POPULATION OF EXCITED ATOMIC STATES AND 
IONIZATION IN A NONEQUILIBRIUM LOW-PRESSURE 
CESIUM PLASMA

M. B. Chelnokov

A system of nonlinear algebraic equations is found for the population of the 20 lowest cesium levels in a nonequilibrium low-pressure plasma, with an account of many elementary processes. The system of equations is solved on a computer. A comparison of the results with the experimental data in the literature shows satisfactory agreement. The solution yields, in addition to the level populations, the ionization coefficient and the density of molecular cesium ions. It is shown that the ionization yield under these conditions is maximal at the $6P_{3/2}$ level, thereafter falling off rapidly, so that the 20 lowest levels are responsible for essentially the entire ionization yield, and neglect of the other levels does not cause an error in the calculated ionization coefficient.

When there is an equilibrium level population, hydrogen atoms are ionized by electron impact primarily from a high-lying level [1], and the ionization yield increases monotonically with increasing level energy. Other elements apparently show qualitatively the same behavior. Under nonequilibrium conditions, however, the level population may differ significantly from the equilibrium; in this case the contributions of the various levels to the ionization are not definitely known.

The ionization yield from the levels is governed by the level populations and the ionization probabilities. Under nonequilibrium conditions, when the level population generally falls off more rapidly than the exponential Boltzmann factor, the product of these two quantities results in a level-energy dependence of the ionization yield for which the ionization is maximal at a certain intermediate level, falling off thereafter, so that in a calculation of the ionization yield and the ionization coefficient it is sufficient to take into account some number of levels which is less than the total number of levels actually existing under the given conditions.

In the study reported here, we have attempted to clarify these questions for the case of a nonequilibrium cesium plasma.

The density of atoms at a given excited level is governed by all the processes which populate and empty the levels [2]. In this study, we determine the density of the 20 lowest levels of cesium. Using the approximation of a uniform plasma in a spherical volume of radius $R$, we find a system of nonlinear algebraic balance equations for the level populations which take into account the following processes: direct and stepped

<table>
<thead>
<tr>
<th>$N_e \cdot 10^{-10}$ cm$^{-3}$</th>
<th>$T_e$, eV</th>
<th>$N_{6P_{3/2}} \cdot 10^{-11}$, cm$^{-3}$</th>
<th>$N_{6P_{1/2}} \cdot 10^{-11}$, cm$^{-3}$</th>
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<td>calc.</td>
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<td>5.8</td>
<td>0.681</td>
<td>4.6</td>
<td>3.4</td>
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Fig. 1. Comparison of calculated ionization coefficients with the experimental values of [3] for a tube 1.5 cm in radius. Curves) Calculated; points) experimental. The curves and points are labeled by the electron temperature $T_e$ in electron volts.

Fig. 2. Comparison of the ionization yields for a 20 level calculation and for calculations with different numbers of levels.

Excitation of the atoms by electron impact, ionization of the atoms by electrons, spontaneous decay of the atoms, collisions of a second kind between atoms and electrons, absorption of photons by atoms, induced radiation, collision of two excited atoms resulting in the formation of a molecular ion, and the recombination of ions at the walls. It is assumed for the calculation that the electrons have a Maxwell distribution and that the basic cause of the spectral-line broadening is the Doppler broadening. The system is solved on a computer by the Newton iterative method. Because of the assumptions adopted, the solution is valid for electron densities no greater than $10^{14}$-$10^{15}$ cm$^{-3}$.

The calculated results were compared with the experimental data of [3]. Table 1 shows some illustrative experimental and calculated data on the population of the cesium resonant level for a pressure of $1 \times 10^{-3}$ torr and for a tube 1.5 cm in radius. Table 2 compares the calculated and experimental results for the population of the $8S_{1/2}$ level for the pressure of $5.8 \times 10^{-4}$ torr and for a tube 1.5 cm in radius.

The experimental and calculated level populations are seen to agree within a factor rarely exceeding two. Figure 1 compares the calculated and experimental ionization coefficients, i.e., the ratio of the ion density to the total density of ions and atoms, for a tube 1.5 cm in radius. The solid curves show the calculated data, while the crosses show the experimental electron densities along the tube axis. The labels on the curves and the crosses show the electron temperature in electron volts.

In view of the accuracy of the experimental determination of the atomic density from the temperature of the saturated vapor, and in view of the fact that the electron density in the experiment decreased from the tube axis toward the wall, where it was several times smaller than at the axis, we conclude that the agreement between calculated and experimental results is completely satisfactory.

There are actually a finite number of levels in an atom. The experimental data of Volkova et al. [3] show that it is more meaningful to speak of a cutoff of the ionization potential with respect to particle separation than with respect to the electron temperature. For example, the level $9S_{1/2}$, whose ionization potential in the free atom is only 0.54 eV, was observed at $T_e \sim 1$ eV in [3].

Calculations show that with $N_e = 10^{12}$ cm$^{-3}$, e.g., the ionization potential is about $10^{-3}$ eV less than for a free atom. In the cesium atom there are about 200 levels.

When the chain of equations is cut off at some level or other, the question arises of how to take into account the links between the levels treated and those discarded. Of these links we took into account only the electron-impact excitation, and carried out calculations with accounts of 5, 10, 16, and 20 levels. In each of these calculations, it turned out that the level density was equal to that calculated with an account of a greater number of levels, except for the three or four upper levels, whose densities differed, as a rule, by no more than 10-20%.