SIMULATION OF EMISSION AND ABSORPTION SPECTRA OF A LASER-PRODUCED PLASMA

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INTRODUCTION

To solve radiation gasdynamics problems it is necessary to know, beside the plasma composition, also the photon absorption coefficients, the emissive power, and other plasma spectral characteristics. A complete problem should involve in principle gasdynamics, radiation transport, equations describing the kinetics of excitation and ionization (de-excitation, recombination) of those ions which are essential in the problem. It should also include a block for the calculation of the probabilities of the corresponding transitions. It is clear, however, that the problem becomes unimaginably complicated even for substances having a moderate atomic number Z. For example, in calculations for heavy atoms by the Hartree–Fock–Slater method account is taken of up to $10^4$ transitions [1] and it is impossible to imagine the use of a corresponding system of kinetic equation. It is not by accident that problems in which kinetics is taken into account constitute subprograms that process and refine results of the main calculation, while the spectral and kinetics parts are, as a rule, relegated to a relatively small region of the spectrum (accordingly, part of the entire kinetics of the transitions) of interest, for example, for the study of laser effects in the x-ray region [2]. There exist, nonetheless, theoretical premises and practically applicable methods of calculating the radiative characteristics of atoms and ions, including those having large Z, for various limiting cases, such as an optically dense equilibrium plasma and an optically transparent plasma [1, 3, 4]. This raises problems connected with the storage of a large volume of information and construction of a theoretically well-founded effective method of interpolating the radiative characteristics of a plasma as a function of its optical thickness. This problem is substantially simpler than the one that includes kinetics of transitions.

The most complicated theoretical problem is that of allowance for the influence of a radiation field on the radiative characteristics of matter, a problem that can be solved, as we have already stated, by interpolating results. A simple method of interpolative calculation of spectral characteristics of a nonequilibrium plasma is based on the use of the fact that in such a plasma a predominant role is played by ions close to their ground states. For an equilibrium plasma this corresponds to appreciably lower temperatures and higher densities than in reality.

On this basis, Albritton [5] was able to obtain a detailed description of the absorption spectrum of a nonequilibrium plasma, using earlier detailed calculations of these quantities for an equilibrium plasma. So detailed a description was implemented by selecting a corresponding effective electron temperature $T_{e\text{eff}}$ and an effective density $\rho_{\text{eff}}$. The best, obviously, will be a choice of $T_{e\text{eff}}$ and $\rho_{\text{eff}}$ such that the average occupation numbers in the equilibrium and nonequilibrium cases coincide. As a rule, such a result cannot be obtained. It is possible to reach equality of the average occupation numbers $N_n$ in equilibrium and nonequilibrium cases for the most important shells. For example, for shells with quantum numbers $n^*$ and $n^* + 1$, where $n^*$ is the maximum principal quantum number of a partially filled shell of an ion in a ground state.

With this choice of $T_{e\text{eff}}$ and $\rho_{\text{eff}}$ one can well describe the average degree of ionization and the spectral characteristics of the plasma, but only in a frequency range corresponding to discrete transitions $n^* \rightarrow n^* + 1$ and photoionization from these shells. There is no satisfactory description, however, of the remainder of the spectrum, owing in particular to the presence of transitions from highly excited states of electrons that are absent in the nonequilibrium case. To describe correctly the other sections of the spectrum, for example at lower energies, additional devices are necessary. In particular, to calculate the spectral characteristics of a coronal plasma using an equilibrium-plasma model it is necessary to assume $N_{n'} = 0$ with $n' > n^* + 1$ in accordance with the coronal model.

The approaches considered do not solve the problem of simulating the emission and absorption spectrum of a laser plasma whose temperature and equilibrium characteristics can vary in a wide range. In addition, the approaches indicated do not take into account, as a rule, the plasma's own radiation, which is assumed to be either in equilibrium or weak enough to be neglected.
Allowance for the plasma’s own radiation is usually made in the two-level approximation by introducing an “escape” factor, etc. [6, 7].

We attempt in the present paper to obtain a most general and a sufficiently simple interpolation model for the calculation of the spectral characteristics of a nonequilibrium plasma with radiation. To construct an interpolation for arbitrary conditions, we use previously obtained spectral characteristics of a plasma in two limiting cases — transparent and opaque plasma. Different models can then be used, such as a detailed account of the ion configuration, of the average ion, etc. By way of an example, the equations derived are used to describe the emission spectrum of an argon plasma with arbitrary layer thickness.

1. MODEL OF AVERAGE ION AND NONEQUILIBRIUM RADIATING PLASMA

The average-atom approximation is used in [4] to describe the composition of a nonequilibrium optically transparent plasma. The equations are of the form

$$\frac{dN_n}{dt} = S_n - L_n,$$

where $N_n$ is the average number of electrons on a level with a principal quantum number $n$, $S_n$ is the summary rate of the processes and leads to the appearance of electrons in the state $n$, and $L_n$ is the rate of decrease of the electrons in the state $n$.

The distribution over the degrees of ionization at each instant of time is calculated in the coronal approximation

$$\frac{J_z}{J_{z+1}} = \frac{R_{z+1}}{C_z},$$

where $N_z$ is the density of ions of multiplicity $z$, $R_{z+1}$ is the total recombination rate of an ion with multiplicity $z + 1$, and $C_z$ is the total rate of impact ionization of an ion with multiplicity $z$.

These equations can be generalized by taking into account the radiation of the plasma proper and assuming an arbitrary detailing over the electron states $\nu$ ($\nu$ is the set of quantum numbers that define the state of the electron).

The equations are

$$\frac{dN_\nu}{dt} = -N_\nu \left\{ \sum_{\mu > \nu} \left[ 1 - \frac{N_\mu}{g_\mu} \right] \left( C_{\nu\mu}^{\text{ex}} + W_{\nu\mu}^{\text{abs}} \right) + \sum_{\mu < \nu} \left[ 1 - \frac{N_\mu}{g_\mu} \right] \left( C_{\nu\mu}^{\text{dex}} + W_{\nu\mu}^{\text{em}} \right) + \sum_{\mu > \nu} N_\mu \left( C_{\mu\nu}^{\text{ex}} + W_{\mu\nu}^{\text{abs}} \right) + \sum_{\mu < \nu} N_\mu \left( C_{\mu\nu}^{\text{ex}} + W_{\mu\nu}^{\text{abs}} \right) + N_e \left( \alpha_\nu^{3-b} + \alpha_\nu^{\text{ph-r}} + \alpha_\nu^{x-r} \right) \right\}.$$ 

Here $C_{\nu\mu}^{\text{ex}}, C_{\mu\nu}^{\text{ex}}$ are the rates of impact excitation and quenching; $W_{\nu\mu}^{\text{abs}}, W_{\mu\nu}^{\text{em}}$ the probabilities of photon absorption and emission; $C_{\nu\mu}^{i}, \alpha_\nu^{3-b}$ the rates of impact ionization in 3-particle recombination; $\alpha_\nu^{\text{ph-i}}, \alpha_\nu^{\text{ph-r}}$ the rates of photoionization and photorecombination, $\alpha_\nu^{x-i}, \alpha_\nu^{d-r}$ the rates of autoionization and dielectron recombination. Very simple expressions for them can be found in [4, 8-10].