Ionization and Recombination Rate Coefficients of Highly Ionized Molybdenum Ions from Spectroscopy of Tokamak Plasmas

C. Breton, C. De Michelis, M. Finkenthal, and M. Mattioli
Association EURATOM–Commissariat à l'Energie Atomique sur la Fusion, Département de Physique du Plasma et de la Fusion Contrôlée, Centre d'Etudes Nucléaires, 92260 Fontenay-aux-Roses, France

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Ionization and recombination rate coefficients have been estimated using the effect of saw-tooth electron-temperature relaxations in a tokamak plasma on the emission of impurity ions. The ionization rate coefficient of highly ionized (of the order of 30) molybdenum has been found to be between 1 and 1.5 times Lotz's semiempirical coefficient. For the first time, we have also estimated the recombination (mainly dielectronic) rate coefficient for the same ions, and have found it to be between 0.5 and 1 times the value given by Burgess's formula.

Knowledge of cross sections of highly ionized positive ions for electron impact is of crucial importance in order to calculate radiation losses from impurity ions in hot plasmas (these losses possibly being the limiting factor in controlled fusion research). Moreover, this knowledge is important to understand the physics of the solar corona.

Ionization cross sections have been measured until now by two methods. The first one, using crossed-beam techniques,[1] is capable of good accuracy over a wide range of electron energies, but has been limited up to now to very low-charge (one or two) ions. The second method, using plasma spectroscopy,[2] allows the rate coefficients (i.e., the product of the cross section and the electron velocity averaged over the Maxwellian electron velocity distribution) to be measured for ions of higher charge, but with less accuracy and for a limited energy range with the rather poor energy resolution determined by the spread of the Maxwellian velocity distribution of the plasma electrons. However, the ionization conditions of this method closely correspond to the situation occurring in present-day fusion plasma devices. This technique depends on time-resolved measurements of spectral line intensities (in arbitrary units) of the ions of interest as emitted by a pulsed laboratory plasma (usually a θ pinch). It involves solving the coupled rate equations for the various ion densities, using measured electron densities and temperatures and approximate theoretical ionization rate coefficients having the correct temperature dependence. Recombination-rate coefficients can in this case be neglected, since these transient plasmas are heated so rapidly that the ions are far from ionization equilibrium. Then, with the assumption corona excitation equilibrium, the emission lines yield the ionization rate coefficients through a comparison of experimental time histories with computed ones. The ion charges accessible with this technique are, however, limited by the electron temperatures obtained in θ pinches (a few hundreds of eV).

We shall describe in this paper a new technique, still based on plasma spectroscopy, which makes use of an MHD (magnetohydrodynamic) instability occurring in practically all present tokamak plasmas. Besides the advantages of the usual spectroscopic method, it is possible here to study very highly ionized ions (as a result of the keV electron temperature of tokamak plasmas), and, moreover, since it involves a stationary plasma, both ionization and recombination rate coefficients are estimated.

Under a large variety of experimental conditions tokamak plasmas exhibit an MHD instability in the central hot region, resulting in the so-called internal disruptions, which manifest themselves as a sawtooth modulation in soft-x-ray signals.[3-6] It has been experimentally demonstrated[6] that these soft-x-ray disruptions in present tokamaks are almost entirely due to electron-temperature sawtooth relaxations (typically of the order of 15%) with only minor electron-density modulations (of the order of 1%). The period of these relaxations is a function of the electron density[7] (typical values are between 1 and 3 ms); the initial temperature decrease is very abrupt, with a time scale of approximately $\frac{1}{30}$ of the period, followed by a slow increase back to the initial value. These temperature relaxations affect several plasma parameters.[6] In particular, we are interested here in the fact that the radiance of highly ionized heavy impurity ions (present in the central hot region) is modulated in correlation with the soft-x-ray signal, but with a much slower initial response time (between 0.5 and 1 ms, depending on the plasma parameters). Figure 1

