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Experimental rate coefficients for electron-impact ionization of Ne VI, Ne VII, and Ne VIII

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Effective ionization rate coefficients of Ne VI, Ne VII, and Ne VIII are derived from the time evolution of these ions in a transient helium plasma produced in a θ-pinch discharge. Good agreement is found with theoretical rate coefficients.

The analysis of line radiation emitted by ions of rapidly ionizing plasmas allows the derivation of the effective rate coefficients for ionization of the respective ionization stages provided the plasma behavior and its parameters are well known. The principle of this method usually described in the literature as the "plasma spectroscopic method" has been discussed previously,[1,2] and Griem has recently published a review of all results.[3]

In a plasma, the densities n_z of the ionization stages z of an atomic species are governed by a set of coupled rate equations

$$\frac{\partial n_z}{\partial t} = n_e(n_{z-1}S_{z-1} - n_z S_z) + n_e(n_{z+1}\alpha_{z+1} - n_z\alpha_z) - \nabla\cdot\Gamma_z \,, \qquad (1)$$

where n_e is the electron density, S_z is the total effective rate coefficient for ionization, α_z is the effective rate coefficient for recombination, and Γ_z represents the particle flux. In the *rapidly ionizing regime*, the electron temperature is high such that recombination is negligible, and Eq. (1) reduces to

$$\frac{\partial n_z}{\partial t} = n_e n_{z-1}S_{z-1} - n_e n_z S_z - \nabla\cdot\Gamma_z \,. \qquad (2)$$

In a θ-pinch plasma, impurity atoms typically constitute a small fraction of the carrier plasma; they are compressed or lost with the fully ionized plasma, and the source term is written as

$$\nabla\cdot\Gamma_z = -\frac{n_z}{n_e}\frac{dn_e}{dt} \,. \qquad (3)$$

The time histories of the ions are thus solely governed by the ionization rates, and these can be derived by calculating time histories of the ions in the well-diagnosed plasma and by varying the rate coefficients S_z until computed and observed time histories match. One certainly has to take into account proper excitation rates of the observed emission lines as well as plasma variations along the line of sight. In tokamak plasmas, diffusion and convective transport[3] determine the source term $\nabla\cdot\Gamma_z$.

The advantages of this experimental method are that it is not restricted to low states of ionization and that it yields "effective" ionization rates which include stepwise ionization via excitation and inner-shell ionization in cases where these contribute. However, one major puzzle remains in pinch experiments as the rate coefficients for many ions with more than two electrons are lower by about 40%, on the average, than theoretically expected.[3] With increasing nuclear charge Z this discrepancy disappears as measurements on the lithiumlike ions Al XI and Si XII have revealed.[4] On the other hand, for ions of the heliumlike and hydrogenlike sequence, the agreement between experiment and theory was very good.[3,5]

A recent investigation of the recombination into excited states of lithiumlike ions showed an effective recombination much larger than theoretical predictions, and it was proposed that charge exchange with neutral hydrogen might be responsible.[6] Since this process could also slow down effective ionization and hence be the cause of a systematic error, we carried out an experiment now using helium as carrier plasma instead. It was seeded with 0.5% neon. Practically all previous experiments of this kind have been performed on hydrogen plasmas.

The investigations were carried out on a θ-pinch discharge, which has been described in detail previously.[5] Electron density and temperature were obtained as a function of time along a diameter of the plasma column in the midplane of the discharge using Thomson scattering. With a filling pressure of 1.5-Pa helium and a reversed bias field, a stable plasma column was obtained, the radial density distribution of which was well described according to that of the rigid-rotor model. For the modeling, the density and temperature were averaged across the radius. The length of the plasma column was obtained from the continuum emission observed through small holes in the coil along the axis. Several lines for each ionization stage were observed in order to ensure that self-absorption did not influence the time history.

The results are shown in Table I for the ions Ne VI, Ne VII, and Ne VIII. Line 1 gives the electron temperature kT_e, line 2, the ratio of electron temperature to the ionization energy of the ground state (kT_e/E_i), and line 3, the average electron density n_e; all values are cited for the time of peak concentration of the respective ionization stage. Line 4 gives the experimental effective ionization rate coefficient S_{expt}. For comparison, theoretical rate coefficients from the ground state are quoted as well. S_{Lotz} refers to the semiempirical rate coefficients of Lotz,[7] S_{CBE} to rate coefficients derived from calculations in the Coulomb-Born-exchange (CBE) approximation by Golden and Sampson[8] and by Vainshtein and Shevelko[9] (both yielding the same values here), and S_Y to calculations in the distorted-wave approximation by Younger.[10] For the

TABLE I. Experimental ionization rate coefficients compared with various theoretical models.

