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ELECTRON EXCITATION RATES IN NON-MAXWELLIAN PLASMAS

M. LAMOUREUX, P. ALATERRE* and J.P. MATTE*

Laboratoire de Spectroscopie Atomique et Ionique, Bât. 350, Université Paris-Sud, F-91405 Orsay Cedex, France
*Institut National de la Recherche Scientifique-Energie, Université du Québec, C.P. 1020, Varennes, Québec, JOL 2P0, Canada

Abstract. Electron excitation rates relative to allowed and forbidden transitions of He-like ions are evaluated for two current types of non-Maxwellian plasmas: plasmas with a suprathermal population and plasmas with electron distribution functions of the form exp-(v/Vm)^M. The rates are shown to be strongly affected by the non-Maxwellian character for moderate and large values of the ratio X/kTe, X being the threshold energy. This should be taken into account and hopefully taken advantage of when modelling X-ray amplifications in such plasmas.

1. Introduction.

In many natural and laboratory plasmas, the free electrons do not follow a Maxwellian distribution with kinetic temperature T_e. First, in an extended group of plasmas, a tail of Maxwellian suprathermal electrons has to be affixed to the cold Maxwellian distribution. This situation is found in astrophysical plasmas [1], Z pinch plasmas [2], tokamak plasmas with runaway electrons as well as in laser plasmas [3,4,5] subject to resonance absorption heating and/or parametric instabilities. Second, in another group of plasmas, the distribution is genuinely non-Maxwellian over the whole velocity range and takes the form exp-(v/Vm)^M with 2 < m < 5. This is the case in plasmas perturbed by ion acoustic turbulences [6] and in laser plasmas where "classical absorption" is the dominant heating mechanism [7,8]. Last situation occurs when using short wavelength lasers, as is usually done to curb the generation of suprathermal electrons deleterious from the viewpoint of inertial fusion. Whichever the cause and the nature of the non-Maxwellian character of the plasma, it will affect the properties which predominantly depend on electrons of energies for which the distribution is far from Maxwellian, that is on electrons energetic in comparison to the average kinetic energy kTe.

2. Calculation of the excited rates for He-like ions.

We consider electron collisional excitations in He-like ions, one is electron being brought to a 2s or 2p subshell. We study the allowed transitions 1s^2 1S → 1p
and the three forbidden transitions $\rightarrow 1s$, $3p$, $3s$ for the atomic numbers $Z=3, 6, 8,$ and $14$. For each excitation considered, we use the collision strength obtained from a close coupling model (1) [9] and expressed in a parametric way. In the following,

![Graph](image)

**Fig. 1** Electron distribution functions for two types of non-Maxwellian plasmas at the (cold) kinetic temperature $kT_e$. Solid upper curve: plasma with a suprathermal population, 5% of the electrons corresponding to the hot temperature $8kT_e$. Dash-dotted lower curve: plasma with the electron distribution $f(v)$ proportional to $\exp(-v/v_m^m)$ with $m=5$. Dashed straight line: reference Maxwellian case.

$\chi$ is the excitation threshold energy, $E=1/2\ M_e\nu^2$ the incident electron energy and $x=E/\chi$ the reduced energy. The rates amount to

$$\langle \sigma v \rangle = \chi a_0^2 \frac{\pi}{(Z-1)^2} \left[ f(x/\chi) \sum_{i=0}^{\infty} d_i \frac{x^{-i}}{\Gamma(1+i)} \right] \left[ \frac{dx}{\sum_{i=0}^{\infty} d_i \langle \sigma v \rangle_i} \right]$$

where $a_0$ is the Bohr radius and $f(E)$ (viz. $f(v)$) the isotropic distribution function normalized by $\int f(x/\chi) \nu^2 \, \nu \, d\nu = 1$. Besides being convenient for numerical evaluations, the fact that the collision strength is written as a sum of terms in relation (1) invites for physical comments. Thus, we point out that the $i=5$ term is present only for the $1s^2 \rightarrow 1p$ transition while the $i=0$ term is present only for the $\rightarrow s$, $l_p$ transitions. For the hydrogenic ions, the ionization rate is proportional to $\langle \sigma v \rangle$, $\chi$ standing for the ionization potential. For the completely stripped ions, the bremsstrahlung emissivity coefficient is proportional to $\langle \sigma v \rangle$ in Kramers approximation, $\chi$ corresponding now to the photon energy.

Results for these four collisional excitations are given below for values of $\chi/kT_e$ ranging from 0.5 to 10.

(1) It would be arduous and hardly affect our results or conclusions to include the atomic resonances neglected in [9], and treated and discussed in [10].
3. Excitation rates in plasmas with a suprathermal population.

The rate is a linear combination of the Maxwellian rates relative to the cold and hot temperatures. Figure 2 shows the evolution of the "elementary rates" \( \langle \sigma v \rangle_i \) defined in (1) versus temperature in the mono-Maxwellian situation; it can easily be accounted for by looking back at the \( x \) dependence in (1) and at the shape of the Maxwellian \( f \propto \text{ex}^{-\left(x \chi/kT_e\right)} \). Consequences on the four excitations considered are shown in Figure 3 in the example of OVII for the bi-Maxwellian plasma whose distribution is indicated in Figure 1. As expected, the ratios increase greatly with the larger values of \( \chi/kT_e \), particularly for the allowed transition.