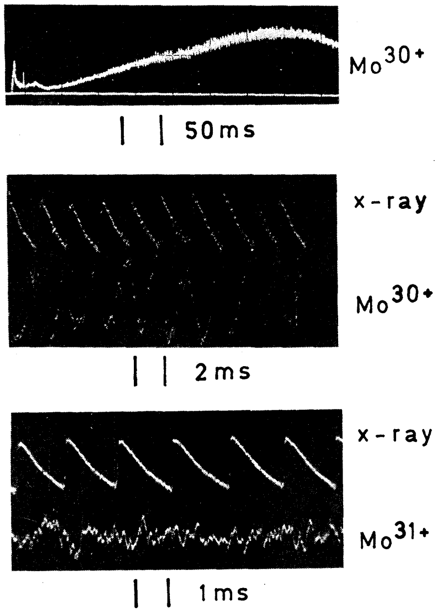

FIG. 1. Radiance of Mo XXXI 117 Å and Mo XXXII 129 Å, correlated with the soft-x-ray signal (15% modulation), at the current plateau (350 ms) of a 300 kA, 50-kG deuterium discharge in TFR (Ref. 6). Time increases from left to right.

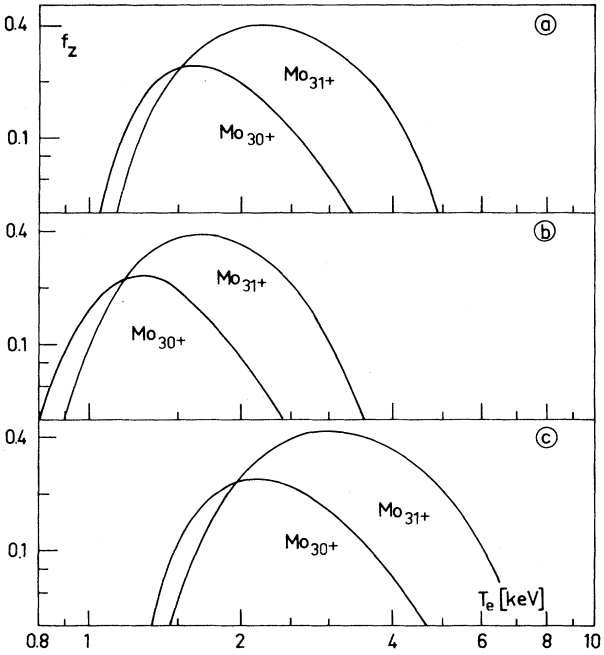

FIG. 2. Fractional abundances f_Z $(=n_Z/\sum_Z n_Z)$ of Mo^{30+} and Mo^{31+} ions. (a) Theoretical rate coefficients discussed in the text. (b) α_Z multiplied by 0.5. (c) α_Z multiplied by 2.

shows the results for the $3s^2\,{}^1S_0-3s3p\,{}^1P_1$ transition of Mo^{30+} (Mg-like, ionization potential $\chi_i = 1805$ eV, wavelength $\lambda = 117$ Å) and the $3s^2\,S_{1/2}-3p^2\,P_{3/2}$ transition of Mo^{31+} (Na-like, $\chi_i = 1870$ eV, $\lambda = 129$ Å) in a TFR deuterium discharge having a central electron temperature of 1.8 ± 0.2 keV.[8] Intensity modulations (of approximately 15%) can be seen on the Mo XXXI radiance but not on the Mo XXXII radiance. They have been shown to result from a displacement of the existing ionization equilibrium conditions, due to the sudden electron-temperature variation. Indeed, our molybdenum ionization equilibrium calculations[9] show that for $T_e = 1.8$ keV the fractional abundance f_{30+} $(=n_{30+}/\sum_Z n_Z)$ of Mo^{30+} is a decreasing function of T_e, while f_{31+} is practically at its maximum abundance (and therefore it is not affected by a 15% variation of T_e). Thus, the line intensities $E_Z = n_e n_Z Q(T_e)$ vary proportionally to n_Z (Z being the ion charge), since the electron density is approximately constant, and the excitation-rate coefficient $Q(T_e)$ is a very weak function of temperature for the observed transitions (which are of the $\Delta n = 0$ type, n being the principal quantum number; these lines are therefore emitted at electron temperatures much higher than their excitation potentials). We shall show in the following that this fact can be used to estimate the accuracy of the rate coefficients used in ionization equilibrium conditions.

