calculations have been done for O^{5+} and C^{3+} with crossings assumed to be at 8 a.u. In this case, two values of ηv_0 were employed, 2.4 $\times10^7$ and 4.1×10^6 cm/sec. The first value comes from fitting the curve in Ref. 11 for U_{01} vs R_c. The second value is close to that which might be expected from the recent calculation of Olson, Shipsey, and Browne[10] for H^0+C^4 interacting at a velocity of 10^7 cm/sec; we still use Eq. (2) in order to extend σ to lower velocities. Again the results are presented in Table II. Electron collisions dominate the excitation of C^{3+} for either value of ηv_0, whereas if we consider the smaller value for the $O^{6+}+H^0$ system, which is isoelectronic to the $C^{4+}+H^0$ system, the charge transfer competes with electron collisions for populating the $n=4$ level. It must be emphasized that only very detailed calculations can provide exact comparisons, and it is hoped that some of these will be forthcoming for the atomic systems which we discuss here.

TABLE II. Calculated ratios, ρ, of rates for excitation by charge transfer to rates for excitation by electron collisions.

Ion	Transition	ηv_0 (cm/sec)	ρ
O^{4+}	2^1S-4^1P	1.9×10^5	0.24
O^{5+}	2^2S-4^2P	2.4×10^7	0.22
		4.1×10^6	1.06
O^{6+}	2^3S-5^3P	1.9×10^5	2.39
O^{3+}	2^2S-3^2P	2.4×10^7	0.02
		4.1×10^6	0.30

Finally, we note that in the model used here that the formation of O^{5+} by charge exchange exceeds the other recombination rates at radii greater than 17 cm when ηv_0 is taken as 4.1×10^6 cm/sec. Self-consistent modeling must, therefore, incorporate charge transfer once the cross sections are known well enough to provide accurate results.

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Experimental Observation and Numerical Simulations of Laser-Driven Ablation

J. P. Anthes, M. A. Gusinow, and M. Keith Matzen
Sandia Laboratories, Albuquerque, New Mexico 87185
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A group of fast ablatively driven ions has been observed by Thomson-parabola and Faraday-cup analyses of an expanding plasma produced by focusing energetic 8-nsec Nd:glass-laser pulses onto thick planar targets. Numerical simulations reveal the formation of an ablation structure with characteristics that agree well with the experimental observations.

With the increasing emphasis on longer laser pulses and ablatively driven targets in laser fusion studies, it is important to gain an understanding of the ablative characteristics of the ion expansion. Long pulses allow sufficient time to establish steady, ablative flow[1,2] from the target surface. In this Letter we report the experimental observation of a characteristic signature of ablation, namely, a group of energetic ablatively driven ions. Calculations have illustrated the formation of this fast-ablation group; the calculated energy of the ablation ions is compared with the experimental measurements.

A Nd:glass-laser system was used for the experiments reported here. The pulses were approximately 8 nsec full width at half maximum (FWHM) and the energy delivered to the target chamber was varied up to 36 J. Pinhole transmission studies similar to those in Ref. 3 gave a focal-spot diameter of 100 μm, defined as containing 90% of the incident energy. The average intensity on target was varied up to approximately 5×10^{13} W/cm^2. (The optical system was effectively $f/5$.) The laser was incident on planar targets (approximately 100 μm thick) at an angle of 17° to the target normal. For the results reported here a Thomson parabola[4] was placed normal to the target surface and a Faraday cup was located 70 cm from the target surface at an angle of 21° from the target normal (38° from the incident laser beam). The background pressure in the target chamber was maintained at less than 3×10^{-6} Torr. Only a small angular dependence was observed when Thomson-parabola traces were obtained simultaneously at both the normal and 21° positions. Although our Thomson parabolas do not measure absolute ion densities,[5] they have been shown to give an accurate measure of the ion energies (± 3%). The ionization stages present in the expanding plasma can be ascertained from the presence of the parabolic traces and qualitative information on the relative densities of the ionization stages can be obtained from the relative brightness of the traces. The results reported here did not vary when a final clean-up dielectric polarizer was removed from the laser. The dielectric polarizer defined p polarization incident on the target. This indicates that resonant absorption is not a significant absorption mechanism in these experiments.

In Figs. 1 and 2(a) Thomson-parabola traces are shown which illustrate the two types of ion expansions observed. The Thomson-parabola device[5] consists of parallel magnetic and electric fields which deflect ions according to their energy (E) and charge state (Z). The electric field

