AMPLIFICATION OF RADIATION IN THE DECAY OF A MAXIMALLY IONIZED PLASMA

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Amplification on atomic lines in a pulsed plasma has been examined [1, 3, 4] only for highly ionized hydrogen; the discussion for other elements and compositions* is far more complicated on account of the

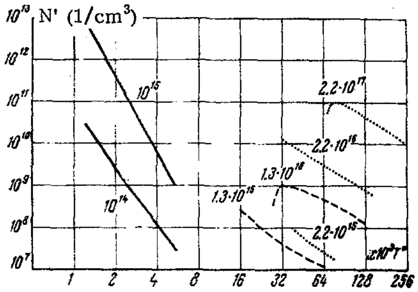

Fig. 1

relaxation problem, and also because we lack accurate values for the probabilities of the processes occurring on collision. It is simplest to consider the population distribution for the discrete levels of a decaying plasma in which most of the heavy particles are stripped nuclei (H^+, He^{2+}, Li^{3+}, etc.), which represents the relaxation of hydrogen-type ions. A similar problem arises for alkali-metal atoms or similar ions:

$$Li^+ + e \to Li^*, \quad Na^+ + e \to Na^*, \ldots,$$

or

$$Be^{++} + e \to (Be^+)^*, \quad Mg^{++} + e \to (Mg^+)^*,$$

$$B^{+++} + e \to (B^{++})^*, \ \ldots.$$

We suppose [1] that the mean energy of the free electrons is much less than the equilibrium value for the degree of ionization. The relaxation of the populations of He^+, Li^{2+}, etc., is very much as for a decaying hydrogen plasma. First a free electron is captured by a highly excited level of the ion via a ternary collision (nucleus + 2e → ion* + + e): then the electron runs through the discrete levels, either mainly via $n \to n - 1$ in inelastic collisions or direct to the ground state, $n \to \to 1$, by radiative transition. The main part is played by collisions with free electrons for the upper discrete levels of the one-electron ion; the probabilities C_n of these radiationless transitions increase with the principal quantum number n. Spontaneous radiative transitions predominate for the lower levels, the probabilities A_n of these increasing as n decreases. The electron lifetime in level n, $\tau_n \approx (A_n + C_n)^{-1}$, is maximal for $n = n^*$, with $A_{n^*} \approx C_{n^*}$. During the decay of such a plasma, a quasi-equilibrium distribution is rapidly established (in a time $\tau \ll \ll \tau_{n^*}$) in levels with $n \gg n^*$, which is related to the population $N_n(t)$ of these levels to the density $N_e(t)$ and mean energy $kT_e(t)$ of the free electrons by Saha's formula. The $N_n(t)$ for lower levels takes the form as for a dam, on account of the minimum transmission at $n = n^*$, for a fairly wide range in $N_e(t)$ and $T_e(t)$. Population inversion is observed for certain levels as the absence of reabsorption for the resonance radiation almost from the start of decay until the end of the quasi-equilibrium state.

The formulas for the terms of a one-electron ion of atomic number z are analogous to those for the hydrogen atom**, except that the increase in the Coulomb interaction causes the energy levels to be further apart by a factor z^2, and so the probability of radiative transitions in the ion is z^4 times that for hydrogen, while the cross-sections for collision processes are z^4 times less.*** Then the population inversion will persist at higher N_e and kT_e. For fairly low T_e, combination of the bare nucleus with an electron is in competition with subsequent acts of recombination, which tends to depopulate all levels of the one-electron ion, though the most important effect is the rapid removal of the n = 1 level, which weakens the reabsorption of the resonance radiation (frequency $\nu_{2,1}$) and facilitates retention of the amplification during the decay.

This may be illustrated via the amplification in a decaying maximally ionized plasma of an element of atomic number z, which may be based on the numerical data of [1,3,4] and also of [5,6] for pulse recombination of highly ionized hydrogen. The relaxation equations for the populations of levels of the one-electron ion are written as for hydrogen if T_e, N_e, N_n, and the characteristic times τ_n of the radiative transitions are converted to those for a hydrogen plasma via

$$N_e = N_e\,(\mathrm{H})\, z^7, \quad N_n = N_n\,(\mathrm{H})\, z^{11} x^{-1},$$
$$T = T\,(\mathrm{H})\, z^2, \quad \tau_n = \tau_n\,(\mathrm{H})\, z^{-4} \qquad (1)$$

in which x is the ratio of N_e to the density of bare nuclei (e.g., x = 2 for completely ionized helium, while x > 2 if the ionization is not complete). Direct use of the results of [1, 3] via (1) for low T_e and high N_e is restricted by the increase in the difference between the neutral hydrogen atom and the charged ion as regards the probability of radiationless transition as a function of the energy of the incident free electron (see the last footnote). The available data indicate (Fig. 1, solid lines for H, broken lines for He^+, dots for Li^{2+}) that there is an optimal T for a given N_e and one-electron ion such that the absolute inversion $N' = N'_{n^*} - N_2'$ is the largest, in which $N_n' = N_n / \Omega_n$, Ω_n and Ω_n is the statistical weight of the state with quantum number n. These T are sufficiently high for the use of external electron sources (a difference from a hydrogen plasma). Rapid decay, which leads to population inversion, can also be obtained by essentially different methods, e.g., isothermal compression.

*The complexity arises if there are several relaxation routes via discrete levels. From this viewpoint, a hydrogen-helium mixture hardly differs from chemically pure hydrogen, since the hydrogen recombines from the highly ionized state, whereas the helium is virtually neutral.

**Here we neglect the fine structure, which is unimportant for the lower levels and which vanishes as a result of interaction for the high levels.

***This is untrue near the threshold values of the excitation energy [2]. The cross-sections for radiationless transitions during collisions do not fall to zero when the energy of the electron slightly exceeds the threshold value but here have maximal values.

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