![Graph showing elementary rates \( \langle \sigma v \rangle_i \) versus \( kT_e/\chi \).](image)

Fig. 2 Elementary rates \( \langle \sigma v \rangle_i \) as defined in relation (1) versus \( kT_e/\chi \) (\( \chi \) being the excitation threshold energy) in Maxwellian plasmas at temperature \( T_e \).

The dramatic sensitivity of the rates to the percentage of hot electrons has already been emphasized, mostly for collisional ionization; the resulting ionization equilibrium is thereby modified [1, 11, 12, 13]. It was already shown in a few cases that this feature should be taken into account to judiciously interpret experimental line intensities [5, 11]. As clearly pointed out here (Figure 3), the fact that the allowed and forbidden transitions respond differently to the suprathermal tail should make one careful when comparing intensities of lines whose upper states are populated by different ways. Thus, in the presence of suprathermal electrons, the temperature diagnostic currently used in tokamaks [14] and consisting in comparing the intensities of the resonant and forbidden lines of ALXII would be invalid, but could then be changed into a diagnostic on the suprathermal electrons. Finally the increase of the rates with the amount of hot electrons can be taken advantage of in working out X-Ray laser schemes. Huge amplifications of the gain were thus foreseen [12, 13] by using suprathermal electrons (monoenergetic for that purpose) which match the excitation threshold energy of the desired upper lasing state.
Fig. 3 Ratios of the non-Maxwellian rates over their Maxwellian counterparts for the transitions $1s \rightarrow 1p$ (allowed), and $\rightarrow 1s, 3p, 3s$ (forbidden) versus $\mathcal{E}/kT_e$, $\mathcal{E}$ being the threshold energy of the transition considered and $T_e$ the kinetic (cold) temperature. Example of OVII, using the distributions of figure 1. The upper part of the figure corresponds to the distribution with a suprathermal tail. The lower part corresponds to the distribution with a depleted tail; also shown are the ratios $f_{m=5}/f_{m=2}$ at threshold and the ratios of the $\langle \sigma v \rangle_m$.

4. Excitation rates in plasmas with electron distributions $\exp(-v/\nu_n)^m$.

Concerning the underdense region of a laser plasma heated by inverse bremsstrahlung, the relation of $2 < m < 5$ to the plasma parameters is given elsewhere [7,8]. It has been obtained by considering a series of laser plasmas studied with Fokker Planck simulations [15]. Above $1/2 \mu_e v^2 = 3kT_e$ the distribution presents a characteristically depleted tail, as seen in figure 1, and therefore leads to drastically reduced rates, contrary to the above case with suprathermal electrons. Figure 3 shows the ratio of the non-Maxwellian rates over their Maxwellian counterparts for the maximum value of $m=5$, that is when electron-electron collisions can be neglected [16]. At $\mathcal{E}/kT_e = 5$, the rates are reduced by around two orders of magnitude (for $m=3.5$ the reduction is of course smaller but still important: one order of magnitude). As illustrated in Figure 3, the ratio $f_{m=5}/f_{m=2}$ at the threshold $\mathcal{E} = 5(x=1)$ represents a rough and overestimated value of the ratio of the rates themselves, because of the steep decrease of $f$ with $\mathcal{E}$. On the other hand,
the factor of reduction corresponding to $<\sigma v>_{5}$ gives an underestimate of them. According to what was said in paragraph 2, the factors of reduction for $<\sigma v>_{5}$ and $<\sigma v>_{6}$ are indeed what we found for collisional ionization [8] and bremsstrahlung [17]. Notice that the four excitation rates of the He-like systems, whether allowed or not, are reduced by a nearly identical factor (very close to the one corresponding to $<\sigma v>_{6}$), almost independent from $Z$ with this abscissa scaling $\chi/kT_e$.

5. Conclusion.

This study of collisional excitation in He-like ions shows in which way the collisional rates are extremely sensitive to the features of the tail of the electron distribution for high values of $\chi/kT_e$ ($\chi$: excitation threshold energy). If the tail is inflated, as when suprathermal are generated, the rates are increased by amounts which depend on the excitation considered and are higher for the allowed ones. This plays in favor of the highly excited states and should be kept in mind when interpreting diagnostics based on line intensities. On the contrary, if the tail is depleted, as often in the underdense region of laser plasmas, the rates are drastically reduced in a similar fashion for all transitions, thus nearly prohibiting the collisional excitations. Here, we restricted ourselves to isotropic distributions, which is valid in the latter physical situation where polarization effects happen to be negligible [7]. However, when the hot electrons are created anisotropic [1] or drift in magnetic fields [18], this aspect should also be considered in a complete investigation of the radiative emission [18] and of the various rates. When dealing with laser plasmas during the irradiation of the target, we generally have to face a non-Maxwellian plasma of one kind or the other. This inevitable fact should be taken care of when modelling X-UV amplification in such mediums. It makes the calculations lengthier but brings with it the opportunity to favor the amplification by playing on these non-Maxwellian effects, as it has actually been once suggested [12,13].

References

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