Figure 2(a) shows the fractional abundances f_Z of Mo^{30+} and Mo^{31+} as a function of T_e, obtained by our calculations.[9] The rate coefficients used for these calculations are discussed by the TFR group[9] and Breton *et al.*[10] Briefly, we have used Lotz's semiempirical ionization rate coefficients, S_Z (taking into account inner-shell ionization, which is important for one or two peripheral electrons[11]); the recombination-rate coefficients, α_Z, are the sums of the contributions from both radiative recombination α_{rZ},[12] and dielectronic recombination, α_{dZ} (calculated by means of the general formula proposed by Burgess,[13] including two resonant transitions). Figure 2b has been obtained by multiplying α_Z by 0.5 and Fig. 2(c) by multiplying α_Z by 2. Since experimentally the Mo XXXI radiance increases when the electron temperature decreases, Fig. 2 shows that only the results of cases (a) and (b) can be accepted. However, it must be pointed out here that the same steady-state ionization equilibrium curves are obtained by changing S_Z and α_Z in such a way that their ratio is kept constant [i.e., for example Fig. 2(b) can be obtained either by multiplying α_Z

by 0.5 or by multiplying S_Z by 2]. On the contrary, time-dependent calculations are sensitive to the individual values of the rate coefficients, even if their ratio is kept constant (i.e., for equal ionization equilibria). Figure 1 shows that the Mo XXXI intensity modulations have a time constant much longer than that associated with the electron-temperature decrease (as measured, for example, by Thomson scattering.[6] Therefore, a comparison of calculated and experimental light emission during the temperature sawtooth modulations will allow the accuracy of the individual rate coefficients used to be estimated.

Time-dependent numerical calculations have been performed for cases (a) and (b) of Fig. 2. The electron temperature has been taken to have a 15% sawtooth modulation with a period of 2.5 ms (this corresponding to one of the best diagnosed experiments, the central electron temperature being 2 ± 0.3 keV), with a fall time of $\frac{1}{30}$ of the sawtooth period (in this case the response time of the Mo XXXI 117-Å radiance was 1 ms). Since no modulations on the radiance of Mo XXXII 129 Å were seen in these experiments, the electron temperature in these calculations was chosen in order to minimize this modulation in the calculations. T_e was therefore assumed to oscillate between 2.2 and 1.9 keV for the case of Fig. 2(a), and between 1.9 and 1.6 keV for the case of Fig. 2(b). The electron density was kept constant at 8×10^{13} cm^{-3} (central value). The initial conditions for the molybdenum ions are given by ionization equilibrium at the maximum electron temperature. The results obtained for the conditions corresponding to Fig. 2(b) are presented in Fig. 3, showing the third relaxation in the calculations (since three relaxations are necessary to obtain repetitive oscillations in the calculations). Figure 3(a) gives the fractional abundances of Mo^{30+}, Mo^{31+}, and Mo^{32+} ions, while Fig. 3(b) shows the emission E_Z (photon cm^{-3} s^{-1}) of three lines, one for each ion, together with the assumed electron-temperature variation. In order to calculate E_{32+} we have considered the $2p$-$3d$ transition, at 4.6 Å, for which $\Delta n = 1$, thus having an excitation rate coefficient strongly dependent on temperature. The excitation-rate coefficients have been taken in the way explained in Ref. 10.

If S_Z and α_Z are multiplied by the same factor (i.e., α_Z/S_Z is kept constant) the response time of the system is changed. This is illustrated in Fig. 4, where cases (a), (b), (c), and (d) are obtained by multiplying both theoretical rate coefficients by 4, 2, 1, and 0.5, respectively [the reference case, Fig. 4(c), corresponding to the calculations of Fig. 2(b)]. These calculations, besides giving a feeling for the accuracy of the method, show that when the rate coefficients are increased the computed emission follows more closely the sawtooth electron-temperature modulation. Incidentally, if only radiative recombination is included in these calculations, the response time of the emission is too long (of the order of 6 ms), thus underlining the importance of dielectronic recombination for these ions.

The comparison of these computations with the relevant spectroscopic data allows the accuracy of the semiempirical formulas used for the rate coefficients to be estimated. The most probable rates with respect to our calculations[10] are comprised between 1 and 1.5 times Lotz's ionization rate coefficient (with a slight preference for the lower value), and between 0.5 and 1 times Burgess's formula for the dielectronic recombination rate coefficient, for highly ionized (of the order of 30) molybdenum ions.