	Ne VI	Ne VII	Ne VIII
kT_e (eV)	80	100	230
kT_e/E_i	0.50	0.48	0.96
n_e (cm^{-3})	2.0×10^{16}	2.5×10^{16}	5.0×10^{16}
S_{expt}	2.9×10^{-10}	1.8×10^{-10}	1.3×10^{-10}
S_{Lotz}	2.4×10^{-10}	1.2×10^{-10}	1.6×10^{-10}
S_{CBE}	2.4×10^{-10}	1.1×10^{-10}	1.5×10^{-10}
S_Y		1.1×10^{-10}	1.5×10^{-10}
$S_{eff,theor}$	2.5×10^{-10}	1.4×10^{-10}	1.7×10^{-10}
$S_{expt}/S_{eff,theor}$	1.16	1.29	0.8

boronlike ion Ne VI ionization of the $2p$ electron as well as of a $2s$ electron contribute to the ionization rate of the ground state.

At the densities of the present pinch experiment, low-lying levels are more or less strongly populated, and ionization from these levels contributes. Therefore, effective rate coefficients taking this into account have been calculated and are given in line $S_{eff,theor}$.

In the case of the lithiumlike Ne VIII ionization stage, the population of the $2\,^2P$ levels has to be considered. It was calculated considering collisional excitation and deexcitation as well as radiative decay; ionization from the ground state and from the excited level was calculated according to Ref. 8. The effective rate coefficient obtained is only slightly larger than that of the ground state for the conditions of the present experiment.

Ne VII is berylliumlike and the $2\,^3P$ metastable levels will have a significantly higher population than the ground state because of the larger statistical weight of these levels.[11-13] Since the ionization rate coefficient from the metastable level is larger than that from the ground state by only 36% (Ref. 10), the effective ionization rate does not depend strongly on the exact population distribution between the two levels: it is larger than the ground-state ionization (S_{CBE} or S_Y) by less than 30%. Ionization from other levels can be neglected.

The boronlike ion Ne VI has several low-lying $n=2$ levels including the metastable $2\,^4P$ levels which are 12.5 eV above the ground state. Again, ionization from the ground state and the metastable levels will dominate; both ionization rate coefficients (Ref. 8) differ by about 10% and the distribution of the population between these levels is thus of little influence.

Comparison of these theoretical effective rate coefficients $S_{eff,theor}$ with the experimental results reveals that within the experimental uncertainty (estimated to be about 40%) we obtain agreement.

In order to come to a conclusion, we have indeed to look at the charge exchange in both plasmas. For low ion velocities corresponding to the experimental conditions of a pinch plasma, the reduced cross sections are nearly independent of the velocity and may be taken from Knudsen, Hangen, and Hvelplund.[14] The cross section for He^+ was estimated using a method described by Presnyakov and Uskov,[15] which is used to obtain cross sections at relative velocities $v < z^{1/2}$ (in a.u.). The method is based on the Keldysh approximation[16] and includes the solution of the time-dependent Schrödinger equation for a system of two colliding heavy particles to obtain the transition probability of the optical electron through the time-dependent potential barrier of the system. Thus, we have

$$\sigma(H)/z \simeq 7\times10^{-16}\,cm^2\,,$$
$$\sigma(He)/z \simeq 2\times10^{-16}\,cm^2\,, \tag{4}$$
$$\sigma(He^+)/z \simeq (1-3)\times10^{-17}\,cm^2\,,$$

where z is the charge of the ion.

We must now compare the charge-exchange rates R^{cx} on the ions of charge z in both a hydrogen and a helium plasma:

$$R^{cx} = n_z n_A \langle v\sigma(A)\rangle = n_e n_z \frac{n_A}{n_e}\langle v\sigma(A)\rangle\,, \tag{5}$$

where A denotes the species H, He, or He^+, respectively.

The ratios n_A/n_e can be estimated for coronal equilibrium.[17] For an electron temperature of about 200 eV, this approximation yields

$$n_H/n_e \simeq 1\times10^{-7};\quad n_{He}/n_e \simeq 7\times10^{-11};$$
$$n_{He^+}/n_e \simeq 3\times10^{-6}\,.$$

The fraction of neutral helium is much lower than that of neutral hydrogen because most helium atoms are ionized to the bare helium nucleus.

Combining these ratios with the cross sections [Eq. (4)] reveals that the charge-exchange rate with neutral helium is smaller than that with neutral hydrogen by several orders of magnitude, but the charge-exchange rate of ions with He^+ is of the same magnitude as that with hydrogen; equal temperatures of the hydrogen and helium plasmas were assumed.

Thus, the effective ionization rates of atomic species are not expected to be different in hydrogen or helium plasmas, and charge exchange should even have no influence on the ionization at all in both cases when the absolute values of the estimated effective rates are considered; they are sufficiently small.[18]

This contradicts the observations and we suggest, therefore, that for some reason not known as yet the concentration of neutral hydrogen in pinch discharges is probably higher than the estimate from equilibrium relations, since the other recombination mechanisms like radiative, dielectronic, and three body are definitely of minor importance. Our present results imply that helium plasmas be used preferably for ionization rate measurements in the future.

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