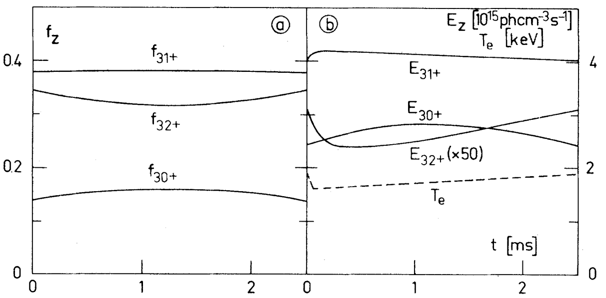

FIG. 3. (a) Computed time dependence of the fractional abundances of three Mo ions during one sawtooth relaxation. (b) Computed line emission for the same ions, and assumed electron temperature modulation.

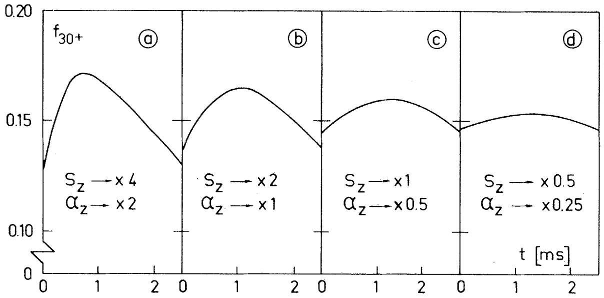

FIG. 4. Computed fractional abundance f_{30+} for four different values of α_Z and S_Z, but keeping the ratio α_Z/S_Z constant.

To conclude, we have demonstrated in this paper a new method of estimating rate coefficients, which can be used with highly ionized ions previously not accessible (because of the lower electron temperature in θ pinches). Given the wide variety of central electron temperatures which can be obtained in existing tokamaks (roughly 100 eV $\lesssim T_e \lesssim$ 3 keV), this method should allow ionization and recombination rate coefficients to be estimated for a large number of ions of the same impurity, and for a large number of elements. The precision of this type of estimations (which is already not much worse than in previous work) can be improved by increasing the signal-to-noise ratio of the observed emission, and probably also by using electron-temperature conditions such that the sawtooth modulations exist on the emission of two successive ions. Finally, previous work on θ pinches has also been used to estimate excitation-rate coefficients, by introducing into the discharge known amounts of a given impurity and measuring the intensities absolutely. This technique is, of course, also possible here.

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Ion-Cyclotron Instability in the TFR Tokamak

TFR Group[a]

Association EURATOM-Commissariat à l'Energie Atomique sur la Fusion, Département de Physique du Plasma et de la Fusion Contrôlée, Centre d'Etudes Nucléaires, 92260 Fontenay-Aux-Roses, France

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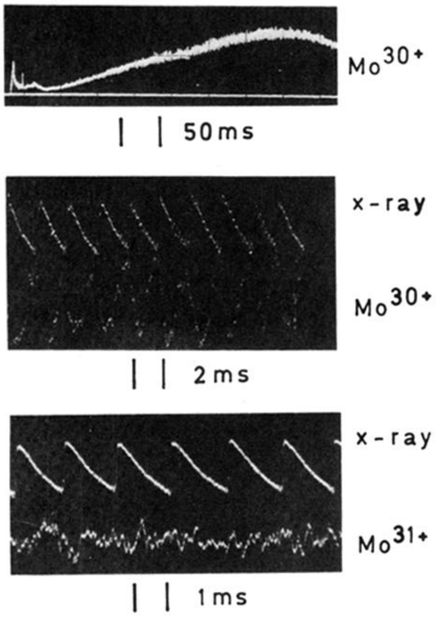
Density fluctuations in the ion-cyclotron frequency range have been observed in the TFR tokamak by microwave scattering. The geometry was such that the selected fluctuation wave vector was aligned across the confining magnetic field in the outside region of the torus. A threshold for the onset of the instability as a function of the discharge current has been observed. A plausible explanation of this instability in terms of current-driven ion-cyclotron electrostatic wave is discussed.

There is an extensive experimental and theoretical literature on ion-cyclotron instability in low-temperature plasma.[1-4] To our best knowledge there is no experimental observation of this kind of instability in tokamak devices. In this Letter, we present the first experimental evidence of the presence of density fluctuations in the region of the ion-cyclotron frequency and its harmonics in the TFR tokamak.

The electron density fluctuations have been observed by means of a microwave scattering experiment. Figure 1 is a schematic block diagram of the experimental arrangement. A 75-GHz, 10-W wave polarized in the extraordinary mode was launched into the plasma. This mode has been chosen because it permits propagation of the wave beam with negligible refraction for most of the TFR operating conditions. For